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Shore Power Deployment Problem—A Case Study of a Chinese Container Shipping Network

Jingwen Qi [1,†], Hans Wang [2,†] and Jianfeng Zheng [3,*]

1 Department of Logistics and Maritime Studies, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; jingwen.qi@connect.polyu.hk
2 Faculty of Business, The Hong Kong Polytechnic University, Hung Hom, Kowloon, Hong Kong, China; hans.wang@polyu.edu.hk
3 Transportation Engineering College, Dalian Maritime University, Dalian 116026, China
* Correspondence: jfzheng@dlmu.edu.cn
† These authors contributed equally to this work.

Abstract: Shipping emissions, especially those in port areas, have become one of the main concerns of the maritime industry. Shore power has been recognized as a promising way to alleviate the problem. However, shore power has not been extensively adopted in China. Therefore, from the government's point of view, this paper conducts a case study of the shore power deployment problem based on the real container shipping network of China, including the Port of Hong Kong. In addition to the basic case, we, also, conduct numerical experiments with different budgets, to analyze its influence on the optimal subsidy plan and cost–benefit analysis. The results give two useful managerial insights: (i) it might be unnecessary to spend a large amount of the budget on subsidization, and (ii) the subsidy expenditure needs to be considered together with the final bunker reduction, while creating the budget.

Keywords: shore power deployment problem; government subsidy; container shipping network; maritime transportation

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1. Introduction

Being the backbone of international trade, maritime transportation constituted over 80% of the total commodity trade volume in 2020 [1]. Despite the impact of the COVID-19 pandemic, UNCTAD projects that world maritime trade will have recovered by 4.3%, in 2021, and growth is predicted to continue over the next five years, namely 2022–2026 [2]. Along with the increasing cargo volume, the emission problem of marine shipping has been identified as one of the main focuses of the maritime industry [3]. The total carbon dioxide (CO_2) emissions from international shipping have increased from 962 million tons in 2012 to 1056 million tons in 2018, and the proportion it accounts for in the global anthropogenic emissions, also, grew from 2.44% to 2.51%, according to the Fourth Greenhouse Gas (GHG) Study, by the International Maritime Organization (IMO) [4]. Besides CO_2, ships, also, discharge other contaminating gases, including nitrogen oxides (NO_X) and sulfur dioxide (SO_2), no matter if they are sailing or berthing. Due to the importance of ports in the local economy and supply-chain network, there are always metropolises accompanying large-scale ports, and, therefore, ship emissions at berth have a particular harm to social benefits, due to the fact that they are in proximity to human habitations [5,6]. Conventionally, ships rely on auxiliary engines and consume marine fuels, to power onboard machines while berthing. As the demand for maritime transportation grows, ships at ports are expected to emit about 70 million tons of CO_2, 0.16 million tons of SO_2, and 1.3 million tons of NO_X, in 2050, according to a prediction by Merk [7].

Shower power (SP) is the most promising way to substitute for auxiliary engines, and it powers onboard machines at berth, by using electricity from the power grid [8,9].

This technology, which is also known as "shore-side power", "on-shore power supply", "alternative maritime power", and "cold-ironing", reduces ship emissions while berthing, to as low as 5% of the original level, by moving the power production from dirty onboard sources to greener and more efficient large-scale power stations [10,11]. In addition to the environmental benefits, the application of SP, also, improves the welfare of seafarers [12,13].

Both onshore and onboard facilities are indispensable to the successful application of SP, and, currently, expensive construction costs block the promotion of this technology. Considering the environmental benefits, governments of various countries cover part of the shore power system installation cost, by providing subsidies to ports and ship operators [14–17]. From the port perspective, the emission reduction efficiency depends on the onboard facility construction of ships visiting the port. On the other hand, from the perspective of ship operators, the utilization rate of the onboard shore power facilities is up to the availability of shore power, at the ports along their sailing routes.

There are multiple studies regarding the application of SP. The efficiency evaluation of different incentive policies for the promotion of the application of SP has been conduct by various scholars [18,19]. Besides, Osses et al. [20] presented a method to assess the emission of vessels at berth, using SP. Standing at the perspective of a port providing SP, Yu et al. [21] develop a multi-objective optimization model, to investigate the problem of berth allocation and quay crane assignment. Zhen et al. [22] developed a column-generation algorithm, to solve the two-stage stochastic programming model, proposed for the low-carbon berth-allocation problem under uncertainty.

Considering the environmental benefits, the local government is the main force for promoting the application of SP. Subsidies have been recognized as a promising method, to improve the SP utilization rate [23,24]. To obtain the optimal subsidy plan, studies have been conducted for subsidy-plan optimization [23,24]. Given that the utilization rate depends on not only the availability of onshore facilities but also the willingness of ships to use it while berthing, it is necessary to consider the subsidy and deployment problem of ports and ships together [24].

In this paper, a multi-level perspective is adopted, to incorporate the decisions of the government, the port authorities, and the shipping companies. Such multi-level optimization models have been extensively adopted in maritime studies [25,26]. A bi-level optimization model has been adopted in this study to describe the problem. Optimization models are extensively used in management problems, for example, project-management [27–29] and transportation-management problems [30–33]. Taking the advantages of these two factors, Wu and Wang [24] developed an optimization model integrating the decision of different parties, to describe the SP deployment problem.

However, the numerical solutions obtained in previous studies cannot be directly applied to a shipping network in reality, due to the complex situations of different countries. At the same time, the analysis and managerial insight are, also, not applicable in practice. Thus, it is necessary to conduct a case study based on a specific shipping network in reality, to provide a practical subsidy plan and managerial suggestions for the government. Moreover, a case study based on a realistic shipping network better proves the efficiency of the model and the solution method developed by Wu and Wang [24]. Identifying a suitable research objective is, also, important. Thanks to the latest port technologies and infrastructure, a group of countries, including Japan, Hong Kong, and Taiwan, have faster turnarounds and, therefore, attract higher numbers of port calls [4]. Thus, in this paper, we conduct a case study based on the major ports in China, including the Port of Hong Kong, to investigate the shore power deployment problem in a container shipping network. In this study, with the aim to maximize the total amount of SP used by the ships operating among the main ports in China, the local government decides which ports and which shipping routes should be subsidized.

The contribution of this paper is three-fold. First, we build the container shipping network, based on the liner shipping routes operated by the largest Chinese shipping company. The scale of the network exceeds previous study on similar topics. The SP facilities that have been built at ports are, also, considered in this case study, which could avoid allocating subsidy budget to ports already equipped with SP systems and, therefore, reduce the total expenditure. Besides, the critical parameters were collected from official websites and shore power system construction cases. Thus, the real-world case study validates the model and algorithm better than randomly generated numerical experiments. Meanwhile, the container shipping network we build can be applied in the investigation of other problems in maritime transportation, since it is quite complete and close to reality. Second, the study yields a detailed shore power subsidy plan that can provide practical suggestions to the government, to promote shore power application in China. Thus, this study can play an important role in the shore power application scheme in China and contribute to ship air-emission alleviation in the port areas. Third, different from Wu and Wang [24], in this study we investigate the influence of the total budget on the final bunker usage. Managerial insights were obtained, based on the analysis of the numerical experiments with different total budgets. The cost–benefit analysis is, also, conducted to further verify the SP subsidy incentive policy.

The remainder of this paper is organized as follows. Section 2 provides the formal problem description and the mathematical model. Numerical experiment and results are presented in Section 4. The paper closes with conclusions in Section 5.

2. Mathematical Model

In this section, we provide the problem description and, then, the mathematical model for the shore power deployment problem in a container shipping network.

Problem Description

Three parties are considered in this paper. First is the government, which is, also, the decision maker, that provides subsidies to ports and ships for the environmental benefits of using SP. Second is the port authorities that decide whether to construct a shore-side SP system, based on their own profits. Third is the shipping companies that operate the shipping routes, as they decide whether to retrofit their vessels on the basis of the operating costs. In this study, we consider a container shipping network consisting of multiple ports and shipping routes. For the environmental benefits, the government aims to promote the application of shore power in the network. To achieve the goal, the government will provide subsidies to cover the construction cost and the operating expenses of the shore-side SP system, for part of the ports, and the ship retrofitting costs, for part of the routes. Maximizing the total amount of SP used by ships, while berthing in the area, the government decides which ports and routes to subsidize. Given the subsidies, the port authorities and route operators decide, based on their own interests, whether to install SP facilities.

The container shipping network considered in this paper consists of a set of ports denoted by $\mathcal{P}$, and a set of shipping routes denoted by $\mathcal{R}$, in which the ports are managed by the government, and the routes are operated by shipping lines within the jurisdiction of the government. In order to alleviate the ship-emission problem at port areas, the government has decided to promote the application of shore power, by providing subsidies to cover the shore power facility construction cost, for certain ports and the ships of certain routes. Currently, part of the ports considered have been quipped with SP facilities, but the utilization rate is still low. It is assumed in this paper that the ports can benefit from selling electricity, and SP is more economical than auxiliary engines, for ships while berthing. Therefore, ports and ships that receive subsidies will be equipped with SP facilities. In addition, ports that do not receive the subsidies will, also, invest and build an onshore SP system, if the profit of selling SP to ships exceeds the construction cost and the operating expenses. Meanwhile, ships without subsidies will, also, be retrofitted and equipped with onboard SP facilities, if the bunker savings by using SP is no lower than the construction cost and the operating expenses. Due to the mutual promotion between the construction of onboard and onshore facilities, increasing numbers of ports and ships will be equipped after the initial government subsidies. Thus, with the aim to maximize the SP utilization, we will recognize the optimal groups of ports and routes to be subsidized. To better show the interdependence between the ports and routes, we consider different phases. Each phase represents a time period, in which ports and shipping companies will make decisions at the beginning, based on the situation at the end of the last phase. Given the SP facilities that have been built in previous phases, the ports decide whether to construct the onshore facilities of SP, and the shipping companies decide whether to retrofit the vessels they operate. The SP deployment will, finally, achieve long-term equilibrium, when no more ports and vessels will be equipped with SP facilities.

Here we display the mathematical model after the notations used in it.

Sets and indices

$\mathcal{P}$ the set of ports, indexed by i, $i = 1, ..., |\mathcal{P}|$;

$\mathcal{R}$ the set of routes, indexed by j, $j = 1, ..., |\mathcal{R}|$;

$\mathcal{N}$ the set of phases, indexed by n, $n = 0, 1, ..., |\mathcal{N}|$;

$\mathcal{P}_j$ the set of ports, visited by route j, $\forall j \in \mathcal{R}$;

$\mathcal{R}_i$ the set of routes, which visit port i, $\forall i \in \mathcal{P}$;

Parameters

$\hat{x}_i$ binary parameter, equals 1 when port i is already equipped with SP facilities at the beginning of phase 0, 0 otherwise $\forall i \in \mathcal{P}$;

$\hat{y}_j$ binary parameter, equals 1 when shipping route j is already equipped with SP facilities at the beginning of phase 0, 0 otherwise $\forall j \in \mathcal{R}$;

F_{ji} the annual fuel cost (USD) of route j for berthing at port i without using SP, $\forall i \in \mathcal{P}, \forall j \in \mathcal{R}_i$;

E_{ji} the annual electricity cost (USD) of route j for berthing at port i using SP, $\forall i \in \mathcal{P}, \forall j \in \mathcal{R}_i$;

U_{ji} the annual profit (USD) of port i selling SP to ships deployed on route j, $\forall i \in \mathcal{P}, \forall j \in \mathcal{R}_i$;

$C_i^{\mathcal{P}}$ the equivalent annual cost (USD/year) of onshore SP facilities at port i, $\forall i \in \mathcal{P}$;

$C_j^{\mathcal{R}}$ the equivalent annual cost (USD/year) of onboard SP facilities for route j, $\forall j \in \mathcal{R}$;

Variables

x_i binary variable, equal to 1 if port i receives government subsidy, 0 otherwise, $\forall i \in \mathcal{P}$;

y_j binary variable, equal to 1 if route j receives government subsidy, 0 otherwise, $\forall j \in \mathcal{R}$;

$\hat{\mathcal{P}}_n$ the set of ports that decide to construct onshore SP facilities at or before phase n, $\forall n \in \mathcal{N}$;

$\hat{\mathcal{R}}_n$ the set of routes that decide to retrofit the ships deployed and construct onboard SP facilities at or before phase n, $\forall n \in \mathcal{N}$;

$\alpha_i(\hat{\mathcal{R}})$ binary variable, equal to 1 if port i will benefit from constructing onshore SP facilities, 0 otherwise, given a set of routes with onboard facilities, which is denoted by $\hat{\mathcal{R}}$,

$$\alpha_i(\hat{\mathcal{R}}) = \begin{cases} 1 & if \sum\limits_{j \in \hat{\mathcal{R}}} U_{ji} \geq C_i^{\mathcal{P}} \\ 0 & if \sum\limits_{j \in \hat{\mathcal{R}}} U_{ji} < C_i^{\mathcal{P}} \end{cases} \tag{1}$$

$\beta_i(\hat{\mathcal{R}})$ binary variable, equal to 1 if route i will benefit from constructing onboard SP facilities, 0 otherwise, given a set of ports with onboard facilities, which is denoted by $\hat{\mathcal{P}}$,

$$\beta_j(\hat{\mathcal{P}}) = \begin{cases} 1 & if \sum_{i \in \hat{\mathcal{P}}} F_{ji} \geq C_j^{\mathcal{R}} + \sum_{i \in \mathcal{P}_j \cap \hat{\mathcal{P}}} E_{ji} + \sum_{i \in \mathcal{P}_j \setminus \hat{\mathcal{P}}} F_{ji} \\ 0 & if \sum_{i \in \hat{\mathcal{P}}} F_{ji} < C_j^{\mathcal{R}} + \sum_{i \in \mathcal{P}_j \cap \hat{\mathcal{P}}} E_{ji} + \sum_{i \in \mathcal{P}_j \setminus \hat{\mathcal{P}}} F_{ji} \end{cases} \quad (2)$$

The SP deployment problem can be described by the following model.

$$[\boldsymbol{M1}] \text{ maximize } Z = \sum_{j \in \hat{\mathcal{R}}_N} \sum_{i \in \mathcal{P}_j \cap \hat{\mathcal{P}}_N} E_{ji} \quad (3)$$

subject to

$$\sum_{i \in \mathcal{P}} C_i^{\mathcal{P}} x_i + \sum_{j \in \mathcal{R}} C_j^{\mathcal{R}} y_j \leq B \quad (4)$$

$$\hat{\mathcal{P}}_0 = \{i | x_i = 1 \cup \hat{x}_i = 1, i \in \mathcal{P}\} \quad (5)$$

$$\hat{\mathcal{R}}_0 = \{i | y_j = 1 \cup \hat{y}_j = 1, j \in \mathcal{R}\} \quad (6)$$

$$\hat{\mathcal{P}}_{n+1} = \hat{\mathcal{P}}_n \cup \{i | \alpha_i(\hat{\mathcal{R}}_n) = 1, i \in \mathcal{P} \setminus \hat{\mathcal{P}}_n\}, n = 0, ..., N-1 \quad (7)$$

$$\hat{\mathcal{R}}_{n+1} = \hat{\mathcal{R}}_n \cup \{j | \beta_j(\hat{\mathcal{P}}_n) = 1, j \in \mathcal{R} \setminus \hat{\mathcal{R}}_n\}, n = 0, ..., N-1 \quad (8)$$

$$\hat{\mathcal{P}}_N = \hat{\mathcal{P}}_{N-1} \quad (9)$$

$$\hat{\mathcal{R}}_N = \hat{\mathcal{R}}_{N-1} \quad (10)$$

$$x_i \in \{0, 1\}, \forall i \in \mathcal{P} \quad (11)$$

$$y_j \in \{0, 1\}, \forall j \in \mathcal{R} \quad (12)$$

The objective function (3) maximizes the SP usage in the shipping network. Considering that the berthing times of ship visits are predetermined, the objective function, also, indicates minimizing the traditional fuels used while berthing, which is equivalent to environmental damage minimization. Constraint (4) shows the limited budget for SP subsidies. Constraints (5) and (6) show that, in the initial phase, the ports and routes that receive government subsidies will construct SP facilities. Constraints (7) and (8) demonstrate the increase in SP facilities, due to the mutual promotion between the facility construction of ports and routes. Constraints (9) and (10) show that the promotion effect will reach the equilibrium on or before the last phase. Constraints (11) and (12) are the ranges of the decision variables.

3. Solution Method

The model $[\boldsymbol{M1}]$ will be solved by an tailored labeling algorithm. We define $\Psi := \mathcal{P} \cup \mathcal{R}$ and

$$\overline{C}_i, \forall i \in \Psi = \begin{cases} C_i^{\mathcal{P}}, & if \quad i \in \mathcal{P}, \\ C_i^{\mathcal{R}}, & if \quad i \in \mathcal{R}. \end{cases} \quad (13)$$

The related notations that will be used are listed as follows.

Set

Ψ the set of all ports and shipping routes considered, $\Psi := \mathcal{P} \cup \mathcal{R}$;

Parameters

$\overline{C}_i$ binary variable, equal to 1 if port i receives government subsidy, 0 otherwise, $\forall i \in \mathcal{P}$;

y_j binary variable, equal to 1 if route j receives government subsidy, 0 otherwise, $\forall j \in \mathcal{R}$;

$\hat{\mathcal{P}}_n$ the set of ports that decide to construct onshore SP facilities at or before phase n, $\forall n \in \mathcal{N}$;

$\hat{\mathcal{R}}_n$ the set of routes that decide to retrofit the ships deployed and construct onboard SP facilities at or before phase n, $\forall n \in \mathcal{N}$.

Here we use label $L = (\overline{\Psi}, \overline{B}, \hat{\Omega})$ to denote the state of a node. In the label L, $\overline{\Psi} = \hat{\mathcal{P}}_0 \cup \hat{\mathcal{R}}_0$ represents the ports and shipping routes that receive government subsidies; $\overline{B}$ represents the remaining budget; and $\hat{\Omega}$ represents the ports and shipping routes with SP facilities in the long-term equilibrium. Meanwhile, we define $Z(L)$ as the usage amount of SP electricity brought by the subsidy plan $\overline{\Psi}$ of L and Φ as the candidate pool for extending L, $\overline{\Psi} = \{i|\overline{C}_i \leq \overline{B}, i \in \Psi \backslash \hat{\Omega}\}$.

Three main dominant rules were developed to improve the algorithm efficiency:

Proposition 1. *Label* $L_1 = (\overline{\Psi}_1, \overline{B}_1, \hat{\Omega}_1)$ *dominates Label* $L_2 = (\overline{\Psi}_2, \overline{B}_2, \hat{\Omega}_2)$ *if (1)* $\hat{\Omega}_1 \supseteq \hat{\Omega}_2$ *and (2)* $\overline{B}_1 \geq \overline{B}_2$.

Proposition 2. *Label* $L_1 = (\overline{\Psi}_1, \overline{B}_1, \hat{\Omega}_1)$ *dominates Label* $L_2 = (\overline{\Psi}_2, \overline{B}_2, \hat{\Omega}_2)$ *if (1)* $\hat{\Omega}_1 \supseteq \hat{\Omega}_2$ *and (2)* $\Phi \backslash \hat{\Omega}_2 = \varnothing$.

Proposition 3. *Label* $L_1 = (\overline{\Psi}_1, \overline{B}_1, \hat{\Omega}_1)$ *dominates Label* $L_2 = (\overline{\Psi}_2, \overline{B}_2, \hat{\Omega}_2)$ *if (1)* $\hat{\Omega}_1 \supseteq \hat{\Omega}_2$ *and (2)* $\overline{B}_1 \geq \max_{i \in \Phi_2 \backslash \hat{\Omega}_1} \overline{C}_1$ *hold, and (3) or (4) holds:*

(3) $|\Phi_2 \backslash \hat{\Omega}_1| \geq 2$, *and* $\overline{B}_2 < \min[2]_{i \in \Phi_2 \backslash \hat{\Omega}_1} \overline{C}_i + \min_{i \in \Phi_2 \backslash \hat{\Omega}_1} \overline{C}_i$;

(4) $|\Phi_2 \backslash \hat{\Omega}_1|$.

For the details of the model and solution method, please refer to the study of Wu and Wang [24].

4. Numerical Experiment

To obtain the optimal subsidy plan for SP deployment in the Chinese container shipping network, including the Port of Hong Kong, we have conducted the case study based on the data collected from studies, reports, and the official websites of the related ports and shipping companies.

4.1. Parameter Settings

In the Chinese container shipping network investigated in this paper, the electricity grid is operated by the local government. To provide SP for ships, the ports need to construct the shore-side SP system within the port area. The electricity will be purchased by the ports at the large industrial electricity price determined by the government and, then, sold to ships at a price determined by the port authorities. The government will provide subsidy to certain ports and shipping routes, and the SP facility construction cost/ship retrofitting cost of them will be fully covered.

For the route information, including the port of calls, the service frequency, and the number of ships deployed, we referred to the official website of the China Ocean Shipping (Group) Company, which is the biggest shipping company in China [34]. In this case study, 91 liner shipping routes from four types, namely the domestic coastal routes, the Yangtze River routes, the Pearl River routes, and the cross-strait routes, were considered, covering 85 ports in total [35]. Please refer to Appendix A, for details about the ports and sailing routes considered. According to a study focusing on the benefit of using shore power and low sulfur fuels at berth in China [36], the ships deployed consume marine fuel with 0.5% of sulfur (750 USD/ton) at port areas, and it takes 300 g of fuel to generate 1 kWh of electricity for onboard machine while berthing.

As for the SP system construction cost, based on various studies and reports on real-world cases [24,36–39], the cost of building a set of shore-side facilities is randomly generated as between USD 1–3 million, and between USD 0.3–0.5 million for onboard facilities. When the SP system is ready, the ports will purchase electricity from the power grid at the large industrial electricity price [40], and we collected the prices at different provinces from the corresponding websites. Meanwhile, the SP selling prices paid by the ships are randomly generated between 1.2–1.4 RMB/kWh (approximately 0.18972–0.22134 USD/kWh), based on the study of Li [36].

To justify the subsidy policy, we, also, estimate the environmental benefit of the fuels saved by using SP and conduct a cost-benefit analysis. The environmental cost of MDO with 0.5% sulfur content is estimated as the weighted average of the environmental damage of the main pollutants, namely SO_X, NO_X, CO_2, and $PM_{2.5}$. According to the Fourth Greenhouse Gas (GHG) Study [4], released by IMO, a ship will emit 0.01 tons of SO_X, 0.167 tons of NO_X, 3.206 tons of CO_2, and 0.00203 tons of $PM_{2.5}$, while consuming one ton of MDO. According to Nunes et al. [41] and Song [42], the social costs associated with these four main components of ships emissions, namely SO_X, NO_X, CO_2, and $PM_{2.5}$, are 11,123 USD/ton, 6282 USD/ton, 33 USD/ton, and 61,179 USD/ton, respectively. As a result, the environmental benefits of saving one ton of MDO equals USD 1320.8. In China, the electricity for ships is purchased from the national grid, so the power station might be distant and out of the jurisdiction of the local government, which is the decision maker in this study. Therefore, the environmental costs to generate the electricity for SP are not considered in this paper. However, it would be easy to take them into account, by subtracting the power-generating costs from the environmental benefits.

Besides, according to the Shore Power Layout Scheme announced by the Ministry of Transport of the People's Republic of China [43], 36 out of the 85 ports have been equipped with SP facilities, but only a few routes have been retrofitted [44]. Please refer to Appendix A for detailed information. Therefore, we set the total budget at 10% of the total SP system construction cost, for all routes and ports. For other parameters, we followed the study by Wu and Wang [24].

4.2. Results and Discussions

The case study was conducted on an HP ENVY Convertible Model 15-dr1008TX laptop, with an i7-10510U CPU, 2.30 GHz processing speed, and 16 GB of memory. The model and the algorithm were implemented in C++ programming.

The result shows that with three ports and nine routes receiving USD 31,924,000 of subsidy for the SP system construction, 82 ports, including the Port of Hong Kong, and 88 routes will, finally, choose to construct an SP system under the network effect mentioned by Wu and Wang [24]. As a result, the annual bunker fuel consumption for all routes decreases from 5.28391×10^8 ton to 2.72231×10^6 ton per year, achieving the environmental benefits of USD 6.94303×10^{11} per year. Detailed information is listed in Table 1, in which "original bunker" and "final bunker" refer to the annual consumption of bunker fuel at berth in the container shipping network, before and after the subsidy; "environmental benefit" refers to the benefits achieved by the usage of SP with the subsidy; "subsidized ports" and "subsidized routes" refer to those that receive the government subsidy; and "ports that finally adopt SP" and "routes that finally adopt SP" refer to those that decided to construct shore power facilities after the network effect.

From Table 1, we can see that the subsidy plan is effective and encourages most of the ports to construct shore-side SP systems and the shipping routes to retrofit their vessels. Moreover, the environmental benefits achieved by subsidizing the ports and shipping routes is way above the total subsidy expenditure, which validates the subsidy plan from the cost–benefit aspect.

In practice, the value of the environmental benefits of using SP changes a lot with a series of factors, including, but not limited to, the port location and the energy source of the power plants. Thus, we conducted a cost–benefit analysis with different values of the environmental benefits. It is revealed that when the environmental benefits are reduced to USD 132.08 (=10% $\times$ USD 1320.8), the annual environmental benefits equal

6.94303×10^{10} USD/year, which is still significantly higher than the total subsidy amount (USD 31,924,000). The subsidy plan, therefore, is still economical. Bunker cost savings is the main driving force behind the shipping companies to retrofit their vessels. Thus, when the MDO price decreases and MDO becomes more economical than SP, the subsidy plan discussed in this paper might be ineffective. In that case, subsidies that lower the SP selling price might be helpful.

Table 1. Detailed information of the case study result.

Content	Value
Original bunker (ton/year)	5.28391×10^8
Final bunker (ton/year)	2.72231×10^6
Environmental benefits (USD/year)	6.94303×10^{11}
Subsidized ports	67,69,77
Subsidized routes	1,13,17,23,24.26,29,72,80
Ports that finally adopt SP	1,2,3,4,5,6,8,9,10,11,12,13,14,15,16,17,18,19,20,21,22,23,24,25,26,27,28,29,30,31,32,34,35, 36,37,38,39,40,41,42,43,44,45,46,47,48,50,51,52,53,54,55,56,57,58,59,60,61,62,63,64,65,66, 67,68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85,86,87,88,89,90,91
Routes that finally adopt SP	1,2,3,4,5,6,7,8,9,10,11,12,13,14,15,16,17,18,20,21,22,23,24,25,26,27,28,29,30,31,32,33,34,35, 36,37,38,39,40,41,42,43,44,45,46,47,48,49,50,51,53,54,55,56,57,58,59,60,62,63,64,65,66,67, 68,69,70,71,72,73,74,75,76,77,78,79,80,81,82,83,84,85

Considering that part of the ports are already equipped with SP facilities, the subsidy amount required would not exceed USD 266,715,633.30. Thus, we conducted numerical experiments with total budgets ranging from 2.5% to 12.5% of the upper limit. The results are listed in the following table.

From Table 2, we can see that both the numbers of subsidized ports and routes increase with the total budget for the subsidy plan. As a result, the final bunker consumption decreases with the total budget, and the emission reduction increases to a higher level, which can be reflected by the rising annual environmental benefits. The columns for the subsidized ports and routes show that when the budget is limited, the most critical ports and routes will be subsidized, and others will be picked if there is a budget surplus.

Table 2. Results of case L-1 to L-5.

Case	Budget Proportion	Final Bunker (ton/year)	Environmental Benefits (USD/year)	Subsidized Ports	Subsidized Routes
L-1	2.5%	1.9588×10^7	6.72027×10^{11}	69,77	7,13,27
L-2	5%	8.45733×10^6	6.87×10^{11}	69,77	1,13,27,72,80
L-3	7.5%	5.36911×10^6	6.91×10^{11}	67,69,77	1,7,13,17,24,27,72,80
L-4	10%	3.8822×10^6	6.93×10^{11}	67,69,77	1,7,13,17,24,26,27,72,80
L-5	12.5%	1.01203×10^6	6.96562×10^{11}	67,69,77	1,7,13,17,23,24,26,29,72,80

Based on the results and discussion, two managerial insights can be obtained, to provide guidance for the government. First, as shown in Table 2, a significant final bunker usage reduction, namely 96.29% ($=(5.28391 \times 10^8 - 1.9588 \times 10^7)/5.28391 \times 10^8$), will be achieved with the total budget equal to only 2.5% of the upper limit. Thus, a relatively small budget would accomplish the emission reduction task excellently, and it might be unnecessary to spend a large amount of budget on the subsidization.

Second, the optimal total budget for the government should be carefully decided. From Table 2, we can see that with the total budget increasing from 2.5% to 12.5% of the upper limit, the final bunker becomes 10 times lower, reaching 1.01203×10^6 tons/year (0.19% of the original bunker). Visually, from Figure 1, we can see that with the growth of the total budget, the final bunker reduction decreases. A significantly higher budget will be required for further bunker usage reduction. The subsidy expenditure needs to be considered together with the final bunker reduction, while making the budget.

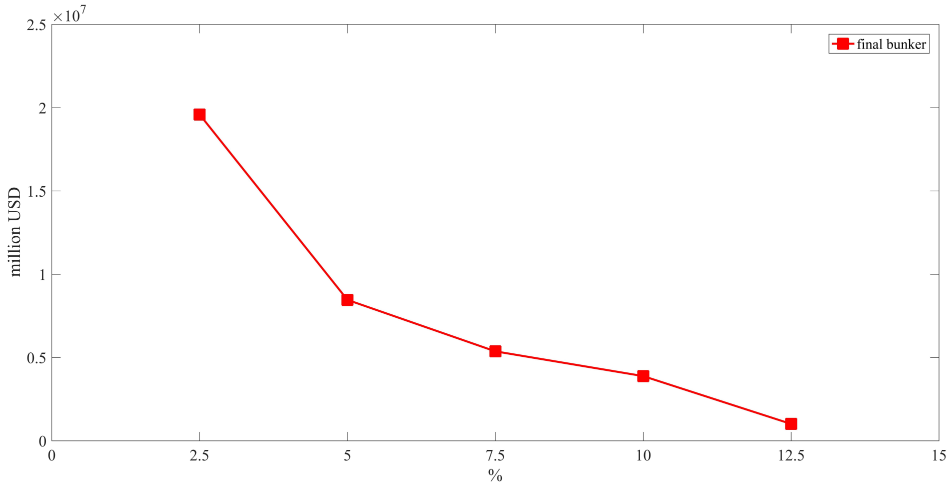

Figure 1. Final bunker with different total budgets.

5. Conclusions

On top of the study by Wu and Wang [24], we conducted a case study of the container shipping network in China, based on real-world port distribution and the container shipping routes operated by COSCO, which is the biggest Chinese shipping company. The result shows that with a limit subsidy budget, the SP utilization rate can be largely improved, and, therefore, ships will cut down on bunker fuels at berth. This case study, also, further validates the model and algorithm proposed by Wu and Wang [24] and shows that the SP deployment problem is worthy of in-depth investigation.

Different from Wu and Wang [24], we consider the ports that are already quipped with SP facilities in the network, and, thus, can prevent budgetary waste on ports and shipping routes that are already equipped with SP facilities. Besides, we, also, conduct cost–benefit analysis, which is not covered by [24], to justify the SP subsidy policy. Moreover, we investigate the influence of the total budget on the final bunker usage. Numerical experiments with various total budgets were conducted. Based on the results, two useful managerial insights are provided for the local government: (i) it might be unnecessary to spend a large amount of budget on the subsidization, and (ii) the subsidy expenditure needs to be considered, together with the final bunker reduction, while making the budget.

In this paper, we have conducted a case study based on a Chinese container shipping network, in which the routes are operated by the largest shipping company in China. In practice, international sailing routes that visit both domestic ports and overseas ports account for a non-negligible part of the ship visits at each domestic port. Therefore, it would be worthwhile to take international routes into consideration in future research.

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Abbreviations

The following abbreviations are used in this manuscript:

UNCTAD	United Nations Conference on Trade and Development
IMO	International Maritime Organization
GHG	greenhouse gas
SP	shore power
CO_2	carbon dioxide
SO_2	sulfur dioxide
NO_X	nitrogen oxides
$PM_{2.5}$	fine particulate matter

Appendix A. Ports and Routes Considered in This Case Study

Appendix A.1. Ports Considered in This Case Study

The shore power columns in Table A1, namely the third and sixth columns, show whether the port is already equipped with shore power facilities; "N" for no and "Y" for yes.

Table A1. Ports considered in this case study.

No.	Port Name	Shore Power	No.	Port Name	Shore Power
1	Anqing	N	46	Xiamen	Y
2	Changshu	N	47	Shantou	Y
3	Changzhou	N	48	Shanghai	Y
4	Dachanwan	N	49	Shekou	N
5	Dalian	Y	50	Shenzhen	Y
6	Dandong	N	51	Shunde	N
7	Deqing	N	52	Suqian	N
8	Dongguan	N	53	Taishan	N
9	Foshan	Y	54	Taizhong	Y
10	Fuzhou	Y	55	Taicang	N
11	Gaolan	N	56	Taizhou	N
12	Gaoming	N	57	Tangshan	Y
13	Gaoxiong	Y	58	Tianjin	Y
14	Guangxi	Y	59	Tongling	N
15	Haian	N	60	Waigaoqiao	N
16	Haikou	N	61	Wuchongkou	N
17	Humen	Y	62	Wuhu	Y
18	Huadong	N	63	Wuzhou	Y
19	Huanghua	N	64	Wuhan	Y
20	Huangpu	N	65	Xianggang	N
21	Huangshi	Y	66	Xinhui	N
22	Huizhou	Y	67	Xuzhou	N
23	Jilong	Y	68	Yantai	Y
24	Jiangmen	Y	69	Yantian	N
25	Jiangyin	N	70	Yangzhou	Y
26	Jinzhou	Y	71	Yangjiang	N
27	Jingzhou	N	72	Yangshan	N
28	Jiujiang	Y	73	Yichang	N
29	Lianyungang	Y	74	Yixing	N
30	Longtan	N	75	Yingkou	Y

Table A1. *Cont.*

No.	Port Name	Shore Power	No.	Port Name	Shore Power
31	Luzhou	N	76	Yueyang	N
32	Nanjing	Y	77	Yunfu	N
33	Nansha	N	78	Zhapu	N
34	Nantong	Y	79	Zhanjiang	N
35	Ningbo	Y	80	Zhangjiagang	N
36	Panjin	N	81	Zhaoqing	Y
37	Qiba	N	82	Zhenjiang	Y
38	Qinzhou	N	83	Zhongshan	Y
39	Qinhuangdao	N	84	Zhongqing	Y
40	Qingdao	Y	85	Zhuhai	Y
41	Qingyuan	N			
42	Quanzhou	N			
43	Rizhao	Y			
44	Sanbu	N			
45	Sanshui	N			

Appendix A.2. Routes Considered in This Case Study

The route type columns in Table A2 indicate which type each route is from; T1 for the domestic coastal routes; T2 for the Yangtze River routes; T3 for the Pearl River routes; and T4 for the cross-strait routes.

Table A2. Routes considered in this case study.

No.	Route Type	Ports of Call	No.	Route Type	Ports of Call
1	T1	75 - 33	46	T2	25 - 80 - 55 - 72
2	T1	75 - 57 - 58 - 4	47	T2	55 - 72
3	T1	58 - 33	48	T2	74 - 55 - 48
4	T1	40 - 43 - 29 - 50 - 11	49	T2	67 - 52 - 55
5	T1	39 - 68 - 33	50	T2	15 - 55
6	T1	5 - 26 - 46 - 33	51	T3	48 - 23 - 54 - 13
7	T1	19 - 33	52	T3	48 - 13 - 54 - 23
8	T1	75 - 58 - 79 - 38	53	T3	5 - 58 - 40 - 29 - 54 - 35
9	T1	26 - 57 - 43 - 38	54	T4	33 - 11 - 51
10	T1	68 - 40 - 46	55	T4	33 - 11 - 45
11	T1	75 - 58 - 42 - 46	56	T4	33 - 11 - 12
12	T1	75 - 58 - 46 - 47	57	T4	33 - 11 - 9
13	T1	42 - 46 - 16	58	T4	33 - 4 - 20
14	T1	75 - 68 - 48	59	T4	33 - 4 - 18
15	T1	26 - 48	60	T4	33 - 17
16	T1	6 - 48	61	T4	33 - 11 - 66
17	T1	48 - 78 - 61	62	T4	33 - 11 - 53 - 44
18	T1	55 - 50 - 17 - 11	63	T4	33 - 11 - 63
19	T1	48 - 42 - 46	64	T4	33 - 11 - 14
20	T1	5 - 75 - 36 - 34	65	T4	33 - 11 - 81
21	T1	58 - 34	66	T4	33 - 11 - 77 - 7
22	T1	40 - 29 - 48	67	T4	33 - 4 - 8
23	T2	31 - 64	68	T4	33 - 4 - 22
24	T2	84 - 64 - 1	69	T4	33 - 11 - 83
25	T2	84 - 1 - 55 - 48	70	T4	33 - 85
26	T2	84 - 64	71	T4	33 - 4 - 41
27	T2	73 - 27 - 76	72	T4	33 - 11 - 71
28	T2	73 - 27 - 64	73	T4	20 - 65 - 20
29	T2	76 - 48	74	T4	65 - 18
30	T2	64 - 21 - 28 - 55 - 48	75	T4	65 - 17

Table A2. *Cont.*

No.	Route Type	Ports of Call	No.	Route Type	Ports of Call
31	T2	1 - 60	76	T4	33 - 65
32	T2	1 - 59 - 55 - 48	77	T4	51 - 9 - 12 - 33
33	T2	1 - 48	78	T4	20 - 33
34	T2	62 - 32 - 48	79	T4	24 - 33
35	T2	32 - 48	80	T4	49 - 65
36	T2	37 - 30 - 55 - 48	81	T4	51 - 49
37	T2	70 - 82 - 56 - 55 - 48	82	T4	9 - 12 - 49
38	T2	3 - 25 - 55 - 48	83	T4	51 - 65
39	T2	80 - 34 - 48	84	T4	69 - 65
40	T2	80 - 34 - 55 - 48	85	T4	79 - 65
41	T2	2 - 55 - 48	86	T4	16 - 65
42	T2	55 - 48	87	T4	38 - 65
43	T2	64 - 72	88	T4	47 - 65
44	T2	21 - 28 - 62 - 72	89	T4	10 - 65
45	T2	32 - 70 - 72	90	T4	46 - 65
			91	T4	65 - 42

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