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# LNG Bunkering Station Deployment Problem—A Case Study of a Chinese Container Shipping Network

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**Abstract:** Liquefied natural gas (LNG) is a promising measure to reduce shipping emissions and alleviate air pollution problem, especially in coastal areas. Currently, the lack of a complete infrastructure system is preventing the extensive application of dual-fueled ships that are mainly LNG-powered. Given that groups of LNG bunkering stations are under establishment in various countries and areas, the construction plan becomes critical. In this paper, we focus on the LNG bunkering station deployment problem, which identifies the locations of the stations to be built. A large-scale case study of China's container shipping network was conducted. The problem scale of this case paper exceeds those in previous academic studies. Thus, this study better validates the model and solution method proposed than numerical experiments that are randomly generated. Sensitive analyses on the LNG price, bunkering station construction costs, and total budget were carried out. The results yielded provide practical suggestions and managerial insights for the competent department. In addition to building a complete bunkering system, subsidies to ship operators for consuming LNG and higher production efficiency in bunkering station construction also help promote the application of LNG as marine fuel.

**Keywords:** LNG bunkering station deployment; maritime transportation; China's container shipping network

**MSC:** 90-10

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## 1. Introduction

The problems of climate change and greenhouse gas (GHG) emission have attracted extensive attention from both industry and academia [1–6]. In the 21st United Nations Climate Change Conference, the United Nations adopted the Paris Agreement, which proposes the target to control the global average temperature rise within 2 degree Celsius compared to pre-industrial levels, and pursuing 1.5 degree Celsius [7]. It is believed that under such relatively mild temperature rise, the risks and impacts of climate change would be significantly reduced. However, the global average temperature rise will reach 3 degrees Celsius by the end of this century without more efficient measures coming into force [8]. The transportation industry and the maritime industry also put efforts on the task of emission reduction [9–21]. According to the latest Review of Maritime Transport, international shipping accounts for approximately 3 percent of global GHG emissions from human activities, and thus decarbonization has become an increasingly urgent priority in the industry [22]. Various emission reduction targets and agreements have been proposed and approved recently. The "Getting to Zero Coalition's Call to Action for Shipping Decarbonization", which is signed by over 200 maritime industry organizations, is committed to implementing the commercial deployment of zero-emission vessels along deep-sea trade routes by 2030 and the entirely net-zero energy sources for international shipping by mid-century [23]. It is highlighted that private party actions must go hand in hand with government actions in the decarbonization of the maritime sector, constructing the necessary infrastructure for scalable zero-emission energy sources, including production, distribution, storage, and bunkering [23]. At the United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) 26, the Dhaka–Glasgow Declaration was launched to establish a mandatory GHG levy on international shipping, and the Clydebank Declaration aims to set zero-emission maritime routes between ports [24,25].

With the ambitious emission-reduction plan, the uptake of zero and net-zero fuels, for example, hydrogen, synthetic non-carbon fuels (ammonia), battery power derived from zero carbon electricity based on solar, wind, hydro or nuclear power, and biomass, is advancing slowly [8,22]. As transitional measures, other alternative fuels are adopted, in which LNG is the most widely used one. LNG is the greenest fossil energy source for ship use, almost eliminates the sulfur emissions and particulate matters, and reduces nitrogen oxides to 20 percent and $CO_2$ emissions to 80 percent of the emission levels of heavy fuel oil (HFO), which is the traditional fuel in the maritime. From the technology and economic perspectives, dual-fuel engines enable ships to be operated on LNG and traditional marine fuels to comply with emission reduction regulations while remaining competitive [8,26,27]. As the transitional fuels for maritime transport, the consumption volume of LNG as marine fuel is growing fast, and the investment on application promotion is also soaring [28].

One of the critical issues in the popularization of dual-fueled vessels is the infrastructure construction, especially the establishment of LNG bunkering facilities [29,30]. According to the statistics, in addition to the existing ones, dozens of LNG bunkering facilities are under construction globally [30]. Therefore, research on the implementation of LNG bunkering facilities is in urgent need.

Numerous studies have been conducted focusing on the promotion of LNG as marine fuel. One branch comprises papers investigating dual-fueled ship retrofitting and deployment from the ship operators' perspective [26,31–34]. The other one comprises studies considering the infrastructure construction, including the design of bunkering facilities [35,36] and number and location of bunkering stations [37,38]. In this paper, we focus on the deployment problem of the LNG bunkering stations, namely, how to arrange the construction work of various LNG bunkering stations. China has seven of the world's top ten container ports, including Hong Kong, and is a pioneer in the promotion of LNG as marine fuel [39,40]. Thus, in this paper, we conduct a case study of the LNG bunkering station deployment problem based on the Chinese shipping network. In the case study, the deployment of ships is considered as well.

Given the literature, the contribution of this paper is threefold. First, we abstract the Chinese container shipping network on the basis of liner shipping routes operated by the China Ocean Shipping (Group) Company (COSCO), which is the largest shipping company in China. Data of LNG bunkering price, traditional fuel price, LNG bunkering station construction costs, and other critical parameters were collected from real-world cases and official websites. This case study validates the model and algorithm proposed in academic research better than numerical experiments that are randomly generated. Second, this study provides specific suggestions for the LNG bunkering station deployment problem in China, and managerial insights can be provided for the competent department. Third, sensitive analyses conducted in this paper also investigate the effectiveness of the deployment plan with different budgets, LNG bunkering station costs, and LNG prices.

The remainder of this paper is organized as follows. Section 2 provides the concrete problem description and the mathematical model. Section 3 introduces the solution method briefly. Section 4 presents the numerical experiments and corresponding results. Last but not least, the paper closes with conclusions in Section 5.

## 2. Model Formulation

The problem description and the specific mathematical model for the LNG bunkering station problem in a container shipping network are provided in this section.

*2.1. Problem Description*

In this study, we consider a container shipping network consisting of multiple ports that will be equipped with LNG bunkering stations. Given the limited construction budget, not all ports will be equipped with an LNG bunkering station. In this paper, from the government's perspective, we determine the number of LNG bunkering stations and the specific ports to provide the LNG bunkering service as well.

The set of physical ports in the container shipping network is denoted by $\mathcal{P} = \{1,2,\ldots,|\mathcal{P}|\}$. A set of liner shipping routes, $\mathcal{R} = \{1,2,\ldots,|\mathcal{R}|\}$, are operated on the shipping network by different shipping companies. On route $j$, $\eta_j$ homogeneous ships are chartered in and deployed to sail along a closed loop. The set of ports of call on route $j$ is denoted by $\mathcal{P}'_j$, and $k \in \mathcal{P}'_j$ represents the $k^{\text{th}}$ one.

Route $j$ can be divided into $\left|\mathcal{P}'_j\right|$ voyages with the sailing distance of $L_{jk}$. Ships deployed on route $j$ berth at port of call $k$ for $m_{jk}$ hours for cargo handling, and sail at the speed of $\mu_j$ knots (nautical mile per hour). For each route, the weekly service frequency should be maintained as stated in previous studies on ship deployment [41–43].

Currently, no LNG bunkering service is available in the network, and therefore all ships deployed consume MDO as the main bunker fuel for power. The weekly chartering cost of such a traditional diesel ship for route $j$ is denoted by $C^j_{\text{MDO}}$. The market bunkering price of MDO is denoted by $O_{\text{MDO}}$ USD/ton. The MDO consumption rate of ship $j$, $g^j_{\text{MDO}}(\mu_j)$ ton/n mile, depends on the sailing speed and is in an approximate third power relationship with $\mu_j$ [41,44,45]. Meanwhile, the consumption rate while berthing, denoted by $g'^j_{\text{MDO}}$, does not change with the sailing speed [28,46]. Due to the damage caused by ship emissions, in this paper, we consider that the environmental costs of $E_{\text{MDO}}$ USD will be incurred when a ton of MDO is consumed.

When the LNG bunkering service is available, dual-fueled ships may also be deployed on route $j$ at the weekly chartering price of $C^j_{\text{Dual}}$ USD. A dual-fueled ship deployed on route $j$ consumes $g^j_{\text{LNG}}(\mu_j)$ tons of LNG per nautical mile and $g'^j_{\text{LNG}}$ tons of LNG per berthing hour. Following [47], it is assumed that the LNG tanker of the dual-fueled ships will be filled up at each bunkering station on its route. MDO will be used if LNG is in short, considering the limited LNG tank capacity, denoted by $W_j$ tons. For MDO, the fuel consumption rates for traditional ships and dual-fueled ships for the same route are the same. Based on this, we have $g'^j_{\text{MDO}} \Big/ g'^j_{\text{LNG}} = g^j_{\text{MDO}}(\mu_j) \Big/ g^j_{\text{LNG}}(\mu_j) = Q (\forall j \in \mathcal{V})$, in which $Q$ is a coefficient, namely, the MDO consumption rate is proportional to the LNG consumption rate. Therefore, for route $j$, when one ton of LNG is consumed, $Q$ tons of MDO are saved [47]. To assure that the study is not trivial, we further assume that LNG is more economical than MDO, namely, $C^j_{\text{Dual}} > C^j_{\text{MDO}}$ and $Q \times O_{\text{MDO}} > O_{\text{LNG}}$, in which $O_{\text{LNG}}$ is the bunkering price of LNG (USD/ton).

Compared with MDO, LNG has a much lower environmental cost $E_{\text{LNG}}$. To lower the ship emission levels, the government will allocate a budget to build LNG bunkering stations at some of the ports. The construction costs of a bunkering station at port $i, i \in \mathcal{P}$, are denoted by $\bar{C}^{\mathcal{P}}_i (\forall i \in \mathcal{P})$ USD. The given total budget for LNG bunkering station construction is denoted by $B_t$ USD. The government decides which LNG bunkering station to build, and shipping companies make the ship deployment decisions. In this paper, the government aims to minimize the annual ship emission costs, and shipping companies minimize their annual operating costs.

*2.2. Mathematical Model*

Here, we list the notations used in the mathematical model.

**Sets and indices**

| | |
|---|---|
| $\mathcal{P}$ | the set of physical ports in the network, $\mathcal{P} = \{1, 2, \ldots, \lvert\mathcal{P}\rvert\}$, indexed by $i$; |
| $\mathcal{R}$ | the set of shipping routes operated by different shipping companies, $\mathcal{R} = \{1, 2, \ldots, \lvert\mathcal{R}\rvert\}$, indexed by $j$; |
| $\mathcal{P'}_j$ | the set of ports of call covered by route $j$, $\forall j \in \mathcal{R}$, indexed by $k$. |

**Parameters**

| | |
|---|---|
| $T_{jki}$ | binary parameter, equal to 1 if the $k^{\text{th}}$ port of call of route $j$ refers to physical port $i$, 0 otherwise, $\forall j \in \mathcal{R}, \forall k \in \mathcal{P'}_j, \forall i \in \mathcal{P}$; |
| $L_{jk}$ | the sailing distance (nm) from the $k^{\text{th}}$ port of call on route $j$ to the $k+1^{\text{th}}$ port of call, $\forall j \in \mathcal{R}, k = 1, \ldots, \lvert\mathcal{P'}_j\rvert - 1$; |
| $L_{j\lvert\mathcal{P'}_j\rvert}$ | the sailing distance (nm) from the $\lvert\mathcal{P'}_j\rvert^{\text{th}}$ port on route $j$ to the 1st port, $\forall j \in \mathcal{R}$; |
| $\bar{\mu}_j$ | the upper limit of sailing speed (knot) of ships deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $\underline{\mu}_j$ | the lower limit of sailing speed (knot) of ships deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $C^j_{\text{MDO}}$ | the weekly chartering cost (USD/week) of traditional diesel ships deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $C^j_{\text{Dual}}$ | the weekly chartering cost (USD/week) of dual-fueled ships deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $O_{\text{MDO}}$ | the bunkering price of MDO (USD/ton); |
| $O_{\text{LNG}}$ | the bunkering price of LNG (USD/ton); |
| $C^{\mathcal{P}}_i$ | the construction cost (USD) of LNG bunkering station at physical port $i$, $\forall i \in \mathcal{P}$; |
| $T$ | the number of stages of the LNG bunkering system deployment plan; |
| $B_t$ | the given budget (USD) that is allocated to LNG bunkering station construction; |
| $Q$ | the coefficient that represents the relationship between the consumption rate of MDO and LNG; |
| $E_{\text{MDO}}$ | the ship emission cost of one ton of MDO (USD/ton); |
| $E_{\text{LNG}}$ | the ship emission cost of one ton of LNG (USD/ton); |
| $W_j$ | the LNG tank capacity of dual-fueled ships that are deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $m_{jk}$ | the berthing time (hour) at the $k^{\text{th}}$ port of call on route $j$, $\forall j \in \mathcal{R}, \forall k \in \mathcal{P'}_j$. |

**Upper-level decision variables**

| | |
|---|---|
| $y_i$ | binary variable, equal to 1 if LNG bunkering station at physical port $i$ will be constructed, 0 otherwise, $\forall i \in \mathcal{P}$. |

**Lower-level decision variables**

| | |
|---|---|
| $x_j$ | binary variable, equal to 0 if traditional diesel ships are deployed on route $j$, equal to 1 if dual-fueled ships are deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $\eta_j$ | integer variable, the number of ships chartered in and deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $\mu_j$ | the sailing speed (knot) of ships chartered in and deployed on route $j$, $\forall j \in \mathcal{R}$; |
| $g^j_{\text{MDO}}(\mu_j)$ | the MDO consumption rate (ton/n mile) of ships deployed on route $j$ while sailing, $\forall j \in \mathcal{R}$; |
| $g'^j_{\text{MDO}}$ | the MDO consumption rate (ton/hour) of ships deployed on route $j$ while berthing, $\forall j \in \mathcal{R}$; |
| $g^j_{\text{LNG}}(\mu_j)$ | the LNG consumption rate (ton/n mile) of dual-fueled ships deployed on route $j$ while sailing, $\forall j \in \mathcal{R}$; |
| $g'^j_{\text{LNG}}$ | the LNG consumption rate (ton/hour) of dual-fueled ships deployed on route $j$ while berthing, $\forall j \in \mathcal{R}$; |
| $\theta_{jk}$ | binary variable, equal to 1 if port of call $k$ on route $j$ has LNG bunkering station, 0 otherwise, $\forall j \in \mathcal{R}, \forall k \in \mathcal{P'}_j$; |
| $\pi^{Leave}_{jk}$ | the LNG remaining volume when dual-fueled ships leave port of call $k$ on route $j$ (after refueling, if any), $\forall j \in \mathcal{R}, \forall k \in \mathcal{P'}_j$; |
| $\pi^{Finish}_{jk}$ | the LNG remaining volume when the cargo handling at port of call $k$ on route $j$ is just finished (before refueling, if any), $\forall j \in \mathcal{R}, \forall k \in \mathcal{P'}_j$; |
| $\hat{\rho}^j_{\text{LNG}}$ | the weekly LNG consumption volume (ton) of route $j$, $\forall j \in \mathcal{R}$; |
| $\hat{\rho}^j_{\text{MDO}}$ | the weekly MDO consumption volume (ton) of route $j$, $\forall j \in \mathcal{R}$. |

**Vectors**

$\vec{y}$ the vector of $y_i$;

$\vec{\theta}_j$ the vector of $\theta_{jk}$, $\vec{\theta}_{jk} = \left(\theta_{j1}, \ldots, \theta_{j|\mathcal{P}'_j|}\right), \forall j \in \mathcal{R}$.

The LNG bunkering system deployment problem can be described by the following model $[MG]$:

$$[\boldsymbol{MG}] \quad \underset{\vec{y}}{\text{minimize}} \sum_{j \in \mathcal{R}} 52\left(E_{\text{LNG}}\hat{\rho}^{j*}_{\text{LNG}} + E_{\text{MDO}}\hat{\rho}^{j*}_{\text{MDO}}\right) \tag{1}$$

subject to

$$\sum_{i \in \mathcal{P}} C_i^{\mathcal{P}} y_i \leq B_t, \tag{2}$$

$$y_i \in \{0,1\}, \forall i \in \mathcal{P} \tag{3}$$

and

$$\left(\hat{\rho}^{j*}_{\text{LNG}}, \hat{\rho}^{j*}_{\text{MDO}}\right) \in \Psi_j(\vec{z}_t), t = 1, \ldots, T \tag{4}$$

where $\Psi_j(\vec{y})(\forall j \in \mathcal{R})$ are determined by the following lower-level model:

$$[\boldsymbol{MR_j}] \quad \hat{\Psi}_j(\vec{y}) = \underset{x_j, \eta_j, \mu_j, \hat{\rho}^j_{\text{LNG}}, \hat{\rho}^j_{\text{MDO}}, \vec{\theta}_j}{\arg\min} (1 - x_j)C^j_{\text{MDO}}\eta_j + x_j C^j_{\text{Dual}}\eta_j + O_{\text{LNG}}\hat{\rho}^j_{\text{LNG}} + O_{\text{MDO}}\hat{\rho}^j_{\text{MDO}} \tag{5}$$

subject to

$$\pi^{Leave}_{jk} = \pi^{Finish}_{jk} + \theta_{jk}\left(W_j - \pi^{Finish}_{jk}\right), \forall k \in \mathcal{P}'_j \tag{6}$$

$$\pi^{Finish}_{jk} = \max\left\{0, \pi^{Leave}_{j,k-1} - L_{j,k-1}g^j_{\text{LNG}}(\mu_j) - m_{jk}{g'}^j_{\text{LNG}}\right\}, k = 2, 3, \ldots, \left|\mathcal{P}'_j\right| \tag{7}$$

$$\pi^{Finish}_{j1} = \max\left\{0, \pi^{Leave}_{j\left|\mathcal{P}'_j\right|} - L_{j\left|\mathcal{P}'_j\right|}g^j_{\text{LNG}}(\mu_j) - m_{j1}{g'}^j_{\text{LNG}}\right\} \tag{8}$$

$$\theta_{jk} = \sum_{i \in \mathcal{P}} z_{ti} T_{jki}, \forall k \in {\mathcal{P}'}_j \tag{9}$$

$$\frac{\sum_{k \in \mathcal{P}'_j} L_{jk}}{\mu_j} + \sum_{k \in \mathcal{P}'_j} m_{jk} \leq 168\eta_j \tag{10}$$

$$\hat{\rho}^j_{\text{LNG}} = x_j \sum_{k \in \mathcal{P}'_j}\left(\pi^{Leave}_{jk} - \pi^{Finish}_{jk}\right) \tag{11}$$

$$\begin{aligned} \hat{\rho}^j_{\text{MDO}} = (1 - x_j)&\left[g^j_{\text{MDO}}(\mu_j)\sum_{k \in \mathcal{P}'_j} L_{jk} + {g'}^j_{\text{MDO}}\sum_{k \in \mathcal{P}'_j} m_{jk}\right] \\ +Qx_j&\left[g^j_{\text{LNG}}(\mu_j)\sum_{k \in \mathcal{P}'_j} L_{jk} + {g'}^j_{\text{LNG}}\sum_{k \in \mathcal{P}'_j} m_{jk} - \sum_{k \in \mathcal{P}'_j}\left(\pi^{Leave}_{jk} - \pi^{Finish}_{jk}\right)\right] \end{aligned} \tag{12}$$

$$\underline{\mu}_j \leq \mu_j \leq \bar{\mu}_j \tag{13}$$

$$\theta_{jk} = 0, 1, \forall k \in {\mathcal{P}'}_j \tag{14}$$

$$x_j = 0, 1 \tag{15}$$

$$\eta_j \in \mathbb{Z}^+ \tag{16}$$

$$0 \leq \pi^{Finish}_{jk} \leq \max\left\{0, W_j - L_{j,k-1}g^j_{\text{LNG}}(\mu_j) - m_{jk}{g'}^j_{\text{LNG}}\right\}, k = 2, \ldots, \left|\mathcal{P}'_j\right| \tag{17}$$

$$0 \leq \pi_{j1}^{Finish} \leq \max\left\{0, W_j - L_{j,\left|\mathcal{P}_j'\right|} g_{\mathrm{LNG}}^{j}(\mu_j) - m_{j1} {g'}_{\mathrm{LNG}}^{j}\right\} \tag{18}$$

$$0 \leq \pi_{jk}^{Leave} \leq W_j, \forall k \in \mathcal{P}_j'. \tag{19}$$

In $[MG]$, which demonstrates the problem faced by the government, the objective function (1) minimizes the annual emission costs of all shipping routes. Constraint (2) indicates the budget constraint. Constraints (3) are the domains of $y_i$.

In $[MR_j]$, which demonstrates the problem faced by the operator of route $j$, the objective function (5) minimizes the weekly operating costs consisting of the ship chartering cost and bunker cost. Constraints (6) calculate the LNG remaining volume at different ports of call $k$. Constraints (7) and (8) state that dual-fueled ships consume MDO if and only if LNG is in short. Constraints (9) show that the LNG tank of dual-fueled ships will be filled up at every port with the LNG bunkering station. Constraint (10) is the weekly service frequency constraint. Constraints (11) and (12) calculate the MDO and LNG consumption volumes. Constraints (13) to (19) are variable domains.

## 3. Solution Method

In this section, based on the problem structure, we convert the original model into an equivalent one that can be directly solved by CPLEX, an off-the-shelf commercial solver.

First, we linearize $[MR_j]$ and reduce the number of candidate solutions. Then, in the second step, we introduce new decision variables to indicate the decisions of shipping companies. Then, the model can be substituted by $[MGS]$, a mixed integer nonlinear model that can be linearized through a standard method, with the following notations.

**Set**

$\mathcal{S}_j$ the set of candidate for optimal solution of $[MR_j]$, if $x^*_{j2|\mathcal{P}|} = 0$ and $\eta^*_{j2|\mathcal{P}|} = \eta^*_{j1}$, $\mathcal{S}_j = \left\{\left(0, \eta^*_{j1}\right)\right\}$, if $x^*_{j2|\mathcal{P}|} = 1$ and $\eta^*_{j2|\mathcal{P}|} = \eta^*_{j1}$, $\mathcal{S}_j = \left\{\left(0, \eta^*_{j1}\right), \left(1, \eta^*_{j1}\right)\right\}$, if $x^*_{j2|\mathcal{P}|} = 1$ and $\eta^*_{j2|\mathcal{P}|} < \eta^*_{j1}$, $\mathcal{S}_j = \left\{\left(0, \eta^*_{j1}\right), \left(1, \eta^*_{j1}\right), \left(1, \eta^*_{j1} - 1\right) \ldots, \left(1, \eta^*_{j2|\mathcal{P}|}\right)\right\}$, $\forall j \in \mathcal{R}$.

For simplicity, we denote the parameters for each potential optimal solution as follows.

**Parameters**

$\tilde{\eta}_{js}$ the value of $\eta_j$ in candidate solution $s$ of $[MR_j]$, $\forall s \in \mathcal{S}_j, \forall j \in \mathcal{R}$;

$\tilde{\mu}_{js}$ the value of $\mu_j$ in candidate $s$ of $[MR_j]$, equal to $\sum_{k \in \mathcal{P}_j'} L_{jk} / \left(168\tilde{\eta}_{js} - \sum_{k \in \mathcal{P}_j'} m_{jk}\right)$, $\forall s \in \mathcal{S}_j, \forall j \in \mathcal{R}$;

$\tilde{g}_{\mathrm{MDO}}^{js}$ the MDO consumption rate of ships in candidate $s$ of $[MR_j]$, equal to $a_j \tilde{\mu}_{js}^{b_j}$, $\forall s \in \mathcal{S}_j$, $\forall j \in \mathcal{R}$;

$\tilde{g}_{\mathrm{LNG}}^{js}$ the LNG consumption rate of ships in candidate $s$ of $[MR_j]$, equal to $\frac{1}{Q} a_j \tilde{\mu}_{js}^{b_j}$, $\forall s \in \mathcal{S}_j, \forall j \in \mathcal{R}$.

**Decision variables**

$\tilde{x}_{js}$ equal to 1 if candidate $s$ of $[MR_j]$ is applied, 0 otherwise, $\forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j$;

$\theta_{jk}$ binary variable, equal to 1 when dual-fueled ships of route $j$ get refueled for LNG at port of call $k$, 0 otherwise, $\forall j \in \mathcal{R}, \forall k \in {\mathcal{P}'}_j$;

$\pi_{jks}^{Leave}$ the LNG remaining volume when dual-fueled ships leave port of call $k$ on route $j$ (after refueling, if any) when candidate solution $s$ of ship deployment problem of route $j$ is applied, $\forall j \in \mathcal{R}, \forall k \in {\mathcal{P}'}_j, s = 2, \ldots \left|\mathcal{S}_j\right|$;

$\pi_{jks}^{Finish}$ the LNG remaining volume when the cargo handling at port of call $k$ on route $j$ is just finished (before refueling, if any) when candidate solution $s$ of ship deployment problem of route $j$ is applied, $\forall j \in \mathcal{R}, \forall k \in {\mathcal{P}'}_j, s = 2, \ldots \left|\mathcal{S}_j\right|$;

$\hat{\rho}_{\mathrm{LNG}}^{js}$ the weekly LNG consumption volume (ton) of route $j$ when candidate $s$ is applied, $\forall j \in \mathcal{R}, s = 2, \ldots, \left|\mathcal{S}_j\right|$;

$\hat{\rho}^{js}_{\text{MDO}}$ the weekly MDO consumption volume (ton) of route $j$ when candidate $s$ is applied, $\forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j$;
$\beta_{jsm}$ equal to 1 if candidate solution $m$ of route $j$ is more economical than candidate solution $s$, 0 otherwise, $\forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j, \forall m \in \mathcal{S}_j$;
$\alpha_{js}$ equal to 1 if solution $s$ of route $j$ is adopted, 0 otherwise, $\forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j$;
$Em_{js}$ the weekly emission cost of candidate solution $s$ of route $j$, equal to 0 when candidate solution $s$ is not adopted, $\forall j \in \mathcal{R}, s = 2, \ldots |\mathcal{S}_j|$.

The model $[MGS]$, is listed as follows.

$$[\boldsymbol{MGS}] \quad \text{minimize} \sum_{j \in \mathcal{R}} 52 \left\{ \sum_{s=2}^{|\mathcal{S}_j|} Em_{js} + \alpha_{j1} E_{\text{MDO}} \sum_{k \in \mathcal{P}'_j} L_{jk} \tilde{g}^{j1}_{\text{MDO}} + m_{jk} {g'}^{j}_{\text{MDO}} \right\} \tag{20}$$

subject to constraints (2) and (3) and the following constraints:

$$\pi^{Leave}_{jks} = \pi^{Finish}_{jks} + \theta_{jk}\left(W_j - \pi^{Finish}_{jks}\right), s = 2, \ldots, |\mathcal{S}_j|, \forall k \in \mathcal{P}'_j, \tag{21}$$

$$\pi^{Finish}_{jks} = \max\left\{0, \pi^{Leave}_{j,k-1,s} - L_{j,k-1} \tilde{g}^{js}_{\text{LNG}} - m_{jk} {g'}^{j}_{\text{LNG}}\right\},$$
$$s = 2, \ldots, |\mathcal{S}_j|, k = 2, \ldots, \left|\mathcal{P}'_j\right|, \tag{22}$$

$$\pi^{Finish}_{j1s} = \max\left\{0, \pi^{Leave}_{j\left|\mathcal{P}'_j\right|s} - L_{j\left|\mathcal{P}'_j\right|} \tilde{g}^{js}_{\text{LNG}} - m_{j1} {g'}^{j}_{\text{LNG}}\right\}, s = 2, \ldots, |S_j| \tag{23}$$

$$\theta_{jk} = \sum_{i \in \mathcal{P}} y_i T_{jki}, \forall k \in {\mathcal{P}'}_j \tag{24}$$

$$Em_{js} = \alpha_{js} \sum_{k \in {\mathcal{P}'}_j} (E_{\text{LNG}} - QE_{\text{MDO}})\left(\pi^{Leave}_{jks} - \pi^{Finish}_{jks}\right) + QE_{\text{MDO}}\left(L_{jk} \tilde{g}^{js}_{LNG} + m_{jk} {g'}^{j}_{\text{LNG}}\right)$$
$$\forall j \in \mathcal{R}, s = 2, \ldots, |\mathcal{S}_j| \tag{25}$$

$$\alpha_{js} \geq 1 - \sum_{m \in \mathcal{S}_j} \beta_{jsm}, \forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j \tag{26}$$

$$\sum_{s \in \mathcal{S}_j} \alpha_{js} = 1, \forall j \in \mathcal{R} \tag{27}$$

$$\beta_{jsm} = 0, \forall j \in \mathcal{R}, \forall s \in \mathcal{S}_j, m = s \tag{28}$$

$$\beta_{jsm} = 1 - \beta_{jms}, \forall j \in \mathcal{R}, s = 2, \ldots, |\mathcal{S}_j|, m = 1, \ldots, s-1 \tag{29}$$

$$\eta_{j1} C^j_{\text{MDO}} - \eta_{jm} C^j_{\text{Dual}} + \sum_{k \in {\mathcal{P}'}_j} \left[ O_{\text{MDO}} L_{jk}\left(\tilde{g}^{j1}_{\text{MDO}} - Q\tilde{g}^{jm}_{\text{LNG}}\right)\right.$$
$$\left. + (QO_{\text{MDO}} - O_{\text{LNG}})\left(\pi^{Leave}_{jkm} - \pi^{Finish}_{jkm}\right)\right] \leq M^B_{jm} \beta_{j1m}$$
$$\forall j \in \mathcal{R}, m = 2, \ldots, |\mathcal{S}_j| \tag{30}$$

$$-\eta_{j1} C^j_{\text{MDO}} + \eta_{jm} C^j_{\text{Dual}} - \sum_{k \in {\mathcal{P}'}_j} \left[ O_{\text{MDO}} L_{jk}\left(\tilde{g}^{j1}_{\text{MDO}} - Q\tilde{g}^{jm}_{\text{LNG}}\right)\right.$$
$$\left. + (QO_{\text{MDO}} - O_{\text{LNG}})\left(\pi^{Leave}_{jkm} - \pi^{Finish}_{jkm}\right)\right] \leq M^B_{jm} (1 - \beta_{j1m})$$
$$\forall j \in \mathcal{R}, m = 2, \ldots, |\mathcal{S}_j| \tag{31}$$

$$(\eta_{js} - \eta_{jm}) C^j_{\text{Dual}} + O_{\text{MDO}} Q \sum_{k \in {\mathcal{P}'}_j} L_{jk}\left(\tilde{g}^{js}_{\text{LNG}} - \tilde{g}^{jm}_{\text{LNG}}\right)$$
$$+ (O_{\text{LNG}} - O_{\text{MDO}} Q) \sum_{k \in {\mathcal{P}'}_j} \left[\left(\pi^{Leave}_{jks} - \pi^{Finish}_{jks}\right) - \left(\pi^{Finish}_{jkm} - \pi^{Finish}_{jkm}\right)\right] \leq M^B_{jm} \beta_{jsm}$$
$$\forall j \in \mathcal{R}, \forall k \in {\mathcal{P}'}_j, s = 2, \ldots, |\mathcal{S}_j| - 1, m = s+1, \ldots, |\mathcal{S}_j| \tag{32}$$

$$(\eta_{jm} - \eta_{js}) C^j_{\text{Dual}} - O_{\text{MDO}} Q \sum_{k \in {\mathcal{P}'}_j} L_{jk}\left(\tilde{g}^{js}_{\text{LNG}} - \tilde{g}^{jm}_{\text{LNG}}\right)$$

$$-(O_{\mathrm{LNG}} - O_{\mathrm{MDO}}Q) \sum_{k \in \mathcal{P}'_j} \left[ \left( \pi_{jks}^{Leave} - \pi_{jks}^{Finish} \right) - \left( \pi_{jkm}^{Finish} - \pi_{jkm}^{Finish} \right) \right] \leq M_{jm}^{B} (1 - \beta_{jsm})$$
$$\forall j \in \mathcal{R}, \forall k \in \mathcal{P}'_j, s = 2, \ldots, |\mathcal{S}_j| - 1, m = s + 1, \ldots, |\mathcal{S}_j|. \quad (33)$$

## 4. Numerical Experiments

In this study, we conducted numerical experiments based on the shipping routes operated by COSCO, which is the largest Chinese shipping company. The solution method is programmed in C++ with Visual Studio 2021, and CPLEX 20.10 was used to solve $[MGSL]$. Computational experiments were conducted on a HP ENVY x360 Convertible 15-dr1xx laptop with i7-10510U CPU, 2.30 GHz processing speed and 16 GB of memory.

### *4.1. Parameter Settings*

A case study was conducted based on a Chinese container shipping network, which was abstracted from the operating routes of COSCO, the biggest shipping company in China [48]. The shipping network consists of 43 container ports and 44 sailing routes in total and covers China's coastline and the Guangdong–Hong Kong–Macao Greater Bay Area. For the specific ports and routes, please see Appendix A. Given the large scale of the case study, CPLEX still solves all the numerical experiments within 120 s.

In this paper, the LNG station construction costs for ports in the shipping network were set between CNY 10,000,000 and CNY 20,000,000 (approximately USD 1,450,000 to USD 2,900,000), referring to real-case LNG bunkering station construction projects [49–51]. Details of deployed ships are obtained from authoritative studies and reports [8,22,27,28,46,52]. The emission costs of MDO and LNG are calculated based on the studies of [28,53,54]. Specifically, four types of emissions are considered in this study, namely $SO_X$, $NO_X$, $CO_2$, and $PM_{2.5}$, which make up more than 99% of ship emissions. When one tonne of MDO is consumed by a shipping vessel, 0.0001 tonnes of $SO_X$, 0.167 tonnes of $NO_X$, 3.206 tonnes of $CO_2$, and 0.00203 tonnes of $PM_{2.5}$ are emitted; when one tonne of LNG is consumed by a shipping vessel, $3.17 \times 10^{-5}$ tonnes of $SO_X$, 0.0466 tonnes of $NO_X$, 2.75 tonnes of $CO_2$, and $1.26 \times 10^{-4}$ tonnes of $PM_{2.5}$ are emitted. The social costs associated with the emissions of $SO_X$, $NO_X$, $CO_2$, and $PM_{2.5}$ are 11,123 USD/ton, 6,282 USD/ton, 33 USD/ton, and 61,179 USD/ton, respectively. As a result, we have $E_{\mathrm{MDO}} = 1,280.31$ USD/ton, $E_{\mathrm{LNG}} = 391.43$ USD/ton. To compare the bunkering station cost investment and the environmental benefits, we adopt a depreciation time of 20 years with 8% of interest rate to convert the LNG bunkering construction costs $C_i^{\mathcal{P}}$ into the equivalent annual costs, denoted by $\bar{C}_i^{\mathcal{P}}$ [27].

Based on the calibration of the study by [41], the fuel consumption rate parameters of route $j$ while sailing, $a_j$ and $b_j$, were randomly generated within the ranges of $[0.01, 0.014]$ and $[2.9, 3.0]$, respectively. As for the fuel consumption rate while berthing, two sets of parameters were required: the auxiliary engine power and the specific fuel consumption. Referring to the GHG studies by the IMO [28,46], the auxiliary engine powers were set at 900 to 1000 kW, and the specific fuel consumption of LNG was set at 135 g fuel/kWh. The concrete sailing distances of each voyage were not available on the official website of COSCO; instead, they were collected from a professional shipping big data online platform [55].

### *4.2. Results and Analyses*

First, we conducted the numerical experiments with the total budget of USD 30,000,000, and the results are listed in Table 1.

From Table 1, we can see that 14 out of 43 ports will be equipped with LNG bunkering stations after the construction work, including Hong Kong. Meanwhile, USD 29,029,000 in total will be spent on the construction of these bunkering stations. As a result, 38 shipping routes will switch from traditional ships to dual-fueled ships, and the annual total emission costs will be reduced by 3,266,300 USD/year, from 24,092,400 to 20,826,100 USD/year. Although the total construction costs spent are higher than the reduced annual emission costs, the annualized construction costs, which equal USD 2,958,060, make the investment worthwhile. Therefore, the LNG bunkering station deployment plan is cost-effective when the durability of the bunkering stations and interest rate are considered.

**Table 1.** Detailed information of the case study result.

| Content | Value |
| --- | --- |
| Final emission costs (USD/year) | 20,826,100 |
| Reduced emission costs (USD/year) | 3,266,300 |
| Construction costs (USD) | 29,029,000 |
| Ports with bunkering stations | 12,16,18,19,22,24,26,27,29,33,36,38,39,41 |
| Routes adopted dual-fueled ships | 1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,19,20,21,22,23,24,25,26, 27,28,30,32,33,36,37,38, 39,40,41,42,43,44 |

Table 1 shows that with the 14 LNG bunkering stations out of the 43 candidate locations being built, most of the shipping routes will switch from traditional vessels to dual-fueled vessels. Such effectiveness is due to the fact that some ports are frequently visited by various shipping routes. Meanwhile, it is not necessary to equip all ports of call with LNG bunkering stations to make dual-fueled vessels preferable for a shipping route, especially for short routes. In this case, among all 125 ports of call in the 44 shipping routes, 73 ports of call are covered by the 14 bunkering stations, and thus most of the routes switch to dual-fueled vessels.

To investigate the deployment plan under various scenarios, we conducted numerical experiments with different values of the total budget, the bunkering station construction costs and the LNG bunkering price.

The third row in Table 2 indicates that the bunkering station construction costs varies from 50% to 150% of that in the original case. Regarding the total budget, we set the value from 5% of the total construction costs of bunkering stations at all the ports, which equals USD 4,611,400, to 100%, which equals USD $92,228,000$. Results are listed in Tables 3–5.

**Table 2.** Values of parameters for sensitive analyses.

| Content | Value |
| --- | --- |
| LNG bunkering price (USD) | 450, 500, 550, 600, 650, 700 |
| Bunkering station construction costs | 0.5, 0.6, 0.7, 0.8, 0.9, 1, 1.1, 1.2, 1.3, 1.4, 1.5 |
| Total budget (USD) | 4,611,400, 9,222,800, 13,834,200, 18,445,600, 23,057,000, 27,668,400, 32,279,800, 36,891,200, 41,502,600, 46,114,000, 50,725,400, 55,336,800, 59,948,200, 64,559,600, 69,171,000, 73,782,400, 78,393,800, 83,005,200, 87,616,600, 92,228,000 |

**Table 3.** Results of sensitive analysis on LNG bunkering price.

| LNG Price (USD/ton) | OptObj (USD/year) | Reduced Emission Costs (USD/year) | Annual Construction Costs (USD/year) |
| --- | --- | --- | --- |
| 450 | 20,666,500 | 3,425,900 | 3,049,050 |
| 500 | 20,826,100 | 3,266,300 | 2,958,060 |
| 550 | 20,954,100 | 3,138,300 | 2,954,180 |
| 600 | 20,991,500 | 3,100,900 | 2,954,180 |
| 650 | 21,224,200 | 2,868,200 | 2,961,620 |
| 700 | 21,375,700 | 2,716,700 | 2,922,390 |

**Table 4.** Results of sensitive analysis on bunkering station construction costs.

| Construction Costs | OptObj (USD/year) | Reduced Emission Costs (USD/year) | Annual Construction Costs (USD/year) |
|---|---|---|---|
| 0.5 | 19,655,800 | 4,436,600 | 3,054,550 |
| 0.6 | 19,941,000 | 4,151,400 | 3,052,110 |
| 0.7 | 20,302,500 | 3,789,900 | 2,948,640 |
| 0.8 | 20,509,800 | 3,582,600 | 2,844,970 |
| 0.9 | 20,623,600 | 3,468,800 | 3,029,550 |
| 1 | 20,826,100 | 3,266,300 | 2,958,060 |
| 1.1 | 20,939,100 | 3,153,300 | 3,048,510 |
| 1.2 | 21,227,300 | 2,865,100 | 2,899,380 |
| 1.3 | 21,331,000 | 2,761,400 | 2,940,970 |
| 1.4 | 21,410,600 | 2,681,800 | 2,950,490 |
| 1.5 | 21,561,500 | 2,530,900 | 2,830,480 |

**Table 5.** Results of sensitive analysis on the total budget.

| Total Budget (USD) | OptObj (USD/year) | Reduced Emission Costs (USD/year) | Annual Construction Costs (USD/year) |
|---|---|---|---|
| 4,611,400 | 23,414,700 | 464,970 | 677,700 |
| 9,222,800 | 22,806,100 | 918,628 | 1,286,300 |
| 13,834,200 | 22,165,900 | 1,403,060 | 1,926,500 |
| 18,445,600 | 21,648,800 | 1,878,730 | 2,443,600 |
| 23,057,000 | 21,331,000 | 2,262,280 | 2,761,400 |
| 27,668,400 | 20,939,100 | 2,771,370 | 3,153,300 |
| 32,279,800 | 20,724,400 | 3,154,420 | 3,368,000 |
| 36,891,200 | 20,587,800 | 3,547,850 | 3,504,600 |
| 41,502,600 | 20,303,600 | 4,047,570 | 3,788,800 |
| 46,114,000 | 20,049,400 | 4,633,190 | 4,043,000 |
| 50,725,400 | 19,932,100 | 5,138,000 | 4,160,300 |
| 55,336,800 | 19,813,100 | 5,547,950 | 4,279,300 |
| 59,948,200 | 19,702,100 | 6,094,130 | 4,390,300 |
| 64,559,600 | 19,638,000 | 6,529,850 | 4,454,400 |
| 69,171,000 | 19,425,600 | 7,046,790 | 4,666,800 |
| 73,782,400 | 19,391,800 | 7,413,630 | 4,700,600 |
| 78,393,800 | 19,318,900 | 7,838,250 | 4,773,500 |
| 83,005,200 | 19,318,900 | 8,278,150 | 4,773,500 |
| 87,616,600 | 19,317,800 | 8,804,770 | 4,774,600 |
| 92,228,000 | 19,317,800 | 8,804,770 | 4,774,600 |

The results of sensitive analyses indicate that the annual emission costs increase with LNG bunkering price and LNG bunkering station costs, and decrease with the total budget for bunkering station establishment. In other words, in addition to allocating a large budget, lowering the LNG bunkering price and the station construction costs help to promote the adoption of LNG as marine fuel and reduce shipping emissions. For the government, two measures can be adopted: (i) giving subsidies to ship operators for consuming LNG as marine fuel, and (ii) reducing the bunkering station construction costs by production optimization and efficiency improvement. Regarding the cost-effectiveness, it is revealed in Table 5 that the reduced annual emission costs exceed the annualized construction costs when the total budget is no lower than USD 27,668,400, which equals 30% of the total costs to build bunkering stations at all ports in the Chinese container shipping network. It should be mentioned that the annual emission costs reach the lowest level when the total budget is USD 87, 616, 600, and further investment brings no environmental benefits. Thus, equipping all ports with bunkering stations is unnecessary from the cost-effective perspective.

For the competent government, in addition to maximizing emission reduction with the given construction budget, it is also viable to set a desired emission reduction target and make a corresponding LNG bunkering station deployment plan with the aim to minimize the total costs. The three methods, namely, investment in LNG bunkering station construction, improve the production efficiency, and a subsidy for consuming LNG can be adopted simultaneously to maximize the emission reduction effect with the given budgets or minimize the total costs to achieve the predetermined emission reduction target.

## 5. Conclusions

In this paper, we conducted a case study of the LNG bunkering station deployment problem based on a Chinese container shipping network. Referring to the shipping routes operated by the biggest shipping company in China, COSCO, a network of 43 ports and 44 shipping routes was abstracted. Generally speaking, LNG bunkering station construction is cost-effective when the facility durability and the inflation rate are taken into consideration. Sensitive analyses on LNG price, bunkering station construction costs, and total budget reveal that the effectiveness of the deployment plan in LNG promotion and emission reduction increases with the total budget and decreases with the LNG bunkering price and the construction costs. Therefore, it is indicated that allocating a large budget is not the only way to promote LNG as marine fuel. Specifically, when the emission reduction effectiveness reaches the highest level before the total budget can cover all the construction works, more investment will be in vain. To sum up, two sets of constructive managerial insights for the governmental were obtained: (i) reducing LNG usage cost and lowering bunkering station construction costs can promote the LNG application, and (ii) it is not always necessary to build bunkering stations at all ports.

This case study is based on a realistic Chinese container shipping network, and it validates the model and solution method proposed in academic studies. The managerial insights obtained provide constructive suggestions for the government and help in identifying the optimal LNG bunkering station deployment plan that reaches an obvious emission reduction plan and avoids extra costs. Compared to previous studies on this topic, this paper investigates the problem of a large-scale realistic shipping network and therefore yields more practical conclusions and managerial insights.

For future research, there are several directions that could be followed. First, when the demands for LNG from ships increase to a high level, the bunkering and storage capacities of bunkering stations should be considered. Second, the establishment of other infrastructure facilities can be integrated into the problem, for example, the transportation approach of LNG to the port-side bunkering stations. Third, the situation in which the ship operator is also the ship owner is worth investigation in the future.

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## Appendix A. Ports and Routes Considered in This Case Study

**Table A1.** Ports considered in this case study.

| No. | Port Name | No. | Port Name | No. | Port Name |
|---|---|---|---|---|---|
| 1 | Dachanwan | 16 | Jinzhou | 31 | Shenzhen |
| 2 | Dalian | 17 | Lianyungang | 32 | Shunde |
| 3 | Dandong | 18 | Nansha | 33 | Taizhong |
| 4 | Foshan | 19 | Nantong | 34 | Taicang |
| 5 | Fuzhou | 20 | Ningbo | 35 | Tangshan |
| 6 | Gaolan | 21 | Panjin | 36 | Tianjin |
| 7 | Gaoming | 22 | Qinzhou | 37 | Wuchongkou |
| 8 | Gaoxiong | 23 | Qinhuangdao | 38 | Hongkong |
| 9 | Haikou | 24 | Qingdao | 39 | Yantai |
| 10 | Humen | 25 | Quanzhou | 40 | Yantian |
| 11 | Huadong | 26 | Rizhao | 41 | Yingkou |
| 12 | Huanghua | 27 | Xiamen | 42 | Zhapu |
| 13 | Huangpu | 28 | Shantou | 43 | Zhanjiang |
| 14 | Jilong | 29 | Shanghai | | |
| 15 | Jiangmen | 30 | Shekou | | |

**Table A2.** Routes considered in this case study.

| No. | Ports of Call | No. | Ports of Call | No. | Ports of Call |
|---|---|---|---|---|---|
| 1 | 41 - 18 | 16 | 3 - 29 | 31 | 13 - 18 |
| 2 | 41 - 35 - 36 - 1 | 17 | 29 - 42 - 37 | 32 | 15 - 18 |
| 3 | 36 - 18 | 18 | 34 - 31 - 10 - 6 | 33 | 30 - 38 |
| 4 | 24 - 26 - 17 - 31 - 6 | 19 | 29 - 25 - 27 | 34 | 32 - 30 |
| 5 | 23 - 39 - 18 | 20 | 2 - 41 - 21 - 19 | 35 | 4 - 7 - 30 |
| 6 | 2 - 16 - 27 - 18 | 21 | 36 - 19 | 36 | 32 - 38 |
| 7 | 12 - 18 | 22 | 24 - 17 - 29 | 37 | 40 - 38 |
| 8 | 41 - 36 - 43 - 22 | 23 | 29 - 14 - 33 - 8 | 38 | 43 - 38 |
| 9 | 16 - 35 - 26 - 22 | 24 | 29 - 8 - 33 - 14 | 39 | 9 - 38 |
| 10 | 39 - 24 - 27 | 25 | 2 - 36 - 24 - 17 - 33 - 20 | 40 | 22 - 38 |
| 11 | 41 - 36 - 25 - 27 | 26 | 13 - 38 - 13 | 41 | 28 - 38 |
| 12 | 41 - 36 - 27 - 28 | 27 | 38 - 11 | 42 | 5 - 38 |
| 13 | 25 - 27 - 9 | 28 | 38 - 10 | 43 | 27 - 38 |
| 14 | 41 - 39 - 29 | 29 | 18 - 38 | 44 | 38 - 25 |
| 15 | 16 - 29 | 30 | 32 - 4 - 7 18 | | |

## References


1. Zhang, L.; Zeng, Z.; Gao, K. A bi-level optimization framework for charging station design problem considering heterogeneous charging modes. *J. Intell. Connect. Veh.* **2022**, *5*, 8–16. [CrossRef]
2. Ortúzar, J.d.D. Future transportation: Sustainability, complexity and individualization of choices. *Commun. Transp. Res.* **2021**, *1*, 100010. [CrossRef]
3. Sun, Z.; Zhang, R.; Gao, Y.; Tian, Z.; Zuo, Y. Hub ports in economic shocks of the melting Arctic. *Marit. Policy Manag.* **2021**, *48*, 917–940. [CrossRef]
4. Attard, M. Active travel and sustainable transport. *Commun. Transp. Res.* **2022**, *2*, 100059. [CrossRef]
5. Liu, Y.; Wang, L.; Zeng, Z.; Bie, Y. Optimal charging plan for electric bus considering time-of-day electricity tariff. *J. Intell. Connect. Veh.* **2022**, *5*, 123–137. [CrossRef]
6. Wang, S.; Tian, X.; Yan, R.; Liu, Y. A deficiency of prescriptive analytics—No perfect predicted value or predicted distribution exists. *Electron. Res. Arch.* **2022**, *30*, 3586–3594. [CrossRef]
7. United Nations. Paris Agreement. 2015. Available online: https://unfccc.int/process-and-meetings/the-paris-agreement/the-paris-agreement (accessed on 1 January 2023).

8. UNCTAD. Review of Maritime Transport 2021. 2021. Available online: https://unctad.org/system/files/official-document/rmt2021_en_0.pdf (accessed on 1 January 2023).
9. Wang, S.; Psaraftis, H.N.; Qi, J. Paradox of international maritime organization's carbon intensity indicator. *Commun. Transp. Res.* **2021**, *1*, 100005. [CrossRef]
10. Ma, W.; Lu, T.; Ma, D.; Wang, D.; Qu, F. Ship route and speed multi-objective optimization considering weather conditions and emission control area regulations. *Marit. Policy Manag.* **2021**, *48*, 1053–1068. [CrossRef]
11. Qi, J.; Wang, S.; Psaraftis, H.N. Bi-level optimization model applications in managing air emissions from ships: A review. *Commun. Transp. Res.* **2021**, *1*, 100020. [CrossRef]
12. El Noshokaty, S. Ship routing and scheduling systems: Forecasting, upscaling and viability. *Marit. Bus. Rev.* **2021**, *6*, 95–112. [CrossRef]
13. Zisi, V.; Psaraftis, H.N.; Zis, T. The impact of the 2020 global sulfur cap on maritime $CO_2$ emissions. *Marit. Bus. Rev.* **2021**, *6*, 339–357. [CrossRef]
14. Yi, W.; Zhen, L.; Jin, Y. Stackelberg game analysis of government subsidy on sustainable off-site construction and low-carbon logistics. *Clean. Logist. Supply Chain* **2021**, *2*, 100013. [CrossRef]
15. Yi, W.; Wu, S.; Zhen, L.; Chawynski, G. Bi-level programming subsidy design for promoting sustainable prefabricated product logistics. *Clean. Logist. Supply Chain* **2021**, *1*, 100005. [CrossRef]
16. Zhang, J.; Long, D.Z.; Wang, R.; Xie, C. Impact of Penalty Cost on Customers' Booking Decisions. *Prod. Oper. Manag.* **2021**, *30*, 1603–1614. [CrossRef]
17. Wu, L.; Adulyasak, Y.; Cordeau, J.F.; Wang, S. Vessel Service Planning in Seaports. *Oper. Res.* **2021**, *70*, 2032–2053. [CrossRef]
18. Zhu, L.; Li, X.; Pan, W. Controlling marine greenhouse gas emissions in Hong Kong: Policy considerations. *Marit. Policy Manag.* **2022**. [CrossRef]
19. Wang, S.; Yan, R. A global method from predictive to prescriptive analytics considering prediction error for "Predict, then optimize" with an example of low-carbon logistics. *Clean. Logist. Supply Chain* **2022**, *4*, 100062. [CrossRef]
20. Yan, R.; Wang, S. Integrating prediction with optimization: Models and applications in transportation management. *Multimodal Transp.* **2022**, *1*, 100018. [CrossRef]
21. Wang, S.; Yan, R. "Predict, then optimize" with quantile regression: A global method from predictive to prescriptive analytics and applications to multimodal transportation. *Multimodal Transp.* **2022**, *1*, 100035. [CrossRef]
22. UNCTAD. Review of Maritime Transport 2022. 2022. Available online: https://unctad.org/webflyer/review-maritime-transport-2022 (accessed on 1 January 2023).
23. Global Maritime Forum. Call to Action for Shipping Decarbonization. 2021. Available online: https://www.globalmaritimeforum.org/content/2021/09/Call-to-Action-for-Shipping-Decarbonization.pdf (accessed on 1 January 2023).
24. Climate Vulnerable Forum. Dhaka Glasgow Declaration of the Climate Vulnerable Forum. 2022. Available online: https://thecvf.org/wp-content/uploads/2021/10/Dhaka-Glasgow-Declaration-of-the-CVF_Final-1.pdf (accessed on 1 January 2023).
25. GOV.UK Department for transport. COP 26: Clydebank Declaration for Green Shipping Corridors. 2022. Available online: https://www.gov.uk/government/publications/cop-26-clydebank-declaration-for-green-shipping-corridors/cop-26-clydebank-declaration-for-green-shipping-corridors#contents (accessed on 1 January 2023).
26. Schinas, O.; Butler, M. Feasibility and commercial considerations of LNG-fueled ships. *Ocean Eng.* **2020**, *122*, 84–96. [CrossRef]
27. International Maritime Organization. Studies on the Feasibility and Use of LNG as a Fuel for Shipping. 2016. Available online: http://www.imo.org/en/OurWork/Environment/PollutionPrevention/AirPollution/Documents/LNG%20Study.pdf (accessed on 1 January 2023).
28. Faber, J.; Hanayama, S.; Zhang, S.; Pereda, P.; Comer, B.; Hauerhof, E.; Smith, T.; Zhang, Y.; Kosaka, H.; Adachi, M.; et al. Reduction of GHG Emissions from Ships: Fourth IMO GHG Study 2020–Final Report. 2020. Available online: https://imoarcticsummit.org/wp-content/uploads/2020/09/MEPC-75-7-15-Fourth-IMO-GHG-Study-2020-Final-report-Secretariat.pdf (accessed on 1 January 2023).
29. Huang, D.; Wang, S. A two-stage stochastic programming model of coordinated electric bus charging scheduling for a hybrid charging scheme. *Multimodal Transp.* **2022**, *1*, 100006. [CrossRef]
30. SEA-LNG. LNG-A Fuel in Transition. 2022. Available online: https://sea-lng.org/wp-content/uploads/2022/03/LNG-2022_A-view-from-the-bridge_.pdf (accessed on 1 January 2023).
31. Yoo, B.Y. Economic assessment of liquefied natural gas (LNG) as a marine fuel for $CO_2$ carriers compared to marine gas oil (MGO). *Energy* **2017**, *121*, 772–780. [CrossRef]
32. Xu, H.; Yang, D. LNG-fuelled container ship sailing on the Arctic Sea: Economic and emission assessment. *Transp. Res. Part D* **2020**, *87*, 102566. [CrossRef]
33. Kana, A.A.; Knight, J.; Sypniewski, M.J.; Singer, D.J. A Markov decision process framework for analyzing LNG as fuel in the face of uncertainty. In Proceedings of the 12th International Marine Design Conference, Tokyo, Japan, 11–14 May 2015.
34. Kana, A.A.; Harrison, B.M. A Monte Carlo approach to the ship-centric Markov decision process for analyzing decisions over converting a containership to LNG power. *Ocean Eng.* **2017**, *130*, 40–48. [CrossRef]
35. Park, S.; Jeong, B.; Yoon, J.; Paik, K. A study on factors affecting the safety zone in ship-to-ship LNG bunkering. *Ships Offshore Struct.* **2018**, *13*, S312–S321. [CrossRef]

36. Tam, J.H. Overview of performing shore-to-ship and ship-to-ship compatibility studies for LNG bunker vessels. *J. Mar. Eng. Technol.* **2022**, *21*, 257–270. [CrossRef]
37. Ursavas, E.; Zhu, S.X.; Savelsbergh, M. LNG bunkering network design in inland waterways. *Transp. Res. Part C* **2020**, *120*, 102779. [CrossRef]
38. Peng, Y.; Zhao, X.; Zuo, T.; Wang, W. A systematic literature review on port LNG bunkering station. *Transp. Res. Part D* **2021**, *91*, 102704. [CrossRef]
39. Yang, K. 2019. Application Status and Prospect of Inland River LNG-Fueled Ships in China. Available online: https://www.sohu.com/a/326031720_269757 (accessed on 1 January 2023).
40. Ministry of Transport of the People's Republic of China. Outline of Inland Navigation Development. 2020. Available online: http://www.gov.cn/zhengce/zhengceku/2020-06/04/content_5517185.htm (accessed on 1 January 2023).
41. Wang, S.; Meng, Q. Sailing speed optimization for container ships in a liner shipping network. *Transp. Res. Part E* **2012**, *48*, 701–714. [CrossRef]
42. Wang, C.; Chen, J. Strategies of refueling, sailing speed and ship deployment of containerships in the low-carbon background. *Comput. Ind. Eng.* **2017**, *114*, 142–150. [CrossRef]
43. Chen, J.; Zhuang, C.; Yang, C.; Wan, Z.; Zeng, X.; Yao, J. Fleet co-deployment for liner shipping alliance: Vessel pool operation with uncertain demand. *Ocean Coast. Manag.* **2021**, *214*, 105923. [CrossRef]
44. Ronen, D. The effect of oil price on the optimal speed of ships. *J. Oper. Res. Soc.* **1982**, *33*, 1035–1040. [CrossRef]
45. Ronen, D. Ship scheduling: The last decade. *Eur. J. Oper. Res.* **1993**, *71*, 325–333. [CrossRef]
46. Smith, T.; Jalkanen, J.; Anderson, B.; Corbett, J.; Faber, J.; Hanayama, S.; O'Keeffe, E.; Parker, S.; Johansson, L.; Aldous, L.; et al. *Third International Maritime Organization Greenhouse Gas Study*; International Maritime Organization: London, UK, 2014.
47. Wang, S.; Qi, J.; Laporte, G. Governmental subsidy plan modeling and optimization for liquefied natural gas as fuel for maritime transportation. *Transp. Res. Part B* **2022**, *155*, 304–321. [CrossRef]
48. China COSCO Shipping Corporation Limited. Cosco. 2022. Available online: http://www.coscoshipping.com/ (accessed on 1 January 2023).
49. Baidu Wenku. Investment Quota of Inland Marine LNG Bunkering Station. 2017. Available online: https://wenku.baidu.com/view/ad6ed685bed5b9f3f90f1cfc.html?_wkts_=1672230235733&bdQuery=LNG%E5%8A%A0%E6%B3%A8%E7%AB%99+%E6%B8%AF%E5%8F%A3+%E8%B4%B9%E7%94%A8 (accessed on 1 January 2023).
50. Guangdong Provincial Development and Reform Commission. Implementation Plan for Construction of LNG Filling Station for Transportation Ships in Guangdong Province. 2021. Available online: http://www.gd.gov.cn/zwgk/gongbao/2021/32/content/post_3678729.html (accessed on 1 January 2023).
51. Finance Sina. The Total Investment Is about 3.05 Billion to Visit the First Shore Based LNG Bunkering Station in Jiangsu Province. 2022. Available online: http://finance.sina.com.cn/jjxw/2022-08-25/doc-imizirav9638624.shtml (accessed on 1 January 2023).
52. UNCTAD. Review of Maritime Transport 2020. 2020. Available online: https://unctad.org/system/files/official-document/rmt2020_en.pdf (accessed on 1 January 2023).
53. Nunes, R.; Alvim-Ferraz, M.; Martins, F.; Sousa, S. Environmental and social valuation of shipping emissions on four ports of Portugal. *J. Environ. Manag.* **2019**, *235*, 62–69. [CrossRef] [PubMed]
54. Song, S. Ship emissions inventory, social cost and eco-efficiency in Shanghai Yangshan port. *Atmos. Environ.* **2014**, *82*, 288–297. [CrossRef]
55. Shanghai Maili Marine Technology Company. Hifleet. 2022. Available online: https://www.hifleet.com/ (accessed on 1 January 2023).