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NETWORK DESIGN AND REFUELING STATION LOCATIONING FOR GREEN MARITIME CORRIDORS AND EMISSION TRADING

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Abstract

The maritime shipping industry, responsible for 3% of global greenhouse gas emissions, is facing increasing pressure to transition towards decarbonization due to the escalating threat of climate change. This has inspired the conceptualization of green maritime corridors—a designated network of shipping routes, ports, and associated infrastructure strategically designed to advocate for shipping practices with low or zero emissions. Despite initial empirical studies highlighting their potential, the design of these shipping networks and the establishment of necessary refueling stations for alternative fuel ships remain underdeveloped. Furthermore, the impact of the European Emission Trading System (EU ETS), implemented in 2024, on maritime stakeholders and its effectiveness in incentivizing investments in carbon-free or zero-carbon technologies is poorly understood. Therefore, in this work, we define the network design and refueling station location problem within green maritime corridors and propose an optimization model to minimize overall costs. We analyze emission fees under the EU ETS across different scenarios and assess the investment costs of building green maritime corridors, highlighting incentives for shipping operators to be involved. Thus we present a first optimization approach for designing green maritime corridors, offering critical guidance to policymakers and industry stakeholders for effective implementation of maritime green corridors.

Keywords

Network Design, Refueling Station Location, Green Maritime Corridor, Emission Trading

Introduction

To transition towards decarbonization and ultimate zero emission for the maritime sector, the International Maritime Organization (Hermeling et al.) has established an ambitious target of reducing 50% Greenhouse Gas (GHG) emissions by 2050 compared with 2008. This urgent need to reduce emissions requires actions of maritime shipping operators. Green maritime corridors can be applied to decarbonize the shipping industry (Song et al., 2023), and it is defined as a designated network of shipping routes, ports, and associated infrastructure strategically designed to advocate for maritime shipping practices with low or zero emissions.

The primary contributor to emissions stems from the combustion of marine fuels. Thus, such green corridors aim to promote alternative fuels instead of fossil fuels at sea. In 2021, the Clydebank Declaration aims to establish at least six shorter green maritime corridors by the mid-2020s and increase long-distance routes by 2030 (Chen, 2024). This idea of creating green maritime corridors has recently attracted considerable attention, with governments, ports, and shipping lines announcing the establishment of green corridors jointly as the first step. In addition, the European Emission Trading System (EU ETS) has entered into practice in maritime transportation to accelerate the decarbonization transition. More knowledge is needed on the impact of EU ETS on shipping costs and how this can incentivize stakeholders to invest in carbon-free measures such as creating green maritime corridors.

Several keys to the success of any green maritime corridor are pointed out in (Global Maritime Forum, 2023), and one significance is developing alternative fuel access and port infrastructure. Regarding the potential adoption of methane or LNG, ammonia, and hydrogen in maritime liner shipping, extensive studies in recent years have positioned them as promising alternative fuels for marine fuels to reduce emissions (Huang & Duan, 2023; Zhao et al., 2023). However, beyond technical feasibility, it is essential to align maritime operations and further plan with the ongoing or near-future energy transition ben2023 (Ben Ahmed et al., 2023). Specifically, implementing these alternative fuel ships in maritime trade requires bunkering infrastructure and corresponding operational capabilities, which are necessary for navigating along designed shipping routes to satisfy the transport requirements between ports. Thus, the design of the shipping network to undertake transport tasks and the investment in bunkering infrastructure to support specific alternative fuel ships are significant for green maritime corridors to succeed from the operational level.

In the literature, researchers primarily focus on governmental policy or technological advancements for conceptualizing green maritime corridors (Bouman et al., 2017). Certain empirical studies, in particular, actively underscore the pivotal role of developing green corridors in advancing decarbonization within the maritime transportation sector. For example, (Pra et al., 2020) and (Moura et al., 2017) have scrutinized the viability of green maritime corridors for soybean exportation in Brazil, reporting notable reductions in logistical costs and greenhouse gas emissions. Moreover, (Hessevik, 2022) illustrates that creating corridor networks empowers individual stakeholders to formulate customized low-carbon or zero-emission solutions, as substantiated through a case study within Norway's offshore shipping sector. However, little attention has been paid to the operational modifications required for the successful implementation of green maritime corridors in practical terms. Notably, the design of the shipping network within the corridor and the requisite bunkering stations to support alternative fuel ships within the network still need to be developed. Additionally, implementing green maritime corridors necessitates collaborative efforts from multiple stakeholders, wherein shipping lines, port operators, and governmental bodies are pivotal contributors, jointly working together to create the corridors. Thus, given the implementation of EU ETS, it is vital to estimate emissions fees that need to be paid within different scenarios and compare them with the investment costs for green maritime corridors, providing incentives for shipping operators to join the corridor establishment.

In this work, we propose a general framework to assist the government and companies in designing effective green maritime corridors. Specifically, we first developed a network design and refueling station location problem with green maritime corridors to minimize the overall costs. Our model captures potential synergies across different routes and geographical regions by considering a network of green corridors. Then, we discuss the emissions fees with EU ETS to show the benefits of creating green maritime corridors and the incentives for maritime shipping operators to invest. To the best of our knowledge, this is the first optimization approach to designing green maritime corridors from the operational level and analyzing the impact of EU ETS on incentivizing these carbon-free measures. Our case study reports the green maritime corridor network with the optimized refueling station location. Incorporating EU ETS shows that even with low carbon emission fees, investment in creating corridors is more cost-saving for shipping operators. Overall, this work contributes to energy transition in the maritime domain.

The reminder of this paper is organized as follows. Section **Literature review** presents a literature review of related works. Section **Problem** describes the optimization problem, while Section **Modelling** provides the mathematical model formulations. The experimental results are shown in Section **Case study**. Finally, Section **Conclusions** summarizes this work and recommends future research.

Literature review

Green maritime corridors are a relatively new and promising concept for decarbonizing maritime transportation. The overarching purpose is to develop a network of designated maritime shipping routes by running alternative fuel ships to minimize carbon emissions. The establishment of green maritime corridors encompasses several key pre-requests. First, alternative fuels in maritime transportation should be applied from a technical perspective. For example, liquefied natural gas (LNG) (Schinas & Butler, 2016; Xu & Yang, 2020), ammonia (Kim et al., 2020; Seddiek & Ammar, 2023), hydrogen (Melnyk et al., 2023; Seddiek et al., 2015; Wang et al., 2023), electrical and fuel cell (Candelo-Beccera et al., 2023; van Biert et al., 2016) have been widely discussed as promising candidates in recent years. Second is the collaboration across the value chain, such as port authorities, shipping companies, cargo owners, and alternative fuel producers/providers. Since COP26, many stakeholders in the maritime shipping industry have been forced to support the development of green corridors, as shown in Figure 1. In detail, Table 1 concludes the name, announced time, vessel type, alternative fuel, status and target time of the planned green maritime corridors. Most of the announced green maritime corridors are in their initial partnerships stage, and the operational planning problem about how to run alternative ships along the corridor routes is still unsolved.

Figure 1

Green maritime corridors planned in the world (Global Maritime Forum, 2023)

Table 1

Overview of the planned green maritime corridors

Corridor name	Announced time	Vessel type	Alternative fuel	Status	Target time
Oslo-Rotterdam	2023/10	Container	H	AN	By 2030
Halifax-Hamburg	2022/09	-	M, H, A	AN	TBD
Rotterdam-Singapore	2022/08	Container	M, H, A	CF	By 2027
FIN-EST	2023/10	Vehicle carrier/roro, ferry	U	AN	TBD
Antwerp-Montreal	2022/04	Container, bulk carrier	U	AN	TBD
European green corridors	2022/03	-	U	PF	TBD
US-UK	2022/11	-	U	AN	TBD
Canada-US Great Lakes-St Lawrence	2022/04	-	M, B, E	AN	TBD
Pacific Northwest to Alaska	2022/05	Cruise	U	CF	TBD
Republic of Korea-United States	2022/11	-	M	PF	by 2050
LA-Nagoya	2023/06	Container	U	AN	TBD
LA-Long Beach-Singapore	2022/11	-	U	CF	TBD
LA-Long Beach-Shanghai	2022/01	Container	U	PI	By 2030
US-Fiji-Pacific blue shipping	2023/03	-	U	AN	TBD
SILK Alliance corridor network	2022/05	Container	U	PI	TBD
Singapore-Australia	2023/06	-	U	PF	TBD
Australia-New Zealand	-	-	U	PF	TBD
Western Australia-North Asia iron ore	2022/04	Bulk carrier	A	PI	TBD
Chile cu-concentrate corridor	-	Bulk carrier	A	CF	TBD
Chile Piscicultura corridor	-	-	H	CF	TBD
South Africa-Europe iron ore	2023/03	Bulk carrier	A	PF	TBD

Note: AN: Announcement; CF: Counducting feasibility assessment; PF: Pre-feasibility assessment; PI: Planning implementation; M: Methanol; H: Hydrogen; A: Ammonia; B: Biofuel; E: Electric; U: Unknown

Limited research in the literature focuses on the perspective of implementing green maritime corridors, that is, how to commercially operate those alternative ships within the planned corridors. From the optimization modelling standpoint, one closely related study in the literature is the liner shipping network design problem (LSNDP). It can informally be defined as follows: given a collection of ports, a fleet of container vessels and a group of origin-destination demands, construct a set of services for the container vessels such that the overall operational expenses are minimized while ensuring that all demands can be routed through the resulting network, respecting the capacity of vessels (Meng et al., 2014). Recently, with the implementation of multiple carbon policies in maritime shipping, many researchers have incorporated the reduction of total emissions in LSNDP by integrating various carbon policies (Cariou et al., 2018; Cariou et al., 2019; Chen et al., 2014; Yang et al., 2021). These studies have shown that these carbon policies can significantly influence the economic performance of LSNDP. From January 2024, EU ETS has been compulsory in maritime transportation. Since its launch in 2005, several studies have discussed the open questions on its potential impact and effectiveness (Hermeling et al., 2015; Psaraftis et al., 2021). The investigation by (Cariou et al., 2021) provides support for the positive impact of EU ETS on providing sufficient incentives for specific emission abatement measures. Considering the massive investment for establishing green maritime corridors, it is important to explore the effects of EU ETS on incentivizing shipping operators to contribute to the construction of alternative fuel ships and refueling infrastructures, thereby promoting the development of green maritime corridors.

Green maritime corridors introduce another dimension to this complex network design problem by integrating clean fuel refueling facilities at ports. Our work aligns closely with existing literature on flow refueling location models (FRLM) that primarily focus on locating alternative fuel facilities for road transport. (Kuby & Lim, 2005) propose the model that relates fuel demand to specific routes defined by their origin and destination. They assume that a refueling station can satisfy the demand only if it is located along the route. Such route-based demand representation is realistic for practical refueling scenarios. Recent advancements have seen the adaptation of the FRLM model for maritime refueling network design, mainly considering LNG as an alternative marine fuel (Alvarez et al., 2020; Nerheim, 2023; Peng et al., 2021). (Kuby et al., 2017) apply the FRLM model to support decision-makers in building an LNG bunkering network, addressing truck-to-ship and pipeline-to-ship refueling. Furthermore, (Doymus et al., 2022) design a multi-period planning framework to optimize the refueling barge fleet and routes for ship-to-ship bunkering operations.

However, very limited studies focus on shipping networks and refueling design simultaneously for establishing green maritime corridors from the operational perspective. Given the overview of the status of the current announced green maritime corridors, providing an implementation plan is necessary to promote achieving their target for decarbonization. Therefore, this paper presents the first optimization approach for designing green maritime corridors considering the integrated shipping and fuel network design problem. Based on this model, we compare the economic impacts of EU ETS and further analyze the potential incentives brought by EU ETS for shipping operators to invest in green corridors.

Problem description

Governments and companies have multiple open questions to address in order to establish successful green maritime corridors facing many different carbon policies, especially the effect of EU ETS. First, how can the shipping routes of alternative fuel ships be organized so that the cargo transport demands among the involved ports can be satisfied? Second, where (which port) and capacity can the bunkering infrastructure be built to support the running of those alternative fuel ships on the established routes? Third, how will EU ETS impact shipping costs and emissions, and can it generate efficient incentives for those ports and shipping lines to motivate them to invest in establishing green corridors? To answer the above questions, we propose a mathematical model for liner shipping network design with refueling station location problem, in which the shipping routes and bunkering infrastructure construction are planned simultaneously. Based on this model, we obtain answers to the most pressing questions about green maritime corridors in the form of:

(1). a weekly plan for the liner shipping company to operate their alternative fuel ships within the green corridor, consisting of the port-call sequence and bunkering port for ships;
(2). port investments (which capacity and where?) on the bunkering infrastructure that can support the running of ships on the established routes, including the location (which port) of the refueling stations and their capacities;
(3). an estimation of shipping costs and emission reduction with and without EU ETS, comparing with the investment cost on green maritime corridors and analysing the incentives for shipping lines and ports.

Based on the definition of green shipping corridor concept in (Song et al., 2023), this section is to design a shipping and fuel network for supporting the establishment of green maritime corridors from the operational level, which consists of zero-emission maritime routes between two or more ports and bunkering infrastructures to refuel alternative-fuel ships at ports. The proposed network design and refueling station location problem supports the establishment of any green maritime corridor based on some alternative fuel energy. Even though the problem is relevant for most types of ocean shipping, we present it from the liner shipping perspective.

Assumptions

We consider a given set of candidate shipping routes visiting a set of ports in a specific sequence, where each pair of ports has a known demand for transportation. Moreover, each sailing leg between two ports has a known distance, enabling a calculation of sailing times on a given sailing speed. The given route will be served by several alternative fuel vessels chosen from a set of candidate vessel capacities given as input to the problem. We assume that each vessel of a given capacity has a known investment cost, sailing fuel cost, and idle fuel cost at the port. In the case of building refueling stations, the investment cost of each type of capacity is also known. Considering other relevant zero-emission technologies supporting the refueling process, we assume that this infrastructure investment cost in each port has already been incorporated with the investment cost with different refueling capacities. We assume that only one type of alternative fuel vessel capacity can be chosen for a given route to ensure a realistic route plan where each departure from a port is serviced by vessels with the same capacity. This assumption is also reasonable for the practice.

Problem definition

At the strategic planning level, the optimal refueling station location that can support alternative-fueled ships on operation needs to be determined. Given that the refueling infrastructure of alternative fuels involves a considerable capital investment, this strategic-level decision is critical. At the tactical planning level, the shipping network that operates alternative-fueled ships (called green shipping network in the following) needs to be designed by creating ship routes, that is, the sequence of port visits by a given fleet and the assignment of ships to these routes. In the operational stage of transformation from traditional routes to green corridors, the quantity of cargo to accept or reject for servicing and which path to use to serve the selected cargo need to be decided by carriers, referred to as the cargo-routing problem in the literature.

The decisions made at different levels are mutually affected by each other. Generally, the decisions at the strategic level set the general guidelines for decisions at the tactical and operational levels, and reversely, the information on cost and revenue generated during the system's operation provides grounded feedback for decisions made at a higher level. Thus, we propose an integrated green network design with the refueling station location model, which also considers the cargo-routing problem for each alternative-fueled ship. In detail, we address LSNDP (Liner Shipping Network Design Problem) within the green corridor to provide implement-level decision support for planned green maritime corridors. Our formulation simultaneously decides the ship-scheduling and cargo-routing problem within the green corridor, in which the refueling station location problem is mainly considered to guarantee the running of the green shipping network.

Mathematical formulation

Notation

All the notations used in the formulation are listed as follows:

Sets:

- V: Set of all vertex on graph $G = (V, E)$;
- E_g: Set of ground edges on graph $G = (V, E)$;
- E_v: Set of voyage edges on graph $G = (V, E)$;
- E_f: Set of fictitious edges on graph $G = (V, E)$;
- E: Set of all edges on graph $G = (V, E)$, $E = E_g \cup E_v \cup E_f$;
- R: Set of routes operated by the involved carriers;
- P: Set of ports where refueling station can be built;
- T: Set of vessel types (different capacity);
- C: Set of refueling station capacity at ports;
- W: Set of all index triplets (o, d, i) with o, d, i representing origin, destination, and day of the week, respectively;
- R_e: Set of routes using arc $e \in E$;
- P_e^r: Set of ports that can refuel arc e on route r, $e \in E_v$;
- E_v^{IN}: Set of incoming edges into vertex v;
- E_v^{OUT}: Set of out-going edges from vertex v;

Parameters:

- $R^{(o,d,i)}$: Unit revenues ($/TEU) by satisfying the demand of $(o, d, i) \in W$;
- c_t^{ι}: Fixed cost of investing one vessel of type $t \in T$;
- c_{pc}^{ω}: Fixed cost of investing and operating one refueling station with capacity c at port p;
- c_{tr}^{θ}: Weekly running cost for one vessel of type $t \in T$ on route $r \in R$;
- c_e^{κ}: Costs of shipping a TEU cargo on edge e or costs of storing or holding a TEU of cargo at port;
- h_t: Fuel consumption (tons per day) for vessels of type $t \in T$ when idle at the port;

- g_t: Fuel consumption (tons per day) for vessels of type $t \in T$ during sailing voyage;
- $D^{o,d,i}$: Demand quantities (in TEUs) from port o to port d on day i, $(o, d, i) \in W$;
- $d_e, e = (v, u)$: The number of days it takes on edge e from vertex v to vertex u;
- N_r: (Minimal) Number of ships to serve route $r \in R$;
- S_r: Sailing time (days) of route $r \in R$;
- I_r: Idle time at port of route $r \in R$;
- L_p: (Maximal) Refueling capacity that port $p \in P$ can provide;
- λ_t : Capacity (in TEUs) for a vessel of type $t \in T$;
- ρ : Fuel price (/ton);
- ϕ: Number of routes to choose due to budget limitation;

Decision variables:

- $q_e^{(o,d,i)}$: The quantity of containers demands (in TEUs) allocated to edge $e \in E$;
- x_r: Binary, equal to 1 if route $r \in R$ is selected, and 0 otherwise;
- y_{rp}^t: Binary, equal to 1 if ships of type $t \in T$ operated on route $r \in R$ choose to refuel at port $p \in P$;
- α_{pc}: Binary, equal to 1 if the refueling station with capacity c is built at port p;
- m_{tr}: Number of vessels of type $t \in T$ assigned to route $r \in R$;

Modeling approach

We define a triplet (o, d, i) to represent a particular demand commodity transport, characterized by the origin port o and the destination port d, and the day i of the week when the supply is available at port o. Given that, generally, no route visits more than one port in one day, and each port is called at least once a week, we consider days as our time units and one week as our planning horizon. We formulate our network design and refueling station location model based on a directed space-time network $G = (V, E)$ with vertex set V and edge set E, similar as described in (Agarwal & Ergun, 2008). Each vertex $v \in V$ represents a port $p \in P$ on the day of the week $i \in \{1,2,3,4,5,6,7\}$, denoted by v_{pi} or v depending on the exposition ease. We define three types of edges in the network $G = (V, E)$. First, we construct voyage edges E_v to represent the movement of ships from one port to another; Second, we create ground edges E_g to show the overnight staying of ships at a port; Third, we also construct fictitious edges E_f for all demands. That is, $E = E_v \cup E_g \cup E_f$.

Figure 2

Illustration of a shipping route in a space-time network with four ports

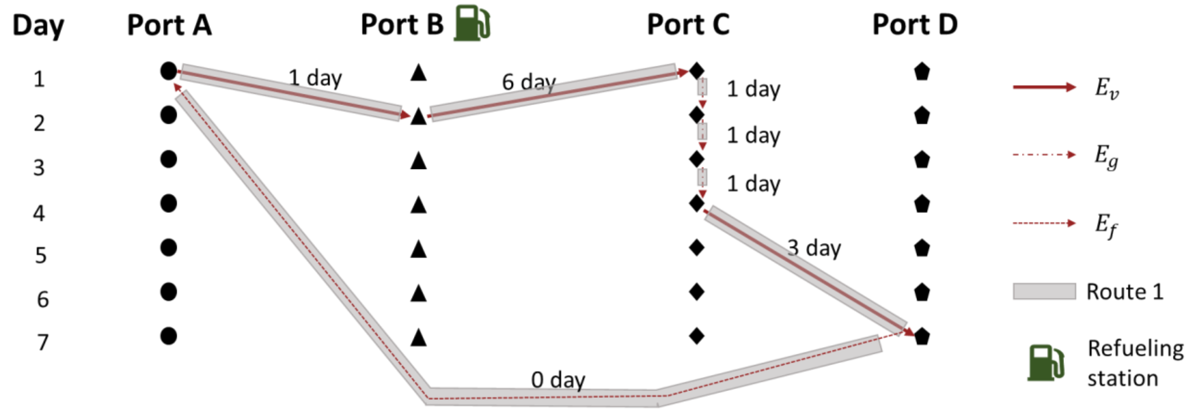


Figure 2 illustrates one shipping route in a space-time network with four ports, in which two ports are invested to provide refueling services for alternative-fueled ships. The length of the edge represents $d_{e(v,u)}$ days it takes for a ship movement on edge $e = (v$, denoted by d_e for simplicity. Correspondingly, $d_e = 1$ for $e \in E_g$ and $d_e = 0$ for $e \in E_f$. Serving such a shipping route with the green corridor, shown in Figure 2, necessitates various variable and fixed costs. In our model, we consider four types of costs. First, c_t^{ι} is the cost for each type $t \in T$ of alternative fuel ship invested by shipping companies. Second, c_{pc}^{ω} is the cost incurred by investing and operating a refueling station with capacity $c \in C$ at port $p \in P$. Third, c_{tr}^{θ} represents the weekly running costs incurred by vessels in operation, and fourth, c_e^{κ} reflects the variable cost by cargo movements. In detail, c_e^{κ} for $e \in E_v$ represents the cost of shipping a TEU cargo on voyage edge, and c_e^{κ} for $e \in E_g$ denotes the cost of holding a TEU cargo at the port. For all fictitious edge $e \in E_f$, the relevant costs are zero. The route set R contains all the routes operated by the involved carriers that N_r can satisfy the number of ships required to maintain a weekly port-call frequency, which can be shown as a sequence of vertices from vertex v_1 to v_r or edges e_1 to e_{r-1}, that is, $r = [v_1, v_2, \dots v_r]$ or $r = [e_1, e_2, \dots e_{r-1}]$.

Formulations

Based on the above notations, we develop our formulation as follows:

$$\min \begin{array}{c} \Sigma_{t\in T}\Sigma_{r\in R} c_t^{\iota} m_{tr} + \Sigma_{c\in C}\Sigma_{p\in P} c_{pc}^{\omega}\alpha_{pc} + \Sigma_{t\in T}\Sigma_{r\in R} c_{tr}^{\theta} m_{tr} \\ + \Sigma_{t\in T}\Sigma_{r\in R}\rho x_r (S_r g_t + I_r h_t) + \Sigma_{(o,d,i)\in W}\Sigma_{e\in E_g\cup E_u} c_e^{\kappa} q_e^{(o,d,i)} - \Sigma_{(o,d,i)\in W}\Sigma_{j=1}^{j=7} R^{(o,d,i)} q_{(v_{dj},v_{oi})}^{(o,d,i)} \end{array} \quad (1)$$

Subject to:

$$\Sigma_{e\in E_v^{IN}} q_e^{(o,d,i)} - \Sigma_{e\in E_v^{OUT}} q_e^{(o,d,i)} = 0 \ \ \forall v \in V, (o,d,i) \in W \tag{2}$$

$$\Sigma_{(o,d,i)\in W} q_e^{(o,d,i)} - \Sigma_{r\in R_e} \Sigma_{t\in T} \lambda_t m_{tr} \leq 0 \ \ \forall e \in E_v \tag{3}$$

$$\Sigma_{j=1}^{j=7} q_{(v_{dj}, v_{oi})}^{(o,d,i)} \leq D^{(o,d,i)} \ \ \forall (o,d,i) \in W \tag{4}$$

$$\Sigma_{t\in T} \Sigma_{r\in R_e} \left(\Sigma_{e\in E_v} g_t d_e y_{rp}^t + \Sigma_{e\in E_g} h_t d_e y_{rp}^t \right) \leq \Sigma_{c\in C} c\alpha_{pc} \ \ \forall p \in P \tag{5}$$

$$\Sigma_{c\in C} c\alpha_{pc} \leq L_p \ \ \forall p \in P \tag{6}$$

$$\Sigma_{p\in P} \Sigma_{c\in C} \alpha_{pc} \leq 1 \tag{7}$$

$$\Sigma_{p\in P} y_{rp}^t = m_{tr} \ \ \forall t \in T, r \in R \tag{8}$$

$$N_r x_r \leq \Sigma_{t\in T} m_{tr} \ \ \forall r \in R \tag{9}$$

$$m_{tr} \leq M x_r \ \ \forall t \in T, r \in R \tag{10}$$

$$m_{tr} \geq x_r \ \ \forall t \in T, r \in R \tag{11}$$

$$\Sigma_{r\in R} x_r \geq \phi \ \ \forall t \in T, r \in R \tag{12}$$

$$q_e^{(o,d,i)} \geq 0 \ \ \forall (o,d,i) \in W, e \in E \tag{13}$$

$$m_{tr} \geq 0 \ \ \forall t \in T, r \in R \tag{14}$$

$$y_{rp}^t \in \{0,1\} \ \forall r \in R, p \in P, t \in T \tag{15}$$

$$\alpha_{pc} \in \{0,1\} \ \forall p \in P, c \in C \tag{16}$$

$$x_r \in \{0,1\} \ \forall r \in R \tag{17}$$

The objective function (1) minimizes the total system costs within the green maritime corridor. The first two terms capture the investment costs of vessels and refueling stations, respectively. The third term represents the weekly costs incurred by operating those alternative fuel ships within the green corridor. The fourth term determines the fuel costs, including consumption while sailing in the sea and idling at the port. The fifth term denotes the costs of shipping cargoes along the routes connecting various origin and destination pairs. The last term computes the revenue generated from fulfilling cargo transport demands, compensating system costs.

Constraint (2) ensures commodity flow balance at each vertex of the space-time network. For each commodity $(o,d,i) \in W$, the total flow into each vertex v must be equal to the flow out of it. Constraint (3) is an edge capacity constraint, which ensures that the total flow on a voyage edge should be within the capacity of all types of vessels operated on that edge. Constraint (4) guarantees that the total flow of a given commodity from its origin port to the destination port cannot exceed the demand at the destination port. Constraint (5) ensures that the capacity of the refueling station must satisfy the alternative fuel demands of all vessels required from this refueling station. We assume that a ship would be fueled up to its capacity, and thus, the required quantity of alternative fuels at the refueling station is equal to the days travelled multiplied by the fuel consumption rate. Constraint 6) requires that the fuel capacity of the refueling station is less than or equal to the maximal alternative fuels that the port can invest. Constraint (7) states that only one capacity can be chosen by a port to build the refueling station. Constraint (8) ensures that all ships allocated running on the route can be refuelled at one port. Constraint (9) states that all types of vessels assigned to each route should not be less than the minimal number of vessels required by this route. Constraints (10-11) define the internal relationship between two variables m_{tr} and x_r, representing that the vessels can only be assigned to the route being selected to operate within the green corridor. Constraint (12) observes the requirement of the selected number of routes. Finally, constraints (13-16) denote the properties of all decision variables.

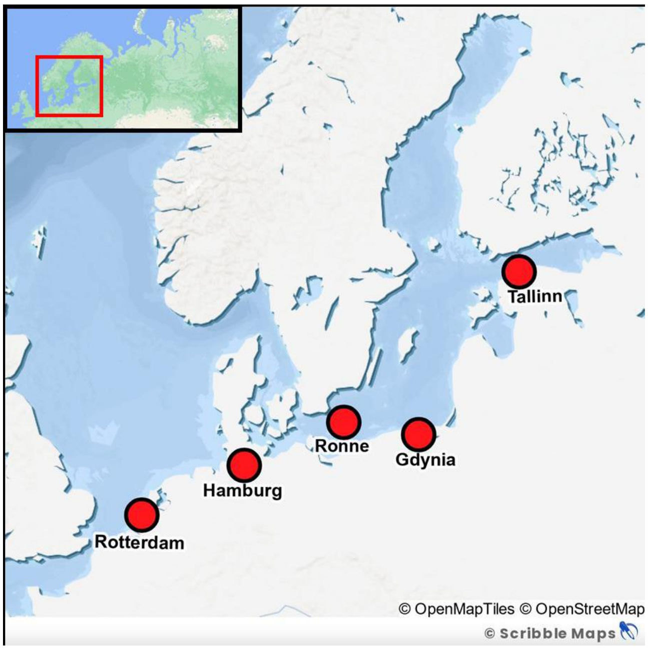
Case study

We consider the Northern European and Baltic Green Corridor project initiated in December 2021. As shown in Figure 3, the project was a collaboration between first mover ports in the Baltic Sea region: the Port of Gdynia, the Port of Roenne, the Port of Rotterdam, the Hamburg Port Authority, and the Port of Tallinn, in partnership with the Maersk Mc-Kinney Moller Center for zero carbon shipping, while it is still at the initial pre-feasibility stage. Our model aims to provide decision support on establishing green shipping corridors from the operational level and drive the maritime industry from decarbonization to a zero-emission future.

In the following, we describe the data input used in creating the Northern European Corridors in Section **Input data**. We follow that by presenting the shipping network and bunkering design suggested by our model for creating the green corridor in Section **Green maritime corridor design suggested by our model**. Next, we study the potential benefits of carbon dioxide emissions with and without considering EU ETS in the Section **Cost comparison with consideration of EU ETS**.

Figure 3

Map of Green Corridor in Northern Europe and the Baltic Sea



Input data

Costs relevant to apply alternative-fuel vessels are shown in Table 2.

Table 2

The parameters values for vessel types utilized in experiments (Brouer et al., 2014; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022)

Parameter	Unit	Type A	Type B
Capacity	TEU	900	1500
Operating speed	Knot	18	18
Fixed vessel investment costs c^{ι}	10^3 \$	48.3	60.4
Fuel consumption at sea g_t	Ton/Day	75	90
Fuel consumption in port h_t	Ton/Day	5	5
Operating costs (to calculate c^{θ})	10^3\$/Day	U [8, 10]	U [14, 16]

In the Northern European and Baltic green maritime corridor, four liner shipping routes are under consideration, including Route 1: Port of Rotterdam → Port of Hamburg → Port of Rønne → Port of Rotterdam, Route 2: Port of Rotterdam → Port of Hamburg → Port of Rønne → Port of Gdynia → Port of Tallinn → Port of Rotterdam, Route 3: Port of Hamburg → Port of Tallinn → Port of Gdynia → Port of Hamburg, and Route 4: Port of Rotterdam → Port of Rønne → Port of Tallinn → Port of Gdynia →

Port of Rotterdam. While currently serviced by conventional vessels, there are plans to introduce alternative-fueled vessels in the coming years to establish environmentally sustainable corridors. We obtained the distance between ports from the website https://www.routescanner.com/ and calculated the days it takes by vessel speed of 18 knots.

Table 3

The route-relevant parameter

Parameter	Unit	Route 1	Route 2	Route 3	Route 4
Number of ships N_r	Ship	1	2	1	2
Sailing time at sea S_r	Day	2	7	6	8
Idle time in port I_r	Day	4	3	1	1

According to (Butler et al., 2021) and (Global Maritime Forum, 2021), port investment costs of bunkering structure are generated randomly from 300 $10^3\$/Ton$ to 700 $10^3\$/Ton$, with the capacity of bunkering station in 10000, 12000, 15000, 18000 tons, respectively. The OD demands are generated according to history data published by Maersk shipping line and (Brouer et al., 2014). The total amount of CO_2 emissions by the traditional fuel vessels by multiplying a factor of converting fuel cost to CO_2 defined by (Corbett et al., 2009):

$$E_{f_2^{co}} = 3.17, \tag{18}$$

representing the amount of tons of CO_2 emissions by burning per ton of traditional fuel.

Green maritime corridor design suggested by our model

Table 4 shows the proposed corridor design for the Northern European Green Maritime Corridor under different value ϕ that represents the limitation of routes number to invest. Regarding the implementation from the operational perspective, several decisions are provided by our model, including alternative-fueled vessel deployment, shipping network design, and bunkering station investment. In detail, we report the selected routes, bunkering station location and capacity, alternative-fueled ship types and numbers, reduced CO_2 emissions, total corridor costs, and the cost for unit reduction of CO_2 emissions. We observe that each type of alternative-fueled ships is deployed one on each selected route, and the Port of Hamburg and the Port of Rotterdam are the two most potential ports where bunkering stations are located. Figure 4 provides a graphical representation of the Northern European Creen Maritime Corridor.

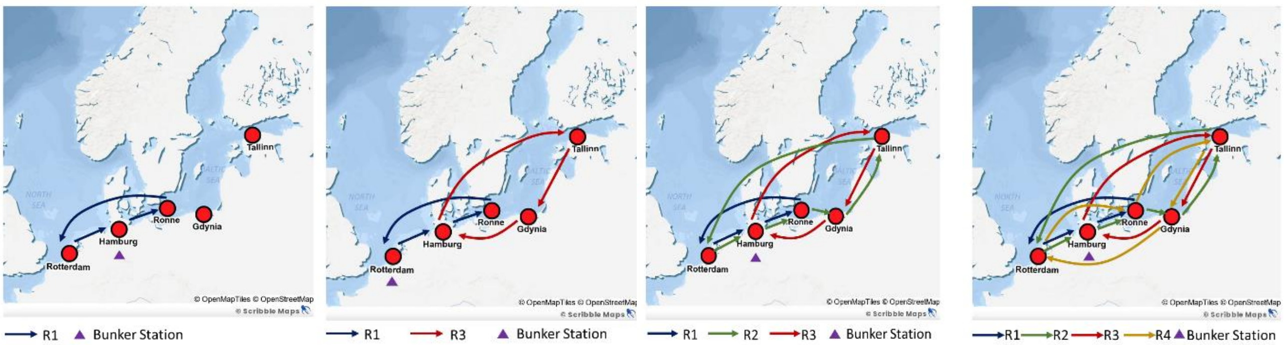
Table 4

Northern European corridor design

ϕ	Selected Route	Bunker Station		Alternative-fueled Ship		Reduced CO_2 Emissions (ton)	Total Corridor Costs (10^3\$)	Unit Cost of CO_2 Reduction (10^3\$/ton)
		Location	Capacity (ton)	Type	Number			
1	R1	Hamburg	10000	A	1	912.96	27735.50	30.38
				B	1			
2	R1, R3	Rotterdam	12000	A	2	1210.94	32255.60	26.64
				B	2			
3	R1, R2, R3	Hamburg	12000	A	3	1965.40	30553.60	15.55
				B	3			
4	R1, R2, R3, R4	Hamburg	15000	A	4	2288.74	42203.60	14.07
				B	4			

Figure 4

Northern European & Baltic green maritime corridor

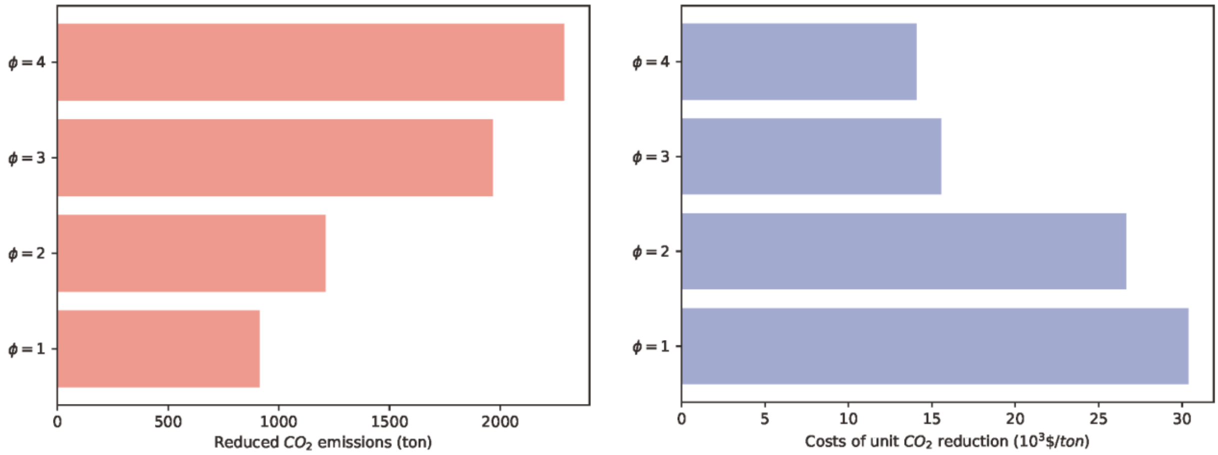


(a) $\phi = 1$ (b) $\phi = 2$ (3) $\phi = 3$ (4) $\phi = 4$

Next, in Figure 5, we compare the total reduction of CO_2 emissions and the cost of unit CO_2 reduction under the different sizes of the network (represented by ϕ). It is shown that the total reduction of CO_2 emissions increases with investing more routes into the green corridors, and the unit cost for emission reduction decreases simultaneously.

Figure 5

Impact of network size on CO_2 emissions



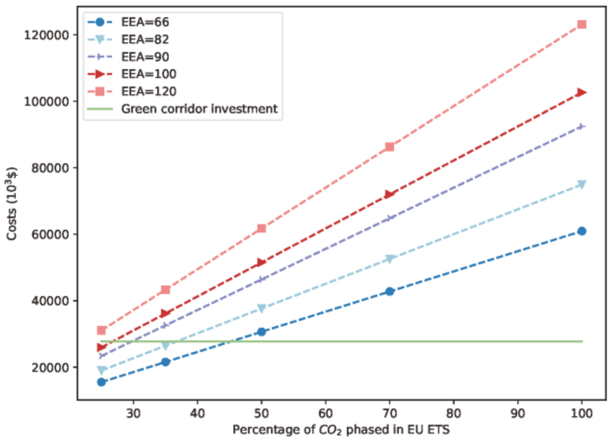
Cost comparison with consideration of EU ETS

Maritime transportation was announced to be included in the European Union Emission Trading System (EU ETS) that entered into force on January 1, 2024. The EU ETS comes from the increasing regulatory landscape imposed by the IMO, which will directly impact the EU maritime shipping market. The high carbon tax fee provides potential incentives for creating green maritime corridors. Therefore, we compare the payment of carbon emissions under the EU ETS regulation with the investment in alternative-fueled ships and bunkering stations, which implies the attraction of creating green maritime corridors.

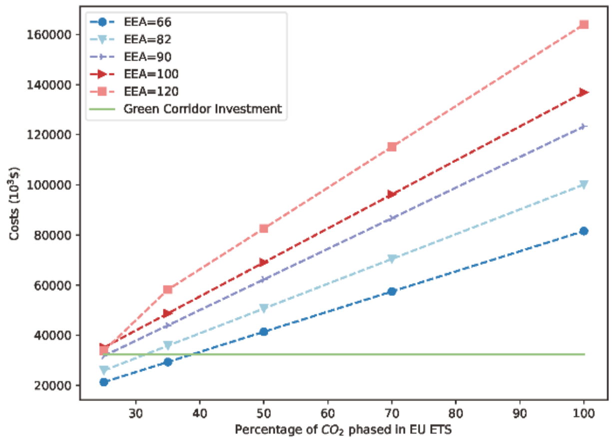
One emission allowance in EU ETS, referred to as EEA in our paper, represents one ton of CO_2 equivalent. For example, $EEA = 66$ means one ton of CO_2 emissions need to pay for 66$ for operators. There is a planned stage to count all CO_2 emissions into EU ETS gradually, thus, in Figure 6, we compare the CO_2 emission costs under different EEA first and under different cases on 25%, 35%, 50%, 70%, 100% percentage of CO_2 emissions phrased-in EU ETS. From Figure 6 (c) and Figure 6 (d), we observed that the investment on establishing at least three routes is attractive for operators under EU ETS. Moreover, the continuously rising prices of the carbon allowances and the expected inclusion of shipping into the EU ETS has created a need to understand the financial exposure related to shipping for operators. Furthermore, as shown in Figure Figure 6 (a) and Figure 6 (c), even with the low EEA, the larger percentage of CO_2 phrased-in EU ETS, the carbon tax payment increased dramatically to exceed the investment on green corridors, which provides sufficient incentives for operators to take specific measures to join establishing green maritime corridors.

Figure 6

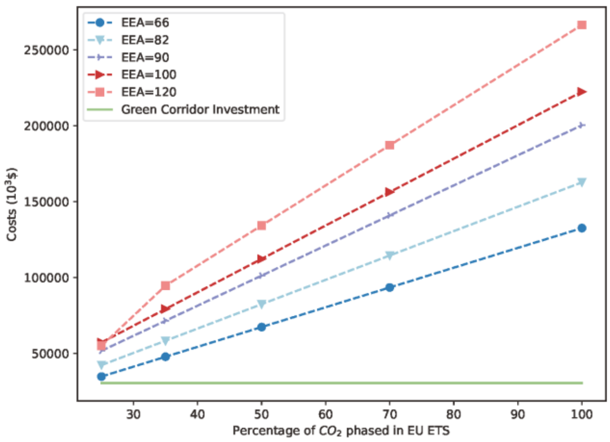
Comparison with consideration of EU ETS



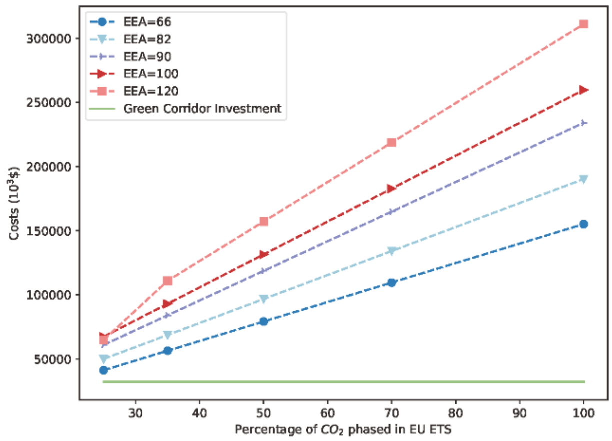
$(a)\ \phi = 1$



$(b)\ \phi = 2$



$(c)\ \phi = 3$



$(d)\ \phi = 4$

Conclusions and future work

In this work, we propose a network design and refueling station location problem for establishing green maritime corridors from the implementation perspective. The decisions include the sequence of port calls, the optimal number of vessels to deploy in the service, and the optimal refueling station location and capacity. The proposed model minimizes the total costs of running alternative ships within the green corridors.

We apply the model to the announced European Green Maritime Corridors. The results show the scale of economy on the cost of CO_2 emission reduction, that is, from 30.38 ($10^3\$/ton$) with running on one route to 14.07 ($10^3\$/ton$) with running on four routes in the corridor. Furthermore, we discuss the impact of EU ETS on shipping costs because of carbon emissions with different emission allowances. We find that even with a low emission allowance, the carbon emission payment caused by EU ETS can significantly exceed the investment cost of establishing green maritime corridors. Therefore, the EU ETS, when applied effectively, can provide attractive incentives for shipping operators and stakeholders to contribute to the design of green corridors.

In future work, the proposed model can be tested on different cases of the announced green corridors, and more types of alternative fuels should also be considered in different corridors.

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