GOVERNMENT SUBSIDY PLAN OPTIMIZATION AND MARITIME OPERATIONS MANAGEMENT IN SHIPPING EMISSION REDUCTION

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Government Subsidy Plan Optimization and Maritime Operations Management in Shipping Emission Reduction

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CERTIFICATE OF ORIGINALITY

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Abstract

Emission reduction and decarbonization are among top priorities in the maritime industry and have attracted extensive attentions. To achieve the ambitious goal of reducing the total ship emission volume to half of the 2008 levels by mid-century, more effective measures are on their way. Joint efforts of the government and the industry are indispensable for the transition to a clean-energy and low-emissions future of the shipping industry. In this thesis, we explore the problems faced by both the government and the industry under the trend of shipping emission reduction. Academic studies on related topics can provide specific and quantitative suggestions for different stakeholder in shipping and give guidance on how to maximization their own benefits. Meanwhile, existing literature leaves plenty room for in-depth research in this area. Therefore, this thesis aims to fill the research gap and investigate the subsidy plan optimization and operational problems faced by the government and industry under the trend of shipping emission reduction. This thesis consists of three studies.

Chapter 2 focuses on the subsidy design in the promotion of liquefied natural gas (LNG) as marine fuel. Alternative fuels have been recognized as a promising method to alleviate the air emission problem of the maritime industry. LNG, as one of the most promising alternative fuels in shipping, has attracted extensive attention, and government subsidies are extensively adopted to promote its application. We consider two-stage subsidy methods in this chapter and aim to find the optimal subsidy plan under different scenarios. Distinguished from previous studies, we obtain the analytical solution to the subsidy plan optimization model, which provides more details about the logic behind the relationship between the subsidy plan and the pro-

motion effect. Influence of critical parameters are also analyzed, and the conclusions we obtain further explain the intuition.

Chapter 3 investigates the ship operation and allowance management plan optimization in liner shipping under maritime emission trading system. Maritime emission trading system (METS) has been discussed as a promising method to limit the global average temperature increase to 2°C compared to the pre-industrial level. However, the impact of METS on liner shipping companies, which are important players in shipping, has not been carefully investigated. To fill the research gap, a stochastic model was developed to optimize the ship operation and allowance management plan in liner shipping under METS. Ship deployment, sailing speed optimization and carbon allowance management were integrated into our model. Important characteristics of METS were also captured. Based on the problem structure, the model was then converted into a deterministic linear one. Various numerical experiments were conducted to validate the model and solution method proposed in this chapter. The results show the necessity for this study and the influence of the changing pattern of market carbon pricing on liner shipping route operations. Moreover, it is revealed that under certain scenarios, a heterogeneous fleet would be deployed to balance the bunker costs, chartering costs, and carbon costs of a liner shipping route.

Chapter 4 explores the ship deployment problem in liner shipping under operational sailing speed limit. To achieve the emission reduction goal set by the International Maritime Organization (IMO), more effective regulations are on their way. Sailing speed limits are a simple and plausible measure that has attracted IMO's attention. Meanwhile, the implementation of sailing speed limits will have direct impacts on ship deployment decisions of ship operators, and lead to higher operating costs. However, this issue has not been covered by existing literature. Thus, this chapter investigates the ship deployment problem in liner shipping under sailing speed limits. A mixed-integer nonlinear model is developed to describe the problem and then solved by a tailored solution method originally proposed. Numerical experiments were conducted to validate the model and solution method. Comparison between results from our model and traditional ship deployment model demonstrates

the necessity of this study and shows the superiority of our model under different transport demand scenarios.
Keywords: Maritime transportation; Liner shipping; Liquefied natural gas (LNG); Maritime Emission Trading System; Sailing speed limits; Government subsidy; Ship deployment

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Chapter 1

Introduction

1.1 Background Information

The problem of climate change and Greenhouse Gas (GHG) emissions has attracted extensive global attentions. In the 21st United Nations Climate Change Conference, the United Nation sets the Paris Agreement and puts forward the goal to restring the global average temperature rise within 2 °C compared to pre-industrial levels, pursuing 1.5 °C (United Nations 2015). However, without introducing new effective regulations or measures, a temperature rise of 3 °C is going to be reached at the end of this century (UNCTAD 2021).

As for the maritime industry that constitutes 3% of the global anthropogenic emissions, which is close to countries like Germany or Japan in emission volume (UNCTAD 2022, Organization for Economic Co-operation and Development 2022), the emission reduction is also an urgent issue. Although relatively low, the proportion keeps growing in the past decade, and the absolute GHG emission volume from the shipping industry also keeps increasing since 2012 (Faber et al. 2020). According to the International Maritime Organization (2019a), maritime transportation makes up approximately 90% of the global cargo delivery, being recognized as the backbone of international trade. The latest Review of Maritime Transportation by the United Nations Conference on Trade and Development (UNCTAD) reveals that the total volume of international seaborne trade reached 10.7 billion tons in 2020, after a 3.8% annual fell due to the COVID-19 pandemic. Fortunately, recovery from the decreasing trend is following closely. As calculated by UNCTAD, global seaborne trade volume rose by 3.2% in 2021, and will keep growing in the next few years at the annual rate of 2.4% (UNCTAD 2021, 2022). Thus, the dominance of maritime in transportation is not likely to be overturned in the near future. With the positive outlook for the maritime industry and the projected increasing trend of seaborne trade volume, the problem of shipping emissions has become one of the major concerns (UNCTAD 2020).

Separately, marine shipping covers 15% of the nitrogen oxides (NO_X), 13% of the sulfur dioxide (SO_2), and 2.7% of the carbon dioxide (CO_2) resulted from human activities (Faber et al. 2020). Taking the social responsibility, various emission reduction targets and agreements have been proposed and approved recently. IMO has set the goal to halve total annual greenhouse gas emissions from the maritime industry on or before 2050, compared to 2008 levels. Meanwhile, the carbon intensity of shipping transport should be reduced by at least 40% by 2030, and 70 % by 2050 (UNCTAD 2021). As calculated in the Fourth IMO GHG study (Faber et al. 2020), the total shipping emission in 2018 equals 90% of that in 2008. With a series of plausible long-term economic and energy scenarios, the total emission from the shipping industry in 2050 will reach 90-130% of 2008 levels, which significantly exceeds the emission target of IMO. The "Getting to Zero Coalition's Call to Action for Shipping Decarbonization", which is signed by over 200 maritime industry organizations, is committed to implement 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 (Forum 2021). 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 (UNCTAD 2021, 2022). It is also 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 (Forum 2021). At United Nations Framework Convention on Climate Change (UNFCCC) Conference of the Parties (COP) 26, the Dhaka-Glasgow Declaration was lunched to establish a mandatory GHG levy on international shipping, and the Clydebank Declaration aims to set zero-emission maritime routes between ports (Forum 2022, UK Department for transport 2022).

To achieve the emission reduction goals, IMO has proposed multiple measures to restrict ship GHG emissions, including operational and technical regulations and market-based measures (Rehmatulla and Smith 2015b,a, Rehmatulla et al. 2017, UNCTAD 2021). Some of them haven been agreed, including Energy Efficiency Design Index (EEDI), Energy Efficiency Existing Ship Index (EEXI), and Carbon Intensity Indicator (CII), which are regulations on energy-efficiency standards for ship design and operation. With the adoption of amendments to MARPOL (International Convention for the Prevention of Pollution from Ships) Annex VI at Marine Environment Protection Committee (MEPC) 62 in 2011, the Energy Efficiency Design Index (EEDI) and the Ship Energy Efficiency Management Plan (SEEMP) became mandatory (International Maritime Organization 2011). The EEDI sets the CO_2 emission volume per capacity mile (gram/tonne-mile) required for new ships or existing ships that have undergone a major conversion, and the highest allowable EEDI value varies with the ship type and dead weight tonnage. Besides, the required EEDIs for all segments keep decreasing over time, which indicates higher decarbonization targets in the future. Meanwhile, in the SEEMP, the Energy Efficiency Operational Indicator (EEOI) is applied to measure the CO_2 emission volume per tonne mile (gram/tonne-mile) cargoes actually carried by the vessel for each voyage (International Maritime Organization 2009). More recently, the Energy Efficiency Existing Ship Index (EEXI) and the carbon intensity indicator (CII) were integrated into the revised version of MARPOL Annex VI (International Maritime Organization 2021c). The EEXI can be regarded as an enhanced version of the EEDI because that it not only has higher requirements on ships from the same category and but also applies to existing ships that have not undergone major revisions as well. The carbon intensity indicator (CII) refers to carbon emissions per transport work, and the highest allowable value within a specific rating level keeps decreasing, which ensures continuous improvement of the ships' operational carbon intensity. Among the energy efficiencies measures taken by the IMO, the EEDI and the EEXI mainly affect the adoption of energy efficiency technologies on board. The EEOI and the CII, meanwhile, highly depend on the operations of ships. For more detailed information and related documents about the IMO measures on carbon emission reduction, please refer to its official website (International Maritime Organization 2021a,b). In addition to the indexes, efforts have also been put to promote the application of alternative marine fuels for ship propulsion. National action plans are encouraged for the reduction of GHG emissions from international shipping. Above measures are short-term ones, for the mid-term goals, market-based measures, including maritime emissions trading system or carbon levy, and the uptake of low- and zero-carbon fuels are considered. The long-term measures that can ensure zero-carbon and fossil-free fuels are still to be discussed (UNCTAD 2021).

In this thesis, we focus on the management problems faced by both the government and the shipping industry, the two critical parties in the application of ship emission reduction measures. The government proposes and then implement regulations, which puts the original intention or the idealized emission reduction effect. Meanwhile, the industry, including port authorities and ship operators, determine the outcome, namely the emission level actually achieved.

Specifically, this thesis considers three measures, namely LNG as alternative marine fuel, maritime emission trading system, and operational speed limit. Adopting LNG as alternative marine fuel is a mature technique, and the deployment of commercial LNG-fueled vessels has succeeded and is developing significantly. Thus, it is the first measure considered in this thesis. Meanwhile, Maritime emission trading system (METS) is a market based measure, and the promotion of it will be more smooth than compulsory regulations. Ship operators might gain extra revenue from the METS by reduce its emission level actively. Thus, the implementation of METS will reduce ship emission effectively without hurting the maritime industry. Given the fact that the emission reduction work has run into a bottleneck, it is in urgent need to introduce a direct and effective measure. Ship operational speed determines the fuel consumption rate and ship emission level, and therefore a limit on the largest operational speed of ships will lead to a emission level reduction immediately. Summing up, the three critical measures are taken into account in this thesis due to their potential for being promising answers to the shipping emission reduction problem.

By answering the management problems in implementing these measures, this thesis aims to give constructive advice to the government on regulation design and to ship operators on ship deployment. As a result, the maritime industry will take a step closer to the emission reduction targets.

1.2 Emission Reduction Measures

Compared with traditional fossil fuels, LNG has a high net calorific value and low impurity level. Therefore, it has been recognized as a promising alternative fuel for maritime (UNCTAD 2022). As the greenest fossil energy source for ship use, LNG almost eliminates the sulfur emissions and particulate particulate matters, and reduces nitrogen oxides to 20 per cent and CO_2 emissions to 80 per cent of the emission levels of heavy fuel oil (HFO), which is the traditional fuel in maritime. From the technology and economic perspectives, dual-fuel engines enables ships to be operated on LNG and traditional marine fuels to comply with emission reduction regulations while remaining competitive (International Maritime Organization 2016, Schinas and Butler 2020, UNCTAD 2021). As the transitional fuels for maritime transport, the consumption volume of LNG as marine fuel grows fast and the investment on application promotion also soars (Faber et al. 2020). LNG is also more cost-effective than traditional marine fuels. The study conducted by the International Maritime Organization (2016) reveals that LNG has a more competitive price than marine diesel oil (MDO) and marine gas oil (MGO), which are extensively adopted by traditional ships under the new sulfur content regulations on marine fuels (International Maritime Organization 2020).

However, with the above advantages, the application of LNG as marine fuel is still limited. The "chicken and egg" problem is barring the extensive adoption of this superior alternative fuel, due to the high ship retrofitting costs and LNG bunkering station construction costs (Lim and Kuby, Ko et al. 2017). Given the environmental benefits, government subsidies are effective method to break the dead lock and promote the application of LNG in maritime transportation (Wang et al. 2022). The subsidy plan optimization is a critical decision to made because it influences the subsidy expenditure as well as the promotion effect directly. Previous studies focus on obtaining numerical solutions to do not explain the correlation between the optimal solution and values of different parameters. Thus, based on a two-stage subsidy method, we try to obtain the analytical solution of the subsidy optimization problem in LNG promotion.

MBMs make an essential supplement to compulsory regulations in the carbon emission reduction of maritime industry. Currently, the MBMs can be divided into two streams: bunker/carbon levy-based measures and emission trading system (ETS)-based measures (Lagouvardou et al. 2020, Psarafits et al. 2021). Bunker/carbon levy-based measures mainly add extra costs on marine fuels and ship emissions, for example, collecting tax on them. The other stream, ETS-based measures, calls for a global or regional ETS. The development of a global ETS has run into the bottleneck, and there has not been any new submissions of proposals since the suspension of the MBM discussion in 2013 (Psarafits et al. 2021). Compared with global ETS, regional ETS has a more promising application in th EU. Currently, the EU ETS consists of social sectors that account for around 41% of the EU's total emissions, and the emissions covered have reduced by 43%, compared with the level in 2005 when the EU ETS was initially introduced. Given the geographical features, shipping plays an significant role in the European Union economy, and accounts for 4% of the GHG emissions in EU, which is obviously higher than the 2.89% global proportion (European Commission 2013). To further carry forward the emission reduction work, the shipping sector will be included in EU ETS in the future.

Emission volume of a container shipping route, to a large extent, depends on deployed ship number and sailing speed. Thus the decision making process will be obviously impacted when the maritime emission trading system (METS) comes into effect. From the perspective of ship operators', it is necessary to take the allowance management into consideration while making ship deployment plans. However, this optimization problem has not been investigated by the literature. Thus, in the second study, we explore ship operation and allowance management plan optimization in liner shipping under maritime emission trading system.

To catch up with the decarbonization plan announced by IMO, more targeted and effective measures are required(Bullock et al. 2022). According to the Fourth IMO GHG study, despite the increase in the share of cleaner marine fuels, including marine diesel oil (MDO), liquid nitrogen gas (LNG), and methanol, heavy fuel oil (HFO), which is notorious for its high level of impurity and emission volume, remains the dominant fuel in international shipping, composing 79% of the total marine fuel consumption by energy content in 2018 (Faber et al. 2020). On the other hand, the majority of energy consumed is used for vessel propulsion across all ship types. For several special types, namely cruise ships, refrigerated bulk, and miscellaneous fishing, the energy demand for propulsion still equals nearly the sum of auxiliary demand and heat energy demand. Besides, as discussed in academic studies and authoritative reports, the marine fuel consumption rate and emission volume are closely related to sailing speed (Ronen 1982, 1993, Wang and Meng 2012, Lack and Corbett 2012, Guo et al. 2022, Wang and Xu 2015, UNCTAD 2019, 2020, 2021, Smith et al. 2014, Faber et al. 2020). Thus, sailing speed limit has been proposed to IMO as an immediate GHG reduction measure to deliver the IMO 2030 target (International Maritime Organization 2019b).

Sailing speed limits is another emission reduction regulation. A scientifically-designed and well-implemented sailing speed limit regulation would lead to a lower sailing speed for certain ships and thus achieve a lower emission level. Compared to other shipping emission reduction measures, such as shore power, wind-propulsion, and alternative marine fuels, sailing speed limit is more practical and ready for implementation. No new technology or vessel retrofitting is required for the implementation of sailing speed limit, changes in operation are sufficient. In fact, due to fuel consumption and emission volume's sensitivity to sailing speed, slow steaming or speed optimization has been adopted by ship operators as a countermeasure to emission reduction regulations, for example the sulfur upper limit of marine fuels used onboard, Emission Control Area (ECA), and EEDI implemented by IMO and negates the emission reduction effectiveness (Smith 2012, Fagerholt et al. 2015, Fagerholt and Paraftis 2015, Zis and Psaraftis 2019). It is in urgent need to integrate the constraint of speed limits into ship deployment optimization models. In the third study, we originally investigate ship deployment problem in liner shipping under operational sailing speed limit. Compared to previous papers, the third study integrates the annual average operational speed limit into the model and loosens some common assumptions in traditional ship deployment problems for the optimality.

This thesis consists of the following five parts:

(i) In Chapter 1, we introduce the background of ship emission reduction and three measures covered in this thesis and explain the necessity of the studies.

(ii) In Chapter 2, we explore the subsidy optimization for LNG bunkering promotion in maritime transportation. Considering the interrelationship between the LNG bunkering station construction and ship retrofitting, a two-stage subsidy method is proposed to promote LNG as marine fuel. Analytical solution to the subsidy optimization problem is obtained, which better demonstrates the logic behind the subsidy decisions and outcomes. In addition, we also explore the optimal LNG bunkering price and analyze the influence of port's LNG purchasing price and the marine diesel oil (MDO) bunkering price.

(iii) In Chapter 3, we investigate ship operation and allowance management plan optimization in liner shipping under maritime emission trading system. A stochastic mixed-integer nonlinear problem is developed to describe the management problem faced by a liner shipping company. Historical data from EU ETS were adopted to estimate the uncertainty of the market carbon price. Based on the problem structure, a tailored solution method is proposed to handle the non-linear elements and convert the model into a mixed-integer linear one. Groups of numerical experiments were conducted to demonstrate the necessity of this study. Managerial insights were obtained on the basis of sensitive analyses.

(iv) In Chapter 4, we focus on the operational speed limits and address the ship deployment problem in liner shipping under this emission reduction regulation. Integrating the annual average operational speed limits into the ship deployment problem, a mixed-integer nonlinear programming model is developed for ship deployment in two periods in a calendar year. For optimality, several frequently-used assumptions are removed from this study. Meanwhile, the concept of ship group is introduced to adapt to the multi-period deployment plan. The originally developed solution method solves the problem without lose of generality. Comparison between results of our method and traditional method show the superiority of ours under various transport demand scenarios.

(v) In Chapter 5, we present main findings obtained in the three studies above and discuss future research directions.

Chapter 2

Promoting Liquefied Natural Gas (LNG) Bunkering for Maritime Transportation: Should Ports or Ships be Subsidized?

2.1 Introduction

2.1.1 Current Application and Barrier

To the year of 2022, a total of 225 LNG-fueled ships are in operation globally, and 2021 witnessed exponential growth in LNG-fueled deep sea-vessel orders. As for the infrastructure, LNG bunkering service is available at 141 ports (SEA-LNG 2022). However, the development of the infrastructure is not geographically balanced, most of the ports with LNG bunkering service are located in Europe (SEA-LNG 2022).

One of the main barriers in the areas where the LNG has not been extensively adopted as marine fuel is the high construction cost of LNG bunkering facility and the ship retrofitting cost. The application requires the joint effort and initial investment of the demand and the supply sides, namely the LNG-fueled ships and the LNG bunkering stations. A complete LNG bunkering system and abundant LNG-fueled ships are interdependent, which means that the absence of one side will discourage the the other side's enthusiasm for investing and therefore lead to the failure of promoting LNG as marine fuel. Currently, LNG has not been extensively adopted as marine fuel, and both sides are still in the preliminary stage, which leads to the "chicken and egg" problem (Lim and Kuby, Ko et al. 2017). Therefore, in the areas without complete LNG bunkering system, the application of LNG-fueled ships is very limited.

2.1.2 Government Subsidy

Being concerned with the environmental issues of the maritime industry, governments become the main impetus to break the dilemma and promote the application of LNG as marine fuel. Governmental subsidy is one of the most commonly used methods. Europe, which is the pioneer in the application of LNG as marine fuel, adopts governmental financial support as the main incentive measure. For example, the European Commission (2012) announces a master plan to cover part of the initial investment for the onshore LNG infrastructure in the Rhine-Main-Danube area. According to Bajic (2020), 20% of the LNG bunkering vessel building cost of the Port of Algeciras, approximately 11,000,000 EUR (approximately 13,400,000 USD), will be provided by the European Commission. China has conducted the Measures for the Administration of Subsidies for the Standardization of Inland River Ship Types (Ministry of Finance of the People's Republic of China and Ministry of Transport of the People's Republic of China, 2014), which regulates that newly built LNG-fueled ships with a dead weight tonnage of no less than 400 tons will receive subsidy between $630,000$–$1,400,000$ CNY (approximately $97,335$–$216,300$ USD).

One of the main management problem in the application of governmental subsidies is to determine the best subsidy plan, including the recipient and the amount they receive. In practice, recipients are the ports that construct LNG bunkering stations and ships that are retrofitted to be fueled by LNG. From the study by Wang et al. (2022), we know that subsidizing both the support and demand sides is more effective than focusing one of them. Besides, the study also reveals that covering only a minor proportion of the investment would be sufficient to significantly promote the application of LNG as marine fuel. In this paper, we consider two-stage subsidy plans and established a mathematical model to demonstrate the subsidy plan optimization problem. To better understand the relationship between the subsidy plan and the effect achieved, we obtain the analytical solution to the model under different scenarios. It turns out that the optimal subsidy plan is closely related to a group of parameters. ****In practice, there are other parties involved in the LNG promotion, including the LNG suppliers for ports. However, in this chapter, we focus on the interrelationship between the government, ports, and ships.

The remainder of this chapter is organized as follows: Section 2.2 gives a detailed review of the literature related to this study. Section 2.3 first describes the problem and presents the optimization model then give the analysis of the basic scenario. Section 2.4 analyzes the scenario with heterogeneous ships. Moreover, section 2.5 investigates the optimal value of LNG selling price from the government's perspective. Finally the conclusions are set in section 2.6.

2.2 Literature Review

In this section, we will review literature related to this study from three perspectives: i) the management problems in the application of LNG as marine fuel, ii) the application of multi-level optimization model in maritime air emission reduction, and iii) the subsidy design for the promotion of green technologies in maritime transportation.

First is the literature regarding the management problems in the application of LNG as marine fuel. Multiple studies have been conducted to investigate the willingness of ports and ships to join in the LNG bunkering market.

From the port side, there are two main angles: the angle of a single port and the angle of an area with multiple ports. For a single port, the bunkering method selection and bunkering station layout design are extensively discussed. Tam (2020) analyzes the compatibility of shore-to-ship and ship-to-ship bunkering methods from various perspectives. Considering the leaked-gas dispersion, Park et al. (2018) investigate the factors impacting the safety zone in ship-to-ship LNG bunkering. Choi et al. (2018), study the relationship between the layout of large storage tanks and the LNG leakage gas's flammable limits. From the angle of an area, the bunkering network design is frequently discussed. Various methods have been adopted to investigate the LNG bunkering network design, including the center of gravity method (Yang 2016), grey forecast model (Ma 2016), and optimization model (Wang 2014, Dai and Yang 2019). Besides, studies based on the situation of a specific country or an area have been conducted to provide solutions that are more practical (Lu et al. 2019, Ursavas et al. 2020, Liu et al. 2019). For more detailed review, please refer to Peng et al. (2021).

For ships, there are two type of main decisions related, namely whether to retrofit the vessel to be dual-fueled and when to conduct the retrofitting work. Schinas and Butler (2016) generally analyze the feasibility of LNG-fueled ships from the regulatory and commercial perspectives. More specifically, there are studies focus on specific vessel types and shipping routes. For example, Kana et al. (2015) and (Kana and Harrison 2017) investigate the influence of the uncertainties in the economic situation, LNG supply chain, and ship emission regulations on the decision whether to retrofit a container ship; Yoo (2017), meanwhile, pays attention to the economic applicability of LNG-fueled CO_2 carriers; Xu and Yang (2020), on the other hand, focus on the Northern Sea Route and study the economic feasibility of deploying LNG-fueled container ships on it.

The second stream of literature is regarding the application of multi-level optimization model in maritime air emission reduction. In practice, governments and nonprofit organizations are the policy makers, but the shipping industry, including the ports and shipping companies, are the ones that determine the outcome of the regulations. Given the hierarchical structure, multi-level optimization models have been used in studies regarding various ship emission regulations, including Energy Efficiency Design Index (EEDI) (Psaraftis 2019a, Lindstad et al. 2019), the Emission Control Areas (ECAs) (Qi et al. 2021), the Vessel Speed Reduction Incentive Program (VSRIP) (Zhuge et al. 2020, 2021), the carbon tax (Wang and Xu 2015, Wang et al. 2018).

The last stream is the literature investigating the subsidy design for the promotion of green technologies in maritime transportation. Wang et al. (2021a) optimize the subsidy amount provided by a port to improve the utilization rate of its shore power facility. Considering the network effect of the shore power facility construction work in an area, Wu and Wang (2020) identify the optimal ports and shipping routes to be subsidized so that more shore power electricity can be consumed. Zhuge et al. (2021) aim to design a suitable subsidy plan for the voluntary VSRIP in the proximity of the port to maximize the profit. Wang et al. (2022) build a trilevel optimization model to obtain the subsidy rate for ports and ships that can maximize the social benefit.

In all previous studies, Wang et al. (2022) is the most similar to this paper. Both of them investigate the subsidy design problem to promote LNG as marine fuel, and consider the decision of ports and shipping lines as well. However, this paper is essentially distinguished from Wang et al. (2022) in three different perspectives. First, in Wang et al. (2022) the subsidy amount is set to be proportional to the LNG bunkering station construction cost (for ports) and ship retrofitting cost (for ships), but in this paper we consider two-stage subsidy plans in which one of the two parties is fully and the other is partially subsidized. Second, with different subsidy plan, the optimization model developed in this paper is different from that of Wang et al. (2022). Third, in this paper, based on the analysis, we obtain the analytical solution to the model originally developed. Besides, we also deduct the influence of critical parameters and then compare it with the intuition. Thus, this paper is essentially different from existing studies.

This chapter aims to fill the research gap and investigate the interrelationship of different stakeholders in the problem of LNG promotion subsidy optimization. The allocation of subsidy to ports ans ships are explored.

The main contributions of this chapter are as follows:

- In this chapter, we propose two-stage subsidy plans that subsidize ports and ships in different ways and then develop an optimization model to describe the subsidy design problem.

- Different from previous studies, this study obtains the analytical solution to the subsidy plan optimization problem. Compared with numerical solution, the analytical solution we obtained provides more information about the correlation between the optimal solution and values of different parameters.
- We compare the relationship between critical parameters and the optimal solution under various scenarios obtained from analytical solution and logical analysis. It is revealed that they corroborate each other.

2.3 Basic Scenario with Homogeneous Ports and Ships

In this section, we investigate the subsidy plan design problem under the basic scenario with homogeneous ports and ships.

2.3.1 Model Formulation

We consider the following setting: a total of M identical ships sail along a route (e.g., along the coastline of Australia) repeatedly and visit N ports uniformly located along the route. The sailing distance between two neighbouring ports is L nautical miles (nm) and hence the total distance of the route is NL. Each ship completes the sailing on the route in T days and then repeats the sailing. The headway between two consecutive ships on the route is T/M days, i.e., a regular service frequency is provided for the ports on the route.

The ships consume marine diesel oil (MDO) as the fuel for propulsion. The price of MDO is γ (USD/ton) and the consumption rate of MDO by one ship is Q tons/nm. The tank capacity of the ship is QL and can sustain the sailing for a distance of L. Therefore, the ship refuels at each of the n ports it visits. The price at which is γ.

The government aims to promote the use of liquefied natural gas (LNG) as the marine fuel because LNG is much cleaner than MDO. To allow the ships to refuel LNG, ports have to install LNG bunkering infrastructure at the equivalent cost of C (USD) per T days. The price at which a port buys LNG, denoted by α USD/ton, is determined by the LNG market. The selling price to the ship, denoted by β USD/ton, is pre-specified by the government. To use LNG, a ship has to be retrofitted with LNG engines[2.1] at the equivalent cost of c (USD) per T days. The ships sail at the same speed when burning LNG as the speed when using MDO and the consumption rate of LNG is q tons/nm.

We assume

i) $\beta q < \gamma Q$. That is, the fuel cost per unit sailing distance using LNG is lower than using MDO.

ii) After retrofitting, the LNG tank capacity of a ship is qL. Therefore, a ship will refill a full tank of LNG whenever it visits a port with LNG bunkering infrastructure.

iii) $N(\gamma QL - \beta qL) > c$, that is, ship owners will retrofit the ships with LNG engines when all of the ports have constructed LNG bunkering infrastructure. Note that this assumption implies Assumption i.

iv) $M(\beta - \alpha)qL > C$, that is, if all of the ships have been retrofitted, then all ports will have the motivation to construct LNG bunkering infrastructure.

Lemma 2.1. *If the government fully subsidizes $N^{\min}$ ports[2.2] (i.e., offers a subsidy of C to each port) for constructing LNG bunkering infrastructure, where*

$$N^{\min} = \left\lceil \frac{c}{\gamma QL - \beta qL} \right\rceil,$$

then, after the $N^{\min}$ ports have constructed LNG bunkering infrastructure, all ships will be retrofitted by their owners without government subsidy, and then, the remaining $N - N^{\min}$ ports will construct LNG bunkering infrastructure without government subsidy.

Since the total number of ships M is large, we allow a fractional quantity of ships to be subsidized or retrofitted in our model.

[2.1] A ship retrofitted with LNG engines has dual-fuel engines: the traditional engines that burn MDO and the new engines that burn LNG; in other words, the ship can burn MDO along a proportion of the route and LNG along the remaining proportion of the route.

[2.2] The subsidy plan works in this way: any port that will construct LNG bunkering infrastructure can submit an application to the government to receive a subsidy of C and the first $N^{\min}$ applications will be supported by the government.

Lemma 2.2. *If the government fully subsidizes $M^{\min}$ ships*[2.3] *(i.e., offers a subsidy of c to each ship) for being retrofitted with LNG engines, where*

$$M^{\min} = \frac{C}{(\beta - \alpha)qL},$$

then, after the $M^{\min}$ ships have been retrofitted, all ports will construct LNG bunkering infrastructure without government subsidy, and then, the remaining $M - M^{\min}$ ships will be retrofitted by their owners without government subsidy.

Lemmas 2.1 and 2.2 show that, to enable all ships to replace MDO with LNG, the minimum amount of subsidy the government has to provide does not exceed $\min\{CN^{\min}, cM^{\min}\}$. Next, we examine two mixed subsidy plans—both ports and ships may be subsidized in each plan—in the next two subsections.

2.3.2 Mixed Subsidy Plan 1: Fully Subsidize Ports First and then Partially Subsidize Ships

The first mixed subsidy plan is more general than the one in Lemma 2.1. In the first mixed subsidy plan, the decision process is as follows.

Step 1: The government fully subsidizes n ports to construct LNG bunkering infrastructure, $n = 0, ..., N^{\min}$, i.e., provides a subsidy of C USD to each of the n port.

Step 2: The government subsidizes $M^{\min}$ ships by providing a subsidy of x USD to each ship's owner, $0 \le x \le c$, making sure that the ship owner has the motivation to spend $c - x$ USD in retrofitting the ship in view that n ports have already constructed LNG bunkering infrastructure.

Step 3: The remaining $N - n$ ports construct LNG bunkering infrastructure by themselves because they will make a profit from it and the remaining

[2.3]The subsidy plan works in this way: any ship that will be retrofitted with LNG engines can submit an application to the government to receive a subsidy of c and the first $M^{\min}$ applications will be supported by the government.

$M - M^{\min}$ ships will be retrofitted with LNG engines by their owners to save fuel costs.

The government aims to design a subsidy plan that has the lowest cost. Define $\mathbb{Z}_+$ as the set of non-negative integers. The problem faced by the government can be formulated as:

$$\text{P1:} \qquad \min Cn + M^{\min}x \tag{2.1}$$

subject to

$$(\gamma QL - \beta qL)n \geq c - x \tag{2.2}$$
$$n \leq N^{\min} \tag{2.3}$$
$$n \in \mathbb{Z}_+ \tag{2.4}$$
$$x \leq c \tag{2.5}$$
$$x \geq 0. \tag{2.6}$$

Theorem 2.1. *An optimal solution to model P1 is shown in Table 2.1.*

Table 2.1: Optimal solution to model P1

	Condition	n^*	x^*	Total subsidy
Case i	$cM^{\min} < C\frac{c}{\gamma QL - \beta qL}$, i.e., $C > (\gamma QL - \beta qL)M^{\min}$	0	c	$cM^{\min}$
Case ii	$C\frac{c}{\gamma QL - \beta qL} \leq cM^{\min} < CN^{\min}$	$N^{\min} - 1$	$C(\frac{c}{\gamma QL - \beta qL} - N^{\min} + 1)\frac{1}{M^{\min}}$	$C\frac{c}{\gamma QL - \beta qL}$
Case iii	$CN^{\min} \leq cM^{\min}$	$N^{\min}$	0	$CN^{\min}$

Proof: Case i: $cM^{\min} < C\frac{c}{\gamma QL - \beta qL}$. Let $(n^\#, x^\#)$ be the optimal solution. If $1 \leq n^\# \leq N^{\min} - 1$, Eq. (2.2) implies $x^\# = (\gamma QL - \beta qL)n^\# - c$. Now consider a different solution $(n, x) = (n^\# - 1, x^\# + \gamma QL - \beta qL)$. This new solution is feasible and its objective value is $C(n^\# - 1) + M^{\min}(x^\# + \gamma QL - \beta qL) = Cn^\# + M^{\min}x^\# + M^{\min}(\gamma QL - \beta qL) - C < Cn^\# + M^{\min}x^\#$. This contradicts the optimality of $(n^\#, x^\#)$. If $n^\# = N^{\min}$, then $x^\# = 0$. Now consider a different solution $(n, x) = (0, c)$. This new solution is feasible and its objective value is $M^{\min}c < C\frac{c}{\gamma QL-\beta qL} \leq CN^{\min}$. This contradicts the optimality of $(n^{\#}, x^{\#})$.

Case ii: $C\frac{c}{\gamma QL-\beta qL} \leq cM^{\min} < CN^{\min}$. Let $(n^{\#}, x^{\#})$ be an optimal solution. If $n^{\#} = N^{\min}$, $x^{\#} = 0$. Then its objective value is larger than that of $(n, x) = (N^{\min} - 1, C(\frac{c}{\gamma QL-\beta qL} - N^{\min} + 1)\frac{1}{M^{\min}})$. If $n^{\#} \leq N^{\min} - 2$, we can increase $n^{\#}$ by 1 and decrease $x^{\#}$ by $\gamma QL - \beta qL$ and this will not increase the objective value; repeating the above procedure, we will obtain an optimal solution with $n = N^{\min} - 1$.

Case iii: $CN^{\min} \leq cM^{\min}$. Let $(n^{\#}, x^{\#})$ be an optimal solution, $n^{\#} \leq N^{\min} - 1$. Now consider a different solution $(n, x) = (n^{\#} + 1, x^{\#} - (\gamma QL - \beta qL))$. This new solution is feasible and its objective value is $C(n^{\#} + 1) + M^{\min}(x^{\#} - (\gamma QL - \beta qL)) = Cn^{\#} + M^{\min}x^{\#} + C - M^{\min}(\gamma QL - \beta qL) \leq Cn^{\#} + M^{\min}x^{\#} + C - M^{\min}\frac{c}{N^{\min}} \leq Cn^{\#} + M^{\min}x^{\#}$, showing the optimality of the new solution; repeating the above procedure, we will obtain an optimal solution with $n = N^{\min}$. $\square$

Case ii of Table 2.1 is noteworthy. Case ii exists because the decision variable n in model P1 must be an integer. For example, if $c/(\gamma QL - \beta qL) = 3.7$, then $N^{\min} = 4$; in this situation, if the total construction cost of LNG bunkering infrastructure at 3.7 ports is smaller than the total cost of retrofitting $M^{\min}$ ships but the total construction cost at 4 ports is larger than that of the ships, then the government should subsidize 3 ports and provides a proportion of the retrofitting cost to $M^{\min}$ ships.

2.3.3 Mixed Subsidy Plan 2: Fully Subsidize Ships and then Partially Subsidize Ports

The second mixed subsidy plan is more general than the one in Lemma 2.2. In the second mixed subsidy plan, the decision process is as follows.

Step 1: The government fully subsidizes m ships to be retrofitted with LNG engines, i.e., provides a subsidy of c USD to each of the m ships. Since the total number of ships M is large, we allow m to be a fractional quantity, i.e., $m \in [0, M^{\min}]$.

Step 2: The government provides a subsidy of y USD to each of $N^{\min}$ ports,

$0 \le y \le C$, making sure that the port has the motivation to spend $C - y$ USD in constructing LNG bunkering infrastructure in view that m ships have already been retrofitted with LNG engines.

Step 3: The remaining $M - m$ ships will be retrofitted with LNG engines by their owners because they will thereby save fuel costs and the remaining $N - n$ ports will construct LNG bunkering infrastructure by themselves because they will make a profit from it.

The government aims to design a subsidy plan that has the lowest cost and this problem can be formulated as:

$$\text{P2:} \qquad \min cm + N^{\min} y \tag{2.7}$$

subject to

$$\begin{aligned} (\beta - \alpha)QLm &\ge C - y & (2.8)\\ m &\le M^{\min} & (2.9)\\ m &\ge 0 & (2.10)\\ y &\le C & (2.11)\\ y &\ge 0. & (2.12) \end{aligned}$$

Theorem 2.2. *An optimal solution to model P2 is shown in Table 2.4.*

Table 2.2: Optimal solution to model P2

	Condition	m^*	y^*	Total subsidy
Case i	$CN^{\min} < \frac{cC}{(\beta-\alpha)QL}$, i.e., $c > (\beta - \alpha)QLN^{\min}$	0	C	$CN^{\min}$
Case ii	$c \le (\beta - \alpha)QLN^{\min}$	$M^{\min}$	0	$cM^{\min}$

Proof: Case i: $c > (\beta - \alpha)QLN^{\min}$. Let $(m^{\#}, y^{\#})$ be the optimal solution, $m^{\#} > 0$. Now consider a different solution $(m, y) = (0, y^{\#} + (\beta - \alpha)QLm)$. This new solution is feasible and its objective value is $0 + N^{\min}(y^{\#} + (\beta - \alpha)QLm)) = N^{\min}(\beta - \alpha)QLm^{\#} +$

$N^{\min}y^{\#} < cm^{\#} + N^{\min}y^{\#}$. This contradicts the optimality of $(m^{\#}, y^{\#})$. Thus, $(0, C)$ is the optimal solution in case (i).

Case ii: $c \leq (\beta - \alpha)QLN^{\min}$. Let $(m^{\#}, y^{\#})$ be an optimal solution, $m^{\#} < M^{\min}$. Now consider a different solution $(m, y) = (M^{\min}, y^{\#} - (\beta - \alpha)QL(M^{\min} - m^{\#}))$. This new solution is feasible and its objective value is $cM^{\min} + N^{\min}(y^{\#} - (\beta - \alpha)QL(M^{\min} - m^{\#})) \leq cM^{\min} + N^{\min}(y^{\#} - \frac{c}{N^{\min}}(M^{\min} - m^{\#})) = cm^{\#} + N^{\min}y^{\#}$, showing that the new solution is optimal and contradicting the optimality of $\left(m^{\#}, y^{\#}\right)$. Thus, in case (ii), $\left(M^{\min}, 0\right)$ is the optimal solution. □

2.3.4 Main Findings

Table 2.1 and Table 2.4 show that mixed subsidy plans do not significantly outperform "pure" subsidy plans in Lemmas 2.1 and 2.2. In general, the government should adopt a "pure" subsidy plan: either subsidize ports only, or subsidize ships only. In reality, however, many governments offer subsidy to both ports and ships (references to be added), which is inefficient based on the above analysis.

2.4 Scenario with Heterogeneous Ships

However, our analysis has a drawback: it assumes the ports are homogeneous and the ships are homogeneous. Next, we will examine cases with heterogeneous ships.

Instead of identical ships, in this scenario we consider ships with different fuel consumption rates. The MDO and LNG consumption rates of ship j are denoted by Q_j and q_j respectively, and it is assumed that $Q_j < Q_i$ and $q_j < q_i$ for $j \in [0, M], i < j$. Since we allow a fractional quantity of ships to be subsidized or retrofitted in our model, we further assume that the MDO and LNG consumption rates of different ships are averagely distributed in the domains $[Q_M, Q_0]$ and $[q_M, q_0]$. As a result, the value of q_j and $Q_j, j \in [0, M]$ can be calculated as $q_j = q_M + (q_0 - q_M)\frac{M-j}{M}$ and $Q_j = Q_M + (Q_0 - Q_M)\frac{M-j}{M}$.

We assume

i) After retrofitting, the LNG tank capacity of ship j is $q_jL, j = 1, ..., M$. Therefore, a ship will refill a full tank of LNG whenever it visits a port with LNG bunkering infrastructure.

ii) $N(\gamma Q_j L - \beta q_j L) \geq N(\gamma Q_M L - \beta q_M L) > c, j = 1, ..., M$, that is, ship owners will retrofit the ships with LNG engines when all of the ports have constructed LNG bunkering infrastructure.

iii) $M(\beta - \alpha) \int_{q_\mathrm{M}}^{q_0} x\, dx L = (\beta - \alpha) \frac{q_0^2 - q_\mathrm{M}^2}{2} L > C, j = 1, ..., M$, that is, if all of the ships have been retrofitted, then all ports will have the motivation to construct LNG bunkering infrastructure.

Lemma 2.3. *If the government fully subsidizes $N^{\min}$ ports (i.e., offers a subsidy of C to each port) for constructing LNG bunkering infrastructure, where*

$$N^{\min} = \left\lceil \frac{c}{\gamma Q_M L - \beta q_M L} \right\rceil,$$

then, after the $N^{\min}$ ports have constructed LNG bunkering infrastructure, all ships will be retrofitted by their owners without government subsidy, and then, the remaining $N - N^{\min}$ ports will construct LNG bunkering infrastructure without government subsidy.

Lemma 2.4. *If the government fully subsidizes $M^{\min}$ ships*[2.4] *(i.e., offers a subsidy of c to each ship) for being retrofitted with LNG engines, where*

$$q_{M^{\min}} = \sqrt{q_0^2 - \frac{2C}{(\beta - \alpha) L}}, M^{\min} = M - \frac{M}{q_0 - q_M} \left(\sqrt{q_0^2 - \frac{2C}{(\beta - \alpha) L}} - q_M \right)$$

then, after the $M^{\min}$ ships have been retrofitted, all ports will construct LNG bunkering infrastructure without government subsidy, and then, the remaining $M - M^{\min}$ ships will be retrofitted by their owners without government subsidy.

Lemmas 2.3 and 2.4 show that, to enable all ships to replace MDO with LNG,

[2.4] The subsidy plan works in this way: any ship that will be retrofitted with LNG engines can submit an application to the government to receive a subsidy of c and the applications of ship 1 to ship $M^{\min}$ will be supported by the government since they consume more LNG and provide higher environmental benefits after retrofitting.

the minimum amount of subsidy the government has to provide does not exceed $\min\{CN^{\min}, cM^{\min}\}$. Next, we examine two mixed subsidy plans—both ports and ships may be subsidized in each plan—in the next two subsections. Following Subsection 2.3.2 and 2.3.3, the mixed subsidy plans with heterogeneous ships are stated as follows.

2.4.1 Mixed Subsidy Plan 1 with Heterogeneous Ships

In the mixed subsidy plan with heterogeneous ships, the decision process is as follows.

Step 1: The government fully subsidizes n ports to construct LNG bunkering infrastructure, $n = 0, ..., N^{\min}$, i.e., provides a subsidy of C USD to each of the n port.

Step 2: The government subsidizes ship 1 to ship $M^{\min}$ by providing a subsidy of x USD to each ship's owner, $0 \le x \le c$, making sure that the ship owner has the motivation to spend $c - x$ USD in retrofitting the ship in view that n ports have already constructed LNG bunkering infrastructure.

Step 3: The remaining $N - n$ ports construct LNG bunkering infrastructure by themselves because they will make a profit from it and the remaining $M - M^{\min}$ ships will be retrofitted with LNG engines by their owners to save fuel costs.

Different from the subsidy plan in Subsection 2.3.2, the second step of Mixed Subsidy Plan 1 under this scenario chooses ports with the larger fuel consumption rates, namely ship 1 to port $M^{\min}$, to minimize the total subsidy cost. This problem can be formulated as:

$$\text{P1'}: \qquad \min Cn + M^{\min}x \tag{2.13}$$

subject to constraints (2.3)–(2.6) and

$$(\gamma Q_{M^{\min}} L - \beta q_{M^{\min}} L)n \ \ \geq \ \ c - x. \tag{2.14}$$

Constraint (2.14) assures that ship $M^{\min}$ will be retrofitted, which indicates that ship 1 to ship $M^{\min}-1$ will also be retrofitted because their LNG consumption volumes and bunker savings are higher than ship $M^{\min}$.

Theorem 2.3. *An optimal solution to model P1' is shown in Table 2.3.*

Table 2.3: Optimal solution to model P1'

	Case i	Case ii	Case iii
Condition	$cM^{\min} < C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L}$	$C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L} \leq cM^{\min} < CN^{\min}$	$CN^{\min} \leq cM^{\min}$
n^*	0	$N^{\min}-1$	$N^{\min}$
x^*	c	$C(\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L} - N^{\min}+1)\frac{1}{M^{\min}}$	0
Total subsidy	$cM^{\min}$	$C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L}$	$CN^{\min}$

Proof: Case i: $cM^{\min} < C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L}$. Let $(n^{\#}, x^{\#})$ be the optimal solution. If $1 \leq n^{\#} \leq N^{\min}-1$, Eq. (2.14) implies $x^{\#} = (\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L)n^{\#} - c$. Now consider a different solution $(n, x) = (n^{\#}-1, x^{\#} + \gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L)$. This new solution is feasible and its objective value is $C(n^{\#}-1) + M^{\min}(x^{\#} + \gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L) = Cn^{\#} + M^{\min}x^{\#} + M^{\min}(\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L) - C < Cn^{\#} + M^{\min}x^{\#}$. This contradicts the optimality of $(n^{\#}, x^{\#})$. If $n^{\#} = N^{\min}$, then $x^{\#} = 0$. Now consider a different solution $(n, x) = (0, c)$. This new solution is feasible and its objective value is $M^{\min}c < C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L} \leq CN^{\min}$. This contradicts the optimality of $(n^{\#}, x^{\#})$.

Case ii: $C\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L} \leq cM^{\min} < CN^{\min}$. Let $(n^{\#}, x^{\#})$ be an optimal solution. If $n^{\#} = N^{\min}$, $x^{\#} = 0$. Then its objective value is larger than that of $(n, x) = (N^{\min}-1, C(\frac{c}{\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L} - N^{\min}+1)\frac{1}{M^{\min}})$. If $n^{\#} \leq N^{\min}-2$, we can increase $n^{\#}$ by 1 and decrease $x^{\#}$ by $\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L$ and this will not increase the objective value; repeating the above procedure, we will obtain an optimal solution with $n = N^{\min}-1$.

Case iii: $CN^{\min} \leq cM^{\min}$. Let $(n^{\#}, x^{\#})$ be an optimal solution, $n^{\#} \leq N^{\min}-1$. Now consider a different solution $(n, x) = (n^{\#}+1, x^{\#} - (\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L))$. This new solution is feasible and the corresponding objective value is $C(n^{\#}+1) +$

$M^{\min}(x^{\#}-(\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L)) = Cn^{\#}+M^{\min}x^{\#}+C-M^{\min}(\gamma Q_{M^{\min}}L-\beta q_{M^{\min}}L) \le Cn^{\#} + M^{\min}x^{\#} + C - M^{\min}\frac{c}{N^{\min}} \le Cn^{\#} + M^{\min}x^{\#}$, showing the optimality of the new solution; repeating the above procedure, we will obtain an optimal solution with $n = N^{\min}$. □

From constraint (2.14) we can see that the partial subsidy for ships makes the benefit of retrofitting ship $M^{\min}$ equals the costs, namely $(\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L)n = c - x$ in the optimal solution. However, for ship $j, 1 \le j < M^{\min}$, we have $(\gamma Q_j L - \beta q_j L)n > c - x$, namely the amount of $[(\gamma Q_j L - \beta q_j L)n] - [(\gamma Q_{M^{\min}}L - \beta q_{M^{\min}}L)n]$ is wasted in ship j. Therefore, the optimal mixed subsidy plan awards larger amount of subsidies than necessary.

2.4.2 Mixed Subsidy Pan 2 with Heterogeneous Ships

The decision process in the second mixed subsidy plan with heterogeneous is as follows.

Step 1: The government fully subsidizes m ships to be retrofitted with LNG engines, i.e., provides a subsidy of c USD to each of the m ships. Since the total number of ships M is large, we allow m to be a fractional quantity, i.e., $m \in [0, M^{\min}]$.

Step 2: The government provides a subsidy of y USD to each of $N^{\min}$ ports, $0 \le y \le C$, making sure that the port has the motivation to spend $C - y$ USD in constructing LNG bunkering infrastructure in view that m ships have already been retrofitted with LNG engines.

Step 3: The remaining $M - m$ ships will be retrofitted with LNG engines by their owners because they will thereby save fuel costs and the remaining $N - n$ ports will construct LNG bunkering infrastructure by themselves because they will make a profit from it.

The government aims to design a subsidy plan that has the lowest cost and this problem can be formulated as:

$$\text{P2'}: \qquad \min cm + N^{\min}y \tag{2.15}$$

subject to constraint (2.9) to (2.12) and

$$(\beta-\alpha)Lm\int_{Q_{M^{\min}}}^{Q_0} x\,dx \quad \geq \quad C-y. \tag{2.16}$$

Constraint (2.16) can be rewritten as

$$\frac{(\beta-\alpha)Lm\left(Q_0^2-Q_{M^{\min}}^2\right)}{2} \quad \geq \quad C-y. \tag{2.17}$$

Theorem 2.4. *An optimal solution to model P2' is shown in Table 2.4.*

Table 2.4: Optimal solution to model P2'

	Condition	m^*	y^*	Total subsidy
Case i	$CN^{\min} < \frac{cC}{(\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)L}$, i.e., $c > (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)LN^{\min}$	0	C	$CN^{\min}$
Case ii	$c \leq (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)LN^{\min}$	$M^{\min}$	0	$cM^{\min}$

Proof: Case i: $c > (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)LN^{\min}$. Let $(m^{\#}, y^{\#})$ be the optimal solution, $m^{\#} > 0$. Now consider a different solution $(m,y) = (0, y^{\#}+\frac{(\beta-\alpha)Lm^{\#}\left(Q_0^2-Q_{M^{\min}}^2\right)}{2})$. This new solution is feasible and the corresponding optimal objective value is $0 + N^{\min}(y^{\#} + \frac{(\beta-\alpha)Lm^{\#}\left(Q_0^2-Q_{M^{\min}}^2\right)}{2}) = N^{\min}(\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)Lm^{\#} + N^{\min}y^{\#} < cm^{\#} + N^{\min}y^{\#}$. This contradicts the optimality of $(m^{\#}, y^{\#})$. Thus, $(0, C)$ is the optimal solution.

Case ii: $c \leq (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)LN^{\min}$. Let $(m^{\#}, y^{\#})$ be an optimal solution, $m^{\#} < M^{\min}$. Now consider a different solution $(m,y) = (M^{\min}, y^{\#} - (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)L(M^{\min}-m^{\#}))$. This new solution is feasible and its objective value is $cM^{\min} + N^{\min}(y^{\#} - (\beta-\alpha)\left(Q_0^2-Q_{M^{\min}}^2\right)L(M^{\min}-m^{\#})) \leq cM^{\min} + N^{\min}(y^{\#} - \frac{c}{N^{\min}}(M^{\min}-m^{\#})) = cm^{\#} + N^{\min}y^{\#}$, showing that the new solution is optimal and contradicting the optimality of $\left(m^{\#}, y^{\#}\right)$. Thus, in case (ii), $\left(M^{\min}, 0\right)$ is the optimal solution. $\square$

Compared with the first subsidy plan in subsection 2.4.1, the optimal subsidy amount does not seem to exceed the necessary level. However, because all ships receive the same amount of subsidy, the value of $N^{\min}$ depends on the ship with the lowest fuel consumption rate, namely the least motivated ship. A more flexible subsidy plan that customizes the subsidy amount for each ship would further reduce the value of $M^{\min}$ and the optimal total subsidy amount.

2.4.3 Main Findings

In this section, we investigate the scenario with heterogeneous ships. Compared with the cases of homogeneous ships, the two mixed subsidy plans in this section perform in a very similar way but with a different method to calculate the value of $M^{\min}$. Based on the analysis, it is revealed that with heterogeneous ships, a more flexible subsidy plan could further reduce the total subsidy amount.

2.5 Optimal LNG Selling Price

We have also assumed that the selling price of LNG to ships β is fixed in our analysis. However, the selling price would influence the subsidy amount because it determines the LNG selling profit of the ports and the bunker cost savings of ships by using LNG, which are the main driven forces behind the adoption of LNG as marine fuel. Therefore, in this section, we will examine how the government can design this price optimally to minimize the total subsidy amount.

2.5.1 Optimal Value of β

From Table 2.1 in Section 2.3.2 we can see that in case i and case iii, the total subsidy amount is independent of β. In case ii, the total subsidy amount equals $C\frac{c}{\gamma QL-\beta qL}$, and the first derivative of it over β can be calculated as

$$\left(C\frac{c}{\gamma QL-\beta qL}\right)' = \frac{Ccq}{L\left(\gamma Q-\beta q\right)^2} \geq 0,$$

which means that the subsidy amount increases with the value of β. Therefore, the task is to identify the lower bound of the value of β, which depends on the problem assumptions and case conditions.

For assumption (i) and (iii), we have $\beta < \frac{\gamma Q}{q}$ and $\beta < \frac{\gamma QNL-c}{qNL}$, which impact the upper bound of the β value. In assumption (iv), we have $M(\beta-\alpha)qL > C$, which indicates $\beta > \alpha + \frac{C}{MqL}$. Besides, from the condition of case ii we obtain two constraints on β value. The first one is $\frac{Cc}{\gamma QL-\beta qL} \leq \frac{Cc}{(\beta-\alpha)qL}$, which can be rewritten as $\beta \geq \frac{\gamma Q+q\alpha}{2q}$. The second one is $\frac{Cc}{(\beta-\alpha)qL} < C\lceil\frac{c}{\gamma QL-\beta qL}\rceil$, which indicates an upper bound of β value.

Thus, under case ii, we have

Theorem 2.5. *The optimal value of β under case ii of model P1 is shown in Table 2.5.*

Table 2.5: Optimal value of β

	Condition	β^*	Total subsidy
Case a	$\frac{\gamma Q}{2q}+\frac{\alpha}{2} \geq \alpha+\frac{C}{MqL}$	$\frac{\gamma Q}{2q}+\frac{\alpha}{2}$	$\frac{2Cc}{\gamma QL-\alpha qL}$
Case b	$\frac{\gamma Q}{2q}+\frac{\alpha}{2} < \alpha+\frac{C}{MqL}$	$\left(\alpha+\frac{C}{MqL}\right)^+$	$\left(\frac{cCM}{M\gamma QL-\alpha qLM-C}\right)^+$

Proof: In case (a), we have $\frac{\gamma Q}{2q}+\frac{\alpha}{2} \geq \alpha+\frac{C}{MqL}$, namely $\alpha \leq \frac{\gamma QML-2C}{qML}$. Thus, the lower bound of β value equals $\frac{\gamma Q}{2q}+\frac{\alpha}{2}$, which is also the optimal value and the corresponding total subsidy amount equals $\frac{2Cc}{\gamma QL-\alpha qL}$. In case (b), we have $\frac{\gamma Q}{2q}+\frac{\alpha}{2} < \alpha+\frac{C}{MqL}$, namely $\alpha < \frac{\gamma QML-2C}{qML}$. In this case, we have $\beta > \alpha+\frac{C}{MqL}$, and the optimal β value can be stated as $\beta^* = \left(\alpha+\frac{C}{MqL}\right)^+$. Meanwhile, the total subsidy amount can be calculated as $\left(\frac{cCM}{M\gamma QL-\alpha qLM-C}\right)^+$. $\square$

2.5.2 Impact of α and γ on Optimal β

As displayed in Table 2.5, the optimal LNG selling price β^* and the corresponding total subsidy amount are closely related to the LNG purchasing price of ports α and the MDO price γ. In Table 2.6, we list the first derivative of β^* and the corresponding total subsidy amount. Since we cannot obtain the optimal value of β and total subsidy amount in case (b), we take the derivatives of the lower bounds instead.

Table 2.6: The first derivative of β^* and total subsidy over α

	Derivative over α		Derivative over γ	
	β^*	Total subsidy	β^*	Total subsidy
Case a	$\frac{1}{2}$	$\frac{2cCqL}{(\gamma QL-\alpha qL)^2}$	$\frac{Q}{2q}$	$\frac{-2CcQL}{(\gamma QL-\alpha qL)^2}$
Case b	1	$\frac{cCqLM^2}{(M\gamma Ql-\alpha qLM-C)^2}$	0	$\frac{-cCM^2QL}{(M\gamma QL-\alpha qLM-C)^2}$

First we discuss the influence of α on the optimal LNG selling price and subsidy amount. Under case (a) and case (b), according to Table 2.6, we know that both the value of β^* and the corresponding optimal total subsidy amount increase with the value of α. This conclusion is intuitive. When the LNG purchasing price α increases, the profit of selling one tonne of LNG for ports, which is denoted by $\beta - \alpha$, decreases. Responding to this, the ports require higher LNG selling price and higher subsidies to be motivated to build the LNG bunkering stations. Given the higher selling price, the ships also needs larger amount of subsidies to be encouraged. As a result, both the optimal LNG selling price β^* and total subsidy amount increase with α.

Next is the influence of the MDO price γ. In case (a), according to Table 2.6, β^* increases with γ while the total subsidy amount decreases with it. The pattern is comprehensible. When γ increases, the bunker cost saving of using LNG to sail one nautical mile, which equals $Q\gamma - q\beta$, increases too. Therefore, the ships would be retrofitted with a lower subsidy level and a higher LNG price β. For the ports, increased LNG selling price means higher profits, which indicates that the subsidy provided for ports can be further reduced. As a result, in case (a),the optimal selling price β^* increases with γ and the corresponding total subsidy amount decreases with it. In case (b), the logic is the same, but the value of β^* is independent of γ. The reason of this is that in case (b), the value of β^* is constrained by assumption iv) $M(\beta - \alpha)qL > c$, which assures that all ports would be motivated to build LNG bunkering stations when all ships are retrofitted. Since the assumption is not related to the price of MDO, the optimal LNG selling value β^* is independent of γ.

2.5.3 Main Findings

In this section, we obtain the optimal LNG selling price that minimizes the total subsidy amount. Based on the result, we further analyze the impact of the LNG purchasing price of ports and the MDO price on the optimal LNG selling price. The patterns obtained from our analytical analysis and the logical judgment corroborate each other.

2.6 Conclusions

LNG has been recognized as one of the most promising alternative fuel for maritime transportation. However, the costly LNG bunkering station and ship retrofitting makes the ports and shipping lines hesitate about making the first move. Given the current situation, government subsidies have been proofed to be an effective method to break the deadlock. The total subsidy amount and its effect depend on the specific subsidy plan, and therefore the optimization of the subsidy design deserves to be studied in depth.

This chapter originally proposes two-stage subsidy plans to promote LNG as marine fuel and optimization models to describe the problem under different scenarios. Different from existing literature, we obtain the analytical solution to the models, which provides more details than the numerical solution. Besides, we also obtain the optimal LNG bunkering price and analyze the impact of LNG purchasing price for ports and the MDO bunkering price on the optimal LNG bunkering price. The result shows that the analytical analysis and the logic intuition corroborate each other.

Chapter 3

Ship Operation and Allowance Management Plan Optimization in Liner Shipping under Maritime Emission Trading System

3.1 Introduction

In line with the aim of the Paris Agreement (United Nations 2015) to control the global average temperature increase within 2°C compared to the pre-industrial level, the European Commission launched the European Green Deal with ambitious targets. The deal claims to make Europe the first climate-neutral continent by 2050 with net-zero greenhouse gas emissions (Commission 2019) and reduce net greenhouse gas emissions by at least 55% by 2030, compared to 1990 levels (European Commission 2020a). To achieve the goal, the European Commission have enacted multiple regulations and policies on shipping emissions reduction, including the EU ETS.

The EU ETS, which is a cap and trade system, is the world's first and biggest carbon market (European Commission 2021a). Under the system, the union-wide emission allowance for 2021 amounts to 1,571,583,007 tonnes of carbon dioxide equivalent[3.1].

The implementation of the EU ETS consists of several phases, and currently it is at the fourth one (2021–2030). To ensure the total carbon emission declining, the allowance per year keeps decreasing at an annual rate of 2.2% at this stage (European Commission 2020b). Each year, annual allowance is allocated for each installation covered, and part of the quota is received for free (43% in 2021) and the rest needs to be bought, from the competent authorities of the Member States. Within the cap, allowances can be traded among installation as needed, and therefore forms the carbon market. Meanwhile, heavy fines will be imposed if the installation fails to surrender enough allowances to cover fully its emissions (European Commission 2021a).

The proposed ETS extension to the maritime sector will apply to CO_2 emissions from vessels above 5,000 gross tonnage. All emissions from voyages within the EU, 50% of emissions from voyages starting or ending outside the EU, and emissions from ships at berth in EU ports will be counted. To facilitate a smooth start, surrendering obligations will be gradually increased from 2023 to 2025. Allowances will need to be surrendered for 100% of verified emissions from the fourth year (in 2027 for 2026 emissions) (European Commission 2021b).

For shipping companies operating in the EU, the cost for ship emission management, which will be used to purchase the emission allowances and pay for the fines. Considering that the shipping emission is closely related to the sailing speed and fuel type used onboard, the emission allowance management problem should be investigated together with the ship operation optimization. Thus, in this paper, we study the ship operation optimization problem in liner shipping, considering the emission allowance management plan under the maritime ETS. According to the EU ETS regulations, the allowances that has not been surrendered at the end of each year can be used later until the end of the current implementation phase (European Commission

[3.1] Tonne of carbon dioxide equivalent means one metric tonne of CO_2 or an amount of Methane (CH_4), Nitrous Oxide (N_2O), Hydrofluorocarbons (HFCs), Perfluorocarbons (PFCs), and Sulphur Hexafluoride (SF_6) with an equivalent global-warming potential.

2003). Therefore, in this chapter, the shipping company aims to minimize the total operating costs through the planning period, which consists of several consecutive calendar years.

The remainder of this chapter is organized as follows: Section 3.2 reviews the literature related to this study in three streams. Section 3.3 give the detailed description of the problem investigated. Section 3.5 shows solution method that handles the nonlinear part and the stochastic element in the original model, and then convert it into a deterministic linear one. Numerical experiments and results of them are displayed in Section 3.6. Finally this chapter ends with the conclusions in Section 3.7.

3.2 Literature Review

In this section, the related literature will be reviewed from three different perspectives, namely ship operation optimization with emission reduction measures, studies on METS and existing papers on similar topics.

Subsection 3.2.1 will review the studies on ship operation optimization with emission reduction measures. Qualitative studies on METS will be briefly introduced in subsection 3.2.2. Subsection 3.2.3 will discuss papers investigating ship operation optimization problem with METS and state the essential distinctions between them and this study.

3.2.1 Ship Operation Optimization with Emission Reduction Measures

Thanks to the extensive attention on environmental protection, ship emission reduction has become one of the priorities of the maritime industry. Ship operation optimization considering emission reduction measures has been widely discussed.

Due to the nearly cubic relationship between the sailing speed and fuel consumption rate, slow steaming has been recognized as an efficient emission reduction measures. The ports of Los Angeles (LSA) and Long Beach (LGB) adopt voluntary vessel speed reduction incentive programs (VSRIPs) to encourage vessels to slow down in the vicinity of ports and then reduce the ship emissions in the port areas. Zhuge et al. (2020, 2021) investigate the sailing speed optimization and schedule design problem under VSRIPs. The shipping route operator decides whether to join the VSRIP and the optimal sailing speed to minimize the total cost, consisting of fuel cost, as well as operating cost, minus dockage refunds for participating in the VSRIP. Ahl et al. (2017) reveal that the percentage of ships participating in the voluntary VSRIP varies by vessel types as well as the value of time for ship operators, and differentiated pricing strategies better motivates the compliance.

Carbon/emission tax is another extensively-adopted ship emission reduction measure that has obvious impact on ship operation. Wang and Xu (2015) study the sailing speed optimization problem of voyage chartering ships under different forms of emission taxation. It is revealed that taxing emissions that exceed a certain threshold is preferred in reducing carbon emission without largely decreasing ship operators' profit. Gao et al. (2022) develop a bi-level programming model to study the liner shipping network design problem and optimize the liner type, calling sequence, calling frequency, and sailing speed simultaneously. Liu et al. (2021) consider liner alliance together with carbon tax in the liner shipping network design problem. Meanwhile, Xin et al. (2019) focus on the scheduling problem of a shuttle tanker fleet considering carbon tax and propose a solution method based on the column generation algorithm.

Another way to achieve the shipping decarbonization is to adopt alternative marine fuels that are more environmentally friendly. Governments of various countries and areas have conducted measures and provide subsidies to promote the application of alternative fuels (European Commission 2012, Ministry of Finance of the People's Republic of China and Ministry of Transport of the People's Republic of China 2014, Ministry of Transport of the People's Republic of China 2017). Wang et al. (2022) investigate the subsidy plan optimization problem for liquefied natural gas (LNG) as marine fuel from the government's perspective. The ship operation optimization that includes the ship retrofitting and LNG bunkering decisions is considered as the third level of the trilevel model developed in the study.

Abundant studies on ship operation optimization with multiple emission reduction measures confirm the necessity to consider the impact of METS while conducting ship operation optimization.

3.2.2 Maritime ETS

The second stream of the related literature consists of the studies on maritime ETS (METS). METS has been reviewed as one of the promising market-based measures to achieve the decarbonization of the maritime transportation by Psarafits et al. (2021), Lagouvardou et al. (2020), and Christodoulou et al. (2021a).

These studies conduct qualitative analyses on METS and compare it with other MBMs from various perspectives, including GHG reduction effectiveness, compatibility with existing legal framework, potential implementation timeline, potential impacts on states, administrative burden, practical feasibility, avoidance of split incentives between ship-owner and charterer, and commercial impacts. Hermeling et al. (2015) investigate the practicability of the regional METS from the legal perspective and find out that there exist incompatibilities between international law and a cost efficient METS.

A stream of studies analyze the influence of METS on the maritime decarbonization on the basis of historical ship sailing and emission data in a quantitative way. Christodoulou et al. (2021b) evaluate the costs for the maritime sector if shipping is included in the EU ETS. The paper assesses the allowance purchasing costs for different maritime segments with the emission volume indicated by the Monitoring, Reporting and Verification (MRV) data in 2019. Cariou et al. (2021) adopt the Automatic Identification System (AIS) data of 2017 to 2019 to assess the potential impact of METS for oil tankers and estimate the effectiveness of METS as a method to promote maritime innovations.

Extant literature has briefly explored the reaction of the ship operators to the METS. Wang et al. (2015) analyze the economic implications of two alternative ETS mechanisms, namely the open METS and the closed METS, on the container and dry bulk shipping sectors. In an open METS, the market carbon price is endogenous and fluctuates with the allowance trading decisions of the ship operators in the system.

Meanwhile, in a closed METS, the market carbon price is exogenous. Different from this paper, Wang et al. (2015) focus on the competition between shipping companies and obtain the equilibrium quantity and speed for a shipping company in the competitive market. Koesler et al. (2015) analyze the potential implications of the METS on the organization and operations of shipping companies from the empirical perspective. Carefully-designed questionnaires and interviews were adopted to collect the opinions from various shipping companies. The analysis result supports the conclusion that METS has the potential to engage the maritime sector into cost-efficient emission reduction.

3.2.3 Existing Papers on Similar Topics

Although there exist papers investigating the influence of the ETS on the ship operation optimization, this paper is essentially different from those papers in both the ship operation and ETS perspectives.

Zhu et al. (2018) study the impact of ETS on the fleet deployment and evaluate the CO_2 mitigation efficiency. In the paper, the decision maker, namely the shipping company that operates a sailing route, makes the ship chartering plan and allowance purchasing plan to minimize the total costs in the planning period. In the ship operation perspective, compared to this paper, Zhu et al. (2018) consider a simplified ship operation plan. Zhu et al. (2018) do not include the sailing speed optimization of deployed ships, and the shipping company only decide the ship type to be chartered. However, the sailing speed has an obvious impact on the ship emissions (Faber et al. 2020) and the bunker cost, which accounts a substantial proportion of the total operating cost, 20-60% depending on the bunker price (Ronen 1993, Golias et al. 2009). Thus, in this paper, we take the sailing speed optimization into consideration, and therefore the ship type and number to be deployed and the sailing speed all become decision variables. Besides, in the case study, Zhu et al. (2018) design a shipping route with only two ports of call; meanwhile numerical experiments with multiple ports of call will be conducted in this paper, which better reflects the characteristics of liner shipping. Regarding the ETS, Zhu et al. (2018) make three main assumptions about the allowances: i) there are two sources of emission allowances, freely allocated by the competent authority and purchased from the carbon market; ii) the allocated number of allowances is given and the same in each year; iii) the allowances obtained in each year will automatically become invalid at the end of the year. After consulting the regulations of the EU ETS (European Commission 2003, 2009, 2019, 2020b), it is assumed in this paper that: i) the allowances can be freely allocated, bought from the authority, or purchased from the carbon market; ii) the number of allocated allowances decline at a certain annual rate; iii) the allowances still valid at the end of each year can be used until the end of the current period. Besides, we also consider the penalty of not surrendering enough allowances for the emissions. As a result, the problem studied in this paper is essentially different from that of Zhu et al. (2018).

Gu et al. (2019) explore the maritime fleet composition and deployment problem faced by a chemical liquid bulk service provider under the ETS. For the ship operation, Gu et al. (2019) consider the voyage-based bulk service and therefore the bulk carriers can be chartered in days to be deployed between the origin and destination ports. In this paper, we focus on the liner shipping which has a route with multiple ports of call and a predetermined service frequency. Besides, although Gu et al. (2019) take the sailing speed optimization into consideration, the speed interval is replaced by a set of alternative speeds, which influences the optimality of the result of solving the model. In this paper, the non-linear relationship between the sailing speed and the fuel consumption rate is handled without influencing the optimality of the solution. In the ETS perspective, Gu et al. (2019) considers the problem in the planning period of one year and assumes allowances can be obtained only by trading with other institutions on the carbon market. Consequently, the phase-wise ETS regulations and the allowance allocation mechanism cannot be well reflected. In contrast to Gu et al. (2019), this paper focuses on the challenge confronting the liner shipping service provider and better depicts the characteristics of the ETS.

Goicoechea and Abadie (2021) focus on the ship operation optimization of a single vessel deployed on a predetermined sailing route. From the ship operation perspective, Goicoechea and Abadie (2021) only consider the sailing speed optimization of a particular ship, which is essentially different from the ship operation of a liner shipping route considered in this paper. Meanwhile, Goicoechea and Abadie (2021) adopt a set of candidate sailing speeds to replace the speed interval of the vessel and then enumerate all the candidates to find the optimal sailing speed. As for the ETS perspective, like Gu et al. (2019), Goicoechea and Abadie (2021) consider the problem within one year and charge all ship emissions at a uniform rate, and thus fails to reflect the phase-wise ETS regulations and the allowance allocation mechanism. As a result, it is safe to say that this paper is obviously distinctive from Goicoechea and Abadie (2021).

3.2.4 Main Contributions

Previous studies have investigated ship operation optimization problem considering various emission reduction measures, including VSRIP, carbon/emission tax, and alternative fuels. As for the restricted literature on METS, qualitative analysis on its effectiveness and impact and quantitative study based on historical ship sailing and emission data constitute the majority of extant papers. The ship operation optimization problem under METS has been explored by several existing studies, in which the characteristics of liner shipping and METS are not well depicted, as discussed in subsection 3.2.3.

This study aims to fill the gap in the literature and investigate the ship operation optimization problem for a liner shipping company covered by METS. The main contributions of this paper are as follows.

- This study develops a nonlinear stochastic mixed-integer model to describe the problem and better reflects the characteristics of the liner shipping operation and the METS mechanism. Different from previous studies, this study takes the ship sailing speed optimization, the phase-wise METS regulations, and the allowance allocation mechanism into consideration. Thus, the optimal result yielded by solving the originally-proposed model better depicts the decisions of a liner shipping company under METS.

- This study proposes a tailored algorithm on the basis of the model structure to solve the problem. Historical data of carbon price in EU ETS were adopted to estimate the changing pattern of the allowance trading price on market, and based on the model structure, the nonlinear elements were handled without undermining the optimality of the result. Then, the problem is converted into a mixed-integer linear programming model that can be solved by off-the-shelf commercial solvers, such as CPLEX.
- Abundant numerical experiments were conducted to show the reaction of liner shipping companies to METS. Interesting managerial insights were obtained. With the METS, the total operating cost of the liner shipping company would decrease due to the extra revenue from the carbon allowance trading. Besides, heterogeneous fleet might be deployed to cope with the METS. The influence of carbon price changing patter under different scenarios is discussed, too.

3.3 Problem Description

In this section, a detailed description of the ship operating and allowance management plan optimization problem is given together with the main assumptions made in this chapter.

3.3.1 Ship Operation

A shipping company operates a short-sea liner shipping route that falls entirely within the territorial sea of a single country. The route consists of a series of ports of call, denoted by $\mathcal{P} = \{1, ..., |\mathcal{P}|\}$. In a typical liner shipping route, ships sail in a closed circle, which means that the last port of call of a round trip, is also the first port of call of the next round trip. Figure 3.1 shows an example of such a shipping line, in which a deployed ship sailing along the dashed line departs from the first port of call, denoted by a triangle, and arrives at it again after visiting all ports of call, denoted by circular dots and a square.

To avoid the duplication of visits to the first port of call in a round trip, the port

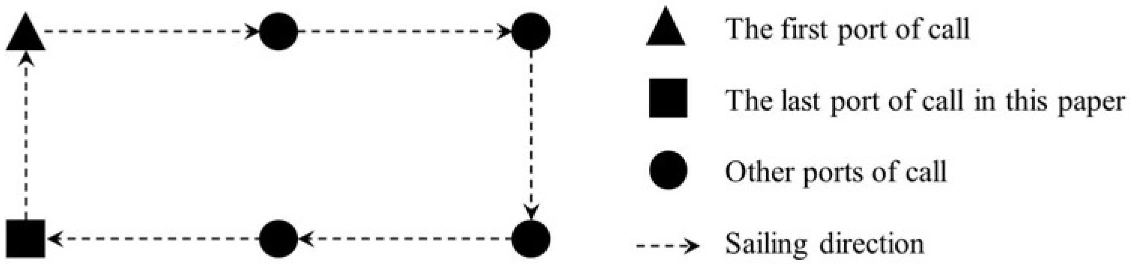

Figure 3.1: An example of a typical liner shipping route

of call denoted by the square is defined as the last port of call of the shipping route in this paper. Thus, the example in Figure 3.1 consists of six ports of call. Connecting the $|\mathcal{P}|$ ports of call are $|\mathcal{P}|$ voyages, in which voyage $i(i = 1, ..., |\mathcal{P}| - 1)$ refers to the voyage from port of call i to $i+1$ and voyage $|\mathcal{P}|$ refers to the voyage from port of call $|\mathcal{P}|$ to 1. The sailing distance of voyage i is denoted by l_i (n miles) and the berthing time at port of call i for cargo handling is denoted by t_i (hours).

Given the route, the shipping company makes the annual operating decisions at the beginning of each year, which include the type and number of ships deployed and the sailing speed of these ships. Ships of multiple types, denoted by $\mathcal{V}$, with different emission control technologies are available on the ship leasing market. The chartering price, denoted by c_j^{Ch} $(j \in \mathcal{V})$, varies obviously based on the availability of emission reduction devices onboard. Due to the regulations enforced by the International Maritime Organization (2021c), the onboard use of marine fuels with a sulfur content above 0.5% (m/m) is forbidden worldwide, and the content cap equals 0.1% in ECAs. As the route stretches along the coast line, the sulfur content cap is set at 0.1% m/m in this study. Thus, the operator can only choose from a list of environmentally friendly vessels, for example LNG-fueled ships, ships equipped with a sulfur scrubber, and traditional ships using low-sulfur marine fuels. To maintain the fixed frequency of the liner shipping service, all ships on the route must sail at the same speed π (knot)[3.2]. Thus it takes $\sum\limits_{i\in\mathcal{P}} \left(\frac{l_i}{\pi} + t_i\right)$ hours for a ship to complete a round trip. We assume that the company provides a weekly service frequency, and therefore at least

[3.2] The knot is a unit of speed equal to one nautical mile per hour.

$\sum_{j\in\mathcal{V}} \eta_j = \lceil \frac{\sum_{i\in\mathcal{P}} \left(\frac{l_i}{\pi}+t_i\right)}{168} \rceil$ ships should be deployed. Then, the weekly chartering cost of the fleet equals $\sum_{j\in\mathcal{V}} c_j^{\mathrm{Ch}} \eta_j$, and the weekly fuel cost equals $\frac{\sum_{j\in\mathcal{V}} c_j^{\mathrm{Bun}} \eta_j q^j(\pi) \sum_{i\in\mathcal{P}} l_i}{\sum_{j\in\mathcal{V}} \eta_j}$, in which $q^j(\pi)$ (tonne/n mile) represents the fuel consumption rate and c_j^{Bun} (USD/tonne) is the price of bunker fuel used by ships of type j. Thus, the ship operating costs can be obtained by combining the bunker costs and the ship chartering costs.

3.3.2 Allowance Management

In line with the goal of the International Maritime Organization (2018) to reduce 50% GHG emissions from shipping by 2050, the government considered in this paper has enacted regulations to integrate the maritime transportation section into the ETS and control the emission allowances for shipping companies. The first phase of the METS implementation consists of M years, and the annual allowances (tonnes of carbon dioxide equivalent[3.3]) are allocated to shipping companies within the jurisdiction at the beginning of each year. A portion of the allowances are distributed to the shipping companies for free and the rest are auctioned. In addition to the allowances from the competent authority, a shipping company is allowed to trade carbon emission allowances with other institutions in the METS. At the end of each year, the authority retrieves allowances from these shipping companies, who then incur harsh penalties, denoted by Pen (USD/ton), for emissions beyond the allowances surrendered. The remaining allowances can be used in the next year. To ensure emission reduction, the total number of allowances for each shipping company decreases at an annual rate of r (%).

Obeying these regulations, the shipping company aims to minimize the total operating costs in M years, namely the ship operating costs and the emission allowance management costs. The company's first set of decisions is related to the

[3.3]'Tonne of carbon dioxide equivalent' means one metric tonne of carbon dioxide (CO_2) or an amount of any other greenhouse gas, namely methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), perfluorocarbons (PFCs), and sulfur hexafluoride (SF_6), with an equivalent global-warming potential.

ship operation in each year: the number of deployed ships from type j in year m, denoted by $\eta_m^j\,(j \in \mathcal{V}, m = 1, ..., M)$; the sailing speed of the fleet in year m, denoted by $\pi_m\,(m = 1, ..., M)$. The carbon emission intensity, the volume of carbon dioxide equivalent emitted for sailing one n mile, also needs to be considered as this depends on the ship type and sailing speed, as denoted by $g^j\,(\pi)$ (tonne/n mile). Considering that emission allowances can be obtained at different prices, that is free, at auction price, or at purchase price, the possibility of a heterogeneous fleet is retained in this problem and the number of deployed ship types is not restricted.

In addition to these conventional decisions, the shipping company needs to make an emission allowance management plan covering M years to obey the regulations at the minimum cost. At the beginning of year m, the shipping company receives the annual allowances a_m^{F} for free. The quota of auctioned allowances, namely the maximum amount of allowances that can be bought from the authority in year m, is denoted by a_m^{U}. Both a_m^{U} and the auction price k^{U} are predetermined by the competent authority. However, the actual amount of allowances bought from the authority in year m, denoted by α_m^{Auc}, is up to the company. Moreover, the company may trade with all other institutions in the ETS. Following papers focusing on similar topics (Koesler et al. 2015, Wang et al. 2015, Gu et al. 2019), we consider an open ETS system in which institutions in different sectors can trade with each other, and therefore the carbon emission allowance price $\tilde{k}_m^{\mathrm{Mar}}$ on the market in year m is exogenous and independent from the company's operations. As the allowance price is volatile, $\tilde{k}_m^{\mathrm{Mar}}$ is defined as a stochastic variable in this paper. The purchased and sold allowances amounts are denoted by α_m^{Pur} and α_m^{Sold}, respectively. After the auction with the competent authority and the transaction with other institutions, the valid allowances owned by the company, denoted by α_m^{B}, are available for use. Then, the company decides to surrender $\alpha_m^{\mathrm{Sur}}(\leq \alpha_m^{\mathrm{B}})$ tonnes of allowances, and the surrendered allowances become invalid automatically. Meanwhile, the company is fined Pen USD per tonne of the annual emissions from the ship operating beyond α_m^{Sur}. Consequently, the allowances management costs of year m equals $k^{\mathrm{U}}\alpha_m^{\mathrm{Auc}} + \tilde{k}_m^{\mathrm{Mar}}\left(\alpha_m^{\mathrm{Pur}} - \alpha_m^{\mathrm{Sold}}\right) + Pen \max\left\{0, E_m\left(\vec{\eta}_m, \pi_m\right) - \alpha_m^{\mathrm{Sur}}\right\}$, in which E_m represents the emissions of the fleet during the year that depend on the decisions on ship numbers

($\vec{\eta}_m$) and sailing speed (π_m). Lastly, the allowances still valid after the surrender, denoted by α_m^{W}, equals $\alpha_{m-1}^{\mathrm{W}} + a_m^{\mathrm{F}} + \alpha_m^{\mathrm{Auc}} + \alpha_m^{\mathrm{Pur}} - \alpha_m^{\mathrm{Sold}} - \alpha_m^{\mathrm{Sur}}$ and can be used in year $m+1$. However, it is assumed that at the end of year M, the allowances left α_M^{W} become invalid, as the regulations of the maritime emission trading system become different in the next phase. Furthermore, α_0^{W} is defined as the amount of valid allowances the shipping company has at the beginning of year 1 before the allocation, which equals 0. Summing up, the variation in valid allowances held by the company can be illustrated by Figure 3.2, in which the blue line shows the variation during the first year of the phase.

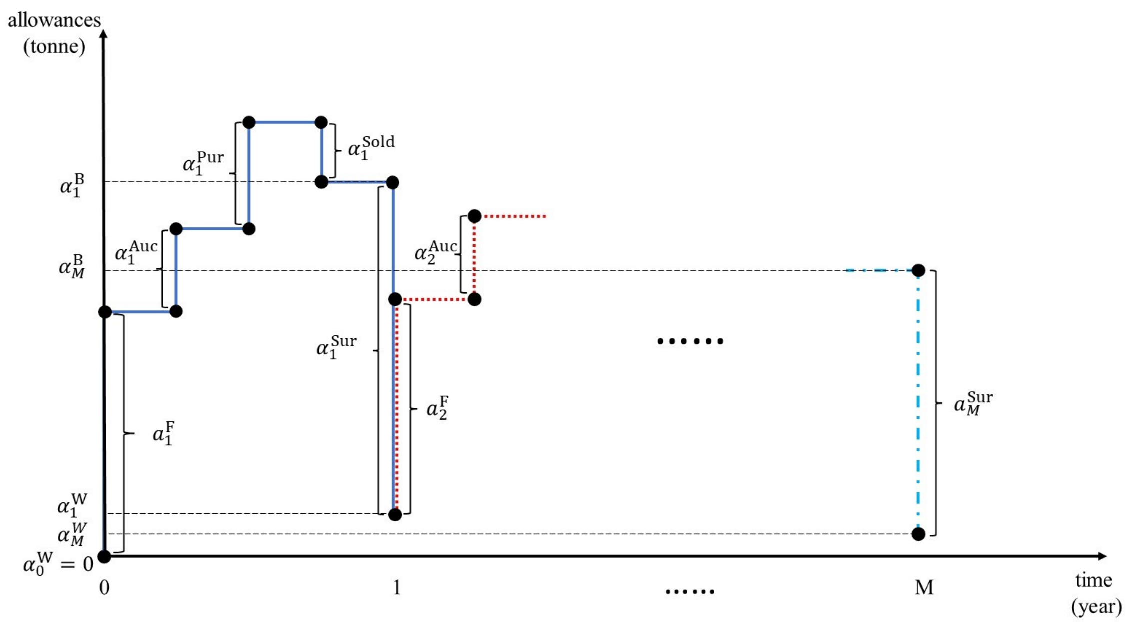

Figure 3.2: Valid allowances held by the company

3.4 Mathematical Model

In this section we provide the mathematical model to demonstrate the ship operating and allowance management plan optimization problem. Before presenting the model, we list the notations used in this paper as follows.

Sets and parameters

$\mathcal{P}$	the set of ports of call along the route, $\mathcal{P} = \{1, 2, ..., \vert\mathcal{P}\vert\}$, indexed by i;
$\mathcal{V}$	the set of ship types available, $\mathcal{V} = \{1, 2, ..., \vert\mathcal{V}\vert\}$, indexed by j;
M	the set of years in the phase considered, indexed by m;
$\mathbb{N}$	the set of non-negative integers, $\mathbb{N} = \{0, 1, 2, ...\}$;
l_i	the sailing distance of deployed ships (n mile) from port of call i to $i+1, i = 1, ..., \vert\mathcal{P}\vert - 1$;
$l_{\vert\mathcal{P}\vert}$	the sailing distance of deployed ships (n mile) from port of call $\vert\mathcal{P}\vert$ to 1;
t_i	the berthing time of deployed ships (hour) at port of call $i, \forall i \in \mathcal{P}$;
$\bar{\pi}$	the upper limit of sailing speed (knot);
$\underline{\pi}$	the lower limit of sailing speed (knot);
Pen	the penalty the shipping company incurs (USD/tonne) for emissions beyond allowances surrendered at the end of each year;
a_m^{F}	the free allowances (tonne) allocated by the competent authority for year m, $m = 1, ..., M$;
a_m^{U}	the quota of auctioned allowances (tonne) allocated by the competent authority for year m, $m = 1, ..., M$;
k^{U}	the price paid by the shipping company for buying allowances from the competent authority (USD/tonne);
c_j^{Ch}	the chartering price (USD/week) of a ship from type $j, \forall j \in \mathcal{V}$;
c_j^{Bun}	the price of bunker fuel (USD/tonne) used by ships from type $j, \forall j \in \mathcal{V}$;
α_0^{W}	the amount of allowances (tonne) the company has before the allocation from the authority of year 1, equals 0;
$q^j(\pi)$	the consumption rate of bunker fuel (tonne/n mile) of ships from type j while sailing at speed of π, $\forall j \in \mathcal{V}$;
$g^j(\pi)$	the CO_2 equivalent (tonne/n mile) emitted by a ship from type for sailing 1 n mile at speed of π knot, $\forall j \in \mathcal{V}$.

Stochastic parameters

$\tilde{k}_m^{\mathrm{Mar}}$	the allowance price on the market (USD/tonne) in year $m, m = 1, ..., M$.

Decision variables

η_m^j	the number of deployed ships from type j in year $m, \forall j \in \mathcal{V}, m = 1, ..., M$;
π_m	the sailing speed of deployed ships (knot) in year m, $m = 1, ..., M$;
α_m^{Auc}	the amount of allowances (tonne) purchased from the authority in year m, $m = 1, ..., M$;
α_m^{Pur}	the amount of allowances (tonne) purchased from the ETS market in year m, $m = 1, ..., M$;
α_m^{Sold}	the amount of allowances (tonne) sold to the ETS market in year m, $m = 1, ..., M$;
α_m^{Sur}	the amount of allowances (tonne) surrendered at the end of year m, $m = 1, ..., M$;
α_m^{W}	the amount of allowances (tonne) left at the end of year m and to be used in the next year, $m = 1, ..., M$.

Then the problem faced by the shipping company can be described as the following model [$M1$]:

$$[\boldsymbol{M1}] \quad \text{minimize}\, \mathbb{E}\left\{\sum_{m=1}^{M}\left\{\sum_{j\in\mathcal{V}} 52\left[c_j^{\text{Ch}}\eta_m^j + \frac{c_j^{\text{Bun}}\eta_m^j q^j(\pi_m)\sum_{i\in\mathcal{P}} l_i}{\sum_{j\in\mathcal{V}}\eta_m^j}\right] + k^{\text{U}}\alpha_m^{\text{Auc}} + \tilde{k}_m^{\text{Mar}}\left(\alpha_m^{\text{Pur}} - \alpha_m^{\text{Sold}}\right) + Pen\max\left\{52\frac{\sum_{j\in\mathcal{V}}\eta_m^j g^j(\pi_m)\sum_{i\in\mathcal{P}} l_i}{\sum_{j\in\mathcal{V}}\eta_m^j} - \alpha_m^{\text{Sur}}, 0\right\}\right\}\right\} \tag{3.1}$$

subject to

$$\sum_{i\in\mathcal{P}}\left(\frac{l_i}{\pi_m} + t_i\right) \le 168\sum_{j\in\mathcal{V}}\eta_m^j, m = 1, ..., M \tag{3.2}$$

$$\alpha_m^{\text{Auc}} \le a_m^{\text{U}}, m = 1, ..., M \tag{3.3}$$

$$\alpha_m^{\text{W}} = \alpha_{m-1}^{\text{W}} + a_m^{\text{F}} + \alpha_m^{\text{Auc}} + \alpha_m^{\text{Pur}} - \alpha_m^{\text{Sold}} - \alpha_m^{\text{Sur}}, m = 1, ..., M \tag{3.4}$$

$$\underline{\pi} \leq \pi_m \leq \bar{\pi}, m = 1, ..., M \tag{3.5}$$

$$\eta_m^j \in \mathbb{N}, \forall j \in \mathcal{V}, m = 1, ..., M \tag{3.6}$$

$$\alpha_m^{\text{Auc}}, \alpha_m^{\text{Pur}}, \alpha_m^{\text{Sold}}, \alpha_m^{\text{Sur}}, \alpha_m^{\text{W}} \geq 0, m = 1, ..., M. \tag{3.7}$$

The objective function (3.1) aims to minimize the total costs through the planning phase, which consist of ship chartering costs, bunker fuel costs, and allowance management costs. Constraints (3.2) ensure the weekly service frequency. Constraints (3.3) state that the allowances bought from the authority cannot exceed the allocated amount. Constraints (3.4) show the variation of valid allowances hold by the company in each year. Constraints (3.5) confine the upper and lower limit of the sailing speed of ships deployed. Constraints (3.6) and (3.7) are the domains of decision variables.

3.5 Solution Method

As we can see, the model $[M1]$ is a non-linear stochastic model, which is extremely hard to solve directly. In this section we will show how to handle nonlinear part and the stochastic element in the original model, and convert it into a deterministic linear one.

3.5.1 Model Linearization

First, we deal with the non-linear elements, namely the consumption rate of of bunker fuel $q^j(\pi_m)$ and the CO_2 equivalent emitted for sailing 1 n mile $g^j(\pi_m)$ in the objective function (3.1), and the reciprocal of the sailing speed $\frac{1}{\pi_m}$ in constraint (3.2).

Before the linearization process, we list the variables required for clear explanation.

Decision variables

η_m	the number of ships deployed in year m, equals $\sum_{j \in \mathcal{V}} \eta_m^j$, $m = 1, ..., M$.

After analytical analysis on the model structure, we establish the following property and proof it.

Property 3.1. For a given number of deployed ships in year m, denoted by η'_m, the corresponding optimal sailing speed π_m, denoted by π'_m can be obtained by $\pi'_m = \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\eta'_m - \sum\limits_{i\in\mathcal{P}} t_i}$.

Proof. We assume that when η'_m ships are deployed in year m and the optimal sailing speed π_m is $\tilde{\pi}_m > \pi'_m = \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\eta'_m - \sum\limits_{i\in\mathcal{P}} t_i}$, which is feasible. Since both $q^j(\lambda_m)$ and $g^j(\lambda_m)$ increase with π_m, the objective function value with $\tilde{\pi}_m$, denoted by $Obj(\tilde{\pi}_m)$, is higher than that with π'_m, denoted by $Obj(\pi'_m)$. Thus the solution (η'_m, π'_m) performs better than $(\eta'_m, \tilde{\pi}_m)$, which violates the premise that $\tilde{\pi}_m$ is the optimal value of π_m when η'_m ship are deployed. □

Consider the upper and lower limits of π_m, the feasible values of $\eta_m, m = 1, ..., M$ can be restricted to a finite set of speeds $S\eta = \left\{ \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil, \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil + 1, ..., \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil \right\}$, indexed by s, $s = 1, ..., \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil - \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil + 1$. The cardinal number of $S\eta$ varies with the range of π_m. When $\lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil = \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil$ we have $|S\eta| = 2$; when $\lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil > \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168}\bar{\pi} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil$ we have $|S\eta| > 2$. For the s^{th} feasible value of η_m, denoted by η^*_s, the corresponding optimal sailing speed π^*_m can be calculated as $\frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\eta^*_s - \sum\limits_{i\in\mathcal{P}} t_i}$. Thus, η_m and π_m can be replaced by the following parameters and decision variables.

Sets

$S\eta$ the set of feasible values of η_m, $S\eta = \left\{ \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil, \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil + 1, ..., \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil \right\}$, indexed by $s, s = 1, ..., \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\underline{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil - \lceil \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\bar{\pi}} + \frac{\sum\limits_{i\in\mathcal{P}} t_i}{168} \rceil + 1$, $m = 1, ..., M$;

$S\pi$ the set of feasible values of π_m, $S\pi = \left\{ \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\eta^*_1 - \sum\limits_{i\in\mathcal{P}} t_i}, ..., \frac{\sum\limits_{i\in\mathcal{P}} l_i}{168\eta^*_{|S\eta|} - \sum\limits_{i\in\mathcal{P}} t_i} \right\}$, indexed by s, $m = 1, ..., M$.

Parameters

η_s^* the s^{th} feasible value of η_m, $s = 1, ..., |S\eta|$;

π_s^* the s^{th} feasible value of π_m, $s = 1, ..., |S\eta|$.

Decision variables

ξ_{ms} binary variable, equal to 1 if (η_s^*, π_s^*) is adopted in year m, 0 otherwise, $m = 1, ..., M$, $s = 1, ..., |S\eta|$;

η_{ms}^j the number of deployed ships from type j in year m if (η_s^*, π_s^*) is adopted, $\forall j \in \mathcal{V}, m = 1, ..., M, s = 1, ..., |S\eta|$;

α_{ms}^{Auc} the amount of allowances (tonne) purchased from the authority in year m if (η_s^*, π_s^*) is adopted, $m = 1, ..., M, s = 1, ..., |S\eta|$;

α_{ms}^{Pur} the amount of allowances (tonne) purchased from the ETS market in year m, $m = 1, ..., M, s = 1, ..., |S\eta|$;

$\alpha_{ms}^{\text{Sold}}$ the amount of allowances (tonne) sold to the ETS market in year m if (η_s^*, π_s^*) is adopted, $m = 1, ..., M, s = 1, ..., |S\eta|$;

α_{ms}^{Sur} the amount of allowances (tonne) surrendered at the end of year m if (η_s^*, π_s^*) is adopted, $m = 1, ..., M, s = 1, ..., |S\eta|$;

α_{ms}^{W} the amount of allowances (tonne) left at the end of year m and to be used in the next year if (η_s^*, π_s^*) is adopted, $m = 1, ..., M, s = 1, ..., |S\eta|$.

Then, model $[M1]$ can be rewritten as an equivalent model $[M2]$:

$$[\boldsymbol{M2}] \quad \text{minimize}\, \mathbb{E}\left\{\sum_{m=1}^{M}\sum_{s\in S\eta}\xi_{ms}\left\{\sum_{j\in\mathcal{V}}52\left[c_j^{\text{Ch}}\eta_{ms}^j + \frac{c_j^{\text{Bun}}\eta_{ms}^j q^j(\pi_s^*)\sum_{i\in\mathcal{P}} l_i}{\eta_s^*}\right] + k^{\text{U}}\alpha_{ms}^{\text{Auc}}\right.\right.$$
$$\left.\left. + \tilde{k}_m^{\text{Mar}}\left(\alpha_{ms}^{\text{Pur}} - \alpha_{ms}^{\text{Sold}}\right) + Pen\max\left\{52\frac{\sum_{j\in\mathcal{V}}\eta_{ms}^j g^j(\pi_m)\sum_{i\in\mathcal{P}} l_i}{\sum_{j\in\mathcal{V}}\eta_{ms}^j} - \alpha_{ms}^{\text{Sur}}, 0\right\}\right\}\right\} \tag{3.8}$$

subject to constraints (3.3), (3.4), (3.7) and

$$\sum_{s=1}^{|S\eta|} \xi_{ms} = 1, m = 1, ..., M \tag{3.9}$$

$$\eta_s^* = \sum_{j\in\mathcal{V}} \eta_{ms}^j, m = 1, ..., M, \forall s \in S\eta \tag{3.10}$$

$$\alpha_m^{\text{Auc}} = \sum_{s\in S\eta} \xi_{ms}\alpha_{ms}^{\text{Auc}}, m = 1, ..., M \tag{3.11}$$

$$\alpha_m^{\text{Pur}} = \sum_{s\in S\eta} \xi_{ms}\alpha_{ms}^{\text{Pur}}, m = 1, ..., M \tag{3.12}$$

$$\alpha_m^{\text{Sold}} = \sum_{s\in S\eta} \xi_{ms}\alpha_{ms}^{\text{Sold}}, m = 1, ..., M \tag{3.13}$$

$$\alpha_m^{\text{Sur}} = \sum_{s\in S\eta} \xi_{ms}\alpha_{ms}^{\text{Sur}}, m = 1, ..., M \tag{3.14}$$

$$\alpha_m^{\text{W}} = \sum_{s\in S\eta} \xi_{ms}\alpha_{ms}^{\text{W}}, m = 1, ..., M \tag{3.15}$$

$$\alpha_{ms}^{\text{Auc}} \geq 0, m = 1, ..., M, \forall s \in S\eta \tag{3.16}$$

$$\alpha_{ms}^{\text{Pur}} \geq 0, m = 1, ..., M, \forall s \in S\eta \tag{3.17}$$

$$\alpha_{ms}^{\text{Sold}} \geq 0, m = 1, ..., M, \forall s \in S\eta \tag{3.18}$$

$$\alpha_{ms}^{\text{Sur}} \geq 0, m = 1, ..., M, \forall s \in S\eta \tag{3.19}$$

$$\alpha_{ms}^{\text{W}} \geq 0, m = 1, ..., M, \forall s \in S\eta \tag{3.20}$$

$$\eta_{ms}^j = 0, 1, \forall j \in \mathcal{V}, m = 1, ..., M, \forall s \in S\eta \tag{3.21}$$

$$\xi_{ms} = 0, 1, m = 1, ..., M, \forall s \in S\eta. \tag{3.22}$$

However, the objective function of model $[M2]$ is still nonlinear.

First is the penalty amount for emission volume that is not covered by surrendered allowances. Considering that it will be in vain to surrender more allowances than the amount emitted, the part $\max\left\{52\frac{\sum\limits_{j\in\mathcal{V}}\eta_m^j g^j(\pi_m)\sum\limits_{i\in\mathcal{P}} l_i}{\sum\limits_{j\in\mathcal{V}}\eta_m^j} - \alpha_m^{\text{Sur}}, 0\right\}$ in the objective function can be replaced by $52\frac{\sum\limits_{j\in\mathcal{V}}\eta_m^j g^j(\pi_m)\sum\limits_{i\in\mathcal{P}} l_i}{\sum\limits_{j\in\mathcal{V}}\eta_m^j} - \alpha_m^{\text{Sur}}$. With a new constraint that α_m^{Sur} is no more than the emission volume in year m. Next are the products of ξ_{ms} and α_{ms}^{Auc}, α_{ms}^{Pur}, $\alpha_{ms}^{\text{Sold}}$, α_{ms}^{Sur}, α_{ms}^{W} and the total cost of different periods with various sailing speeds. Then model [$M2$] can be rewritten as an equivalent linear model [$M2'$]. For details, please see Appendix A.

3.5.2 Deterministic Model

The model [$M2'$] is still difficult to solve because of the stochastic parameter $\tilde{k}_m^{\text{Mar}}$ presenting the allowance price in year m. Following previous studies on market carbon price (Zhu et al. 2018, Herve-Mignucci 2010, Abadie and Chamorro 2008), Geometric Brownian Motion (GBM) was adopted to describe the price structure of the analysis horizon in this paper. Thus, the variable CO_2 emission allowance price can be defined as:

$$\mathrm{d}\hat{k}_m^{\text{Mar}} = u\hat{k}_m^{\text{Mar}}\mathrm{d}t + \sigma\tilde{k}_m^{\text{Mar}}\mathrm{d}W_m, \tag{3.23}$$

where d is a differential sign, $\tilde{k}_m^{\text{Mar}}$, u, σ and W_m represent the emission allowance price at time m, the expected drift percentage, the instantaneous volatility percentage of $\tilde{k}_m^{\text{Mar}}$ and a standard Brownian Motion with normal distribution. A typical solution for equation (3.23)

$$\tilde{k}_m^{\text{Mar}} = \hat{k}_0^{\text{Mar}} e^{\left(u-\gamma^2/2\right)m+\sigma W_m} \tag{3.24}$$

is adopted, and $\hat{k}_0^{\text{Mar}}$ denotes the initial allowance price. Based on the historical allowance price of EU ETS in a certain period, the values of u and σ can be computed. Then, with the random realization of W_m, we can obtained a group of scenarios of $\tilde{k}_m^{\text{Mar}}$, denoted by $\hat{k}_{nm}^{\text{Mar}}$.

Set

K^{Mar} the set of market price scenarios, $K^{\text{Mar}} = \left\{K_1^{\text{Mar}}, ..., K_{|K^{\text{Mar}}|}^{\text{Mar}}\right\}$;

K_n^{Mar} the set of market prices of scenario n in the considered period, $K_n = \left\{\hat{k}_{n1}^{\text{Mar}}, ..., \hat{k}_{nM}^{\text{Mar}}\right\}$, $n = 1, ..., \left|K^{\text{Mar}}\right|$.

Parameter

$\hat{k}_{nm}^{\text{Mar}}$ the allowance market price of year m in scenario n, $n = 1, ..., \left|K^{\text{Mar}}\right|, m = 1, ..., M$;

Obj_n the objective value when the market price scenario n is adopted, $n = 1, ..., \left|K^{\text{Mar}}\right|$;

Pro_n the probability of market price scenario n, $n = 1, ..., \left|K^{\text{Mar}}\right|$.

Thus, model $[M2']$ can be rewritten as deterministic model $[M3]$ to minimize the expectation of the total cost:

$$[\boldsymbol{M3}] \quad \text{minimize} \sum_{n \in K^{\text{Mar}}} Pro_n Obj_n \tag{3.25}$$

subject to constraints (3.3), (3.4), (3.7), (3.9)–(3.22), (A.6)–(A.26) and (A.2)–(A.5) with different scenarios of k_m^{Mar}.

After the conversion, model $[M3]$ is a deterministic linear programming model, which can be solved by an off-the-shelf solver CPLEX.

3.6 Numerical Experiments

Multiple numerical experiments were conducted to validate the model and the solution method proposed. 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. The model $[M3]$ is programmed in C++ with Visual Studio 2019, and we used CPLEX 12.10 to solve the mixed-integer linear programming model obtained.

3.6.1 Parameter Settings

To validate the model and solution method developed in this paper, we consider a domestic liner shipping route consisting of ten ports of call. Obeying the emission regulations, the route operator has three options for the type of ship to deploy and the fuel they use, namely traditional ships using very low sulfur fuel oil (VLSFO), ships with scrubbers using heavy fuel oil (HFO), and LNG-fueled ships using LNG. Considering the differences in ship chartering costs, fuel consumption rates, and fuel bunkering prices, each of the three ship types has its own advantages. The specific fuel consumption rates are obtained by the investigation of Wang and Meng (2012) and the net calorific values of the different fuels. The sailing speed range is set at $[2, 30]$ knots. The bunkering prices are set at 1,050 USD per ton, 737.5 USD per ton and 563.1 USD per ton for VLSFO, HFO, and LNG, respectively.

A 5-year ETS system planning period is considered. The original emission volume of the route, denoted by $EWithout$, is obtained by solving the problem without the ETS system, namely case $CWithout$ (for details please see Appendix B). In the first year, the total emission allowance amount is set at $90\% EWithout$, in which $EWithout$ is the emission volume of the optimal solution in $CWithout$. Within the total allowances, 85% are given for free and the rest need to be auctioned from the authority at the price of 10 USD per ton ($k_{\mathrm{U}} = 10$). Over the whole period, the allowance number decreases at an annual rate of 5%. Following the Fourth GHG Study led by the International Maritime Organization (IMO) (Faber et al. 2020), the emissions of CO_2, CH_4, N_2O and HFCs in the marine exhaust gases are taken into account and converted into carbon dioxide equivalent (Forster et al. 2007). The parameters of Equation (3.24) are computed based on historical data on carbon prices in the EU ETS. With the random realization of W_m, we generate 25 scenarios of market carbon prices and the probability $Pro_n, (n = 1, ..., N)$ is equal to $0.04 (= 1/25)$. For emissions not covered by allowances surrendered, a penalty of 400 USD per ton is imposed ($pen = 400$).

Theoretically, when the market carbon price increases, the shipping company can benefit from purchasing extra allowances and selling them later. Pursuing a lower total cost over the whole planning period, the shipping company tends to purchase a great number of allowances at a lower price. However, such a management plan leads to a high total cost in certain periods, bringing financial issues. Thus, in the numerical experiments, we set an upper bound for the total costs of each period.

3.6.2 Results

In the case without the METS, denoted by $CWithout$, the route operator chooses to deploy three LNG-fueled ships on the route. Meanwhile, the annual operating cost equals 63,727,410 USD, which consists of 16,927,410 USD in bunker costs and 46,800,000 USD in ship chartering costs, and the deployed ships generate 4,607,506 tons of air emissions annually. According to the emission volume in $CWithout$, the allowance amounts in different periods of the case with the basic parameter settings, denoted by $CBasic$, are stated in Table 3.1. Details of the optimal solution of $CBasic$ are displayed in Table 3.2.

Table 3.1: Allowance amounts for $CBasic$

Content	Period 1	Period 2	Period 3	Period 4	Period 5	Sum
a_m^{F} (ton)	3,524,742	3,348,505	3,172,268	2,996,031	2,819,794	15,861,341
a_m^{U} (ton)	622,013	590,913	559,812	528,711	497,611	2,799,060

From 3.2, we can see that with the METS, the average annual route operating cost decreases. The main reason is that facing the open carbon market and the relatively high proportion of free allowances, the shipping company benefits from trading the carbon allowances. Free allowances that are not surrendered to cover the emissions are sold. The route operator also purchases extra allowances when the price is low, Period 1 and Period 2 in CBasic, and sells them later, in Periods 3 to 5 in this case. From this perspective, the application of METS provides extra revenue for the route operator and thus the total cost declines significantly. The emission volume of this route also decreases from 4,607,506 tons per year in $CWithout$ to a very low level, namely 7,213,489 tons for five years. This finding shows the necessity for this study. If the shipping company sticks to the operation plan in $CWithout$, the total cost will

Table 3.2: Results of *CBasic*

Content	Period 1	Period 2	Period 3	Period 4	Period 5	Sum
Total Cost (USD)	637,274,100	411,485,991	637,274,100	637,274,100	-637,274,100	-863,062,209
Chartering Cost (USD)	65,000,000	65,000,000	65,000,000	78,000,000	78,000,000	351,000,000
Bunker cost (USD)	12,575,020	12,575,020	12,575,020	8,588,774	8,588,774	54,902,606
Carbon cost (USD)	559,699,080	333,910,972	-714,849,120	-723,862,874	-723,862,874	-1,268,964,815
Ship number	5	5	5	6	6	NA
Ship type	Type 1	Type 1	Type 1	Type 1	Type 1	NA
Emission volume (ton)	1,617,048	1,617,048	1,617,048	1,181,172	1,181,172	7,213,489
α_m^{Auc} (ton)	622,013	590,913	559,812	528,711	497,611	2,799,060
α_m^{Pur} (ton)	50,414,377	26,864,076	0	0	0	77,278,453
α_m^{Sold} (ton)	0	0	37,691,449	30,029,215	21,004,700	88,725,365
α_m^{Sur} (ton)	1,617,048	1,617,048	1,617,048	1,181,172	1,181,172	7,213,489
α_m^{W} (ton)	52,944,085	82,130,531	46,554,114	18,868,468	0	NA

definitely increase due to the carbon cost of covering the ship emissions. Meanwhile, taking the METS into consideration when making the operation plan can create significant savings for the shipping company and make the total cost much lower than that in *CWithout*, according to Table 3.2.

Market Carbon Price

The historical data on the EU ETS reveal that the market carbon price may increase, decrease, or fluctuate around the initial price, which is as yet determined yet. To show the influence of market prices, we conducted numerical experiments with different initial prices and price changing patterns. The results are displayed in Table 3.3.

Table 3.3: Optimal total costs of cases with different carbon market price patterns (USD)

Initial (USD)	Changing pattern		
	Decreasing	Fluctuating	Increasing
Low	333,125,894	-118,927,597	-790,321,030
Medium	225,530,179	-89,398,948	-1,475,089,286
High	48,215,346	-410,934,530	-2,118,916,590

As shown in 3.3, the total cost is closely related to the market carbon price.

Specifically, a high initial price and an increasing changing pattern reduce the cost. In these cases, the route operator chooses to deploy more vessels and sells the free or auctioned carbon allowances for profit. Thus, a high initial price leads to higher allowance selling profit and reduces the total cost. As for the changing pattern, when the market price increases, the route operator is able to purchase extra carbon allowances from the market and sell them later at a higher price. This profit is reduced if the market price fluctuates around the initial price or decreases.

Free/Auction Allowance Proportion

In the cases discussed above, a large amount of extra revenue from carbon allowance trading is obtained due to the high proportion of free and auctioned allowances allocated to the shipping company. However, with the development of the METS, if the quotas of free or auctioned allowances are reduced to a very low level even zero, the carbon costs will soar. Therefore, in this subsection, we conducted numerical experiments without free or auctioned allowances, namely $a_m^{\mathrm{F}} = a_m^{\mathrm{U}} = 0, m = 1, ..., M$, under different market carbon price changing patterns. The results are presented in Table 3.4.

Table 3.4: Optimal total costs of cases with no free or auctioned allowances (USD)

Initial (USD)	Changing pattern		
	Decreasing	Fluctuating	Increasing
Low	393,691,487	-4,254,828	-537,578,209
Medium	519,542,950	575,035,321	-216,527,733
High	608,777,756	776,739,703	22,638,905

Comparing Table 3.4 and Table 3.2, we can see that under the same market carbon price pattern, having no free or auctioned allowance quotas drives up the total cost. The cost increase is intuitive because a lower allowance quota means that the route operator needs to pay more to obtain sufficient allowances to cover the emissions. In addition, it is also revealed that when there are no free or auctioned allowances, the higher initial carbon price and increasing trend do not necessarily lead to a lower total cost, unlike the situation in Table 3.2. This is mainly due to the upper bound of the total cost in each period. In cases without free or auctioned allowances, the cost to cover the emissions increases with the market carbon price, and leaving a lower budget for purchasing extra carbon allowances. In that case, with the same initial price, a fluctuating or increasing trend can bring both profit from trading carbon allowances and a higher cost of covering emissions. On the other side, with the same trend of fluctuating or increasing, a higher initial price means higher profit for trading one ton of extra allowances and a lower number of extra allowances can be purchased. To sum up, the influence of the initial carbon price and trend is more complicated when there are no free or auctioned allowances.

Delivery Time

In the aforementioned cases, following existing studies on ship deployment (Wang and Meng 2012, Zheng et al. 2018, Zhen et al. 2020), we consider that the freight revenue is fixed due to the weekly service frequency. For more time-sensitive cargoes, the transporting time, namely the time from port of origin to port of destination, is also critical. Thus, the sailing speed must be no lower than a given value, which means the number of deployed ships must be smaller than an upper bound. Therefore, we conducted the case with a given range of deployed ship numbers

$$\sum_{s=4}^{|S_\eta|} \xi_{ms} = 0, m = 1, ..., M \tag{3.26}$$

and the results are listed in Table 3.5.

Comparing Table 3.5 with Table 3.2, we find that while keeping the same service frequency and delivery time, the shipping company can still maintain the total operating cost at a very low level when the METS is promulgated. The ship deployment plan is the same as that in $CWithout$, but the negative carbon cost reduces the total cost. Given the relatively lower auction price and the increasing trend of the market carbon price, the route operator buys as many allowances as possible from the competent authority in every period to cover part of the emissions. The rest of the emissions are covered by allowances purchased from the market in Periods 1 and

Table 3.5: Results of the case with no more than 3 ships deployed

Content	Period 1	Period 2	Period 3	Period 4	Period 5	Sum
Total Cost (USD)	637,274,100	547,059,053	-637,274,100	-637,274,100	-637,274,100	-727,489,147
Chartering Cost (USD)	46,800,000	46,800,000	46,800,000	46,800,000	46,800,000	234,000,000
Bunker cost (USD)	16,927,410	16,927,410	16,927,410	16,927,410	16,927,410	84,637,051
Carbon cost (USD)	573,546,690	483,331,643	-701,001,510	-701,001,510	-701,001,510	-1,046,126,198
Ship deployment	Ty3-3	Ty3-3	Ty3-3	Ty3-3	Ty3-3	NA
Emission volume (ton)	4,607,506	4,607,506	4,607,506	4,607,506	4,607,506	23,037,532
α_m^{Auc} (ton)	622,013	590,913	559,812	528,711	497,611	2,799,060
α_m^{Pur} (ton)	51,675,706	39,101,959	0	0	0	90,777,664
α_m^{Sold} (ton)	0	0	36,966,987	29,087,696	20,345,850	86,400,533
α_m^{Sur} (ton)	4,607,506	4,607,506	4,607,506	4,607,506	4,607,506	23,037,532
α_m^{W} (ton)	51,214,955	89,648,825	51,806,412	21,635,952	0	NA

2. The purchased allowances that are not used to cover the emissions were sold for profit in Periods 3 to 5.

Heterogeneous Fleet

In the previous cases, the route operator deploys a homogeneous fleet consisting of vessels of the same type on the route. But, considering the different sources of carbon allowances, namely free, auctioned, and purchased, a heterogeneous fleet consisting of vessels of different ship types may be preferable under certain scenarios. To confirm this deduction, we conducted a series of numerical experiments with various proportions of free or auctioned allowances. It turns out that a heterogeneous fleet would be adopted in some cases. One example is the case where i) the total allowance quota decreases at a 20% annual rate; ii) 50% of the total allowance quota is given for free; iii) no more than three vessels can be deployed; iv) the bunker price of HFO is 600 USD per ton; and v) the initial carbon price is low and keeps decreasing. The detailed results for this case are listed in Table 3.6.

As shown in Table 3.6, the route operator deploys two vessels of Type 2 and one vessel of Type 3 in Periods 1, 2 and 5, one vessel of Type 1 and two vessels of Type 2 in Period 3, and three vessels from Type 3 in Period 4. The changing ship deployment plan results from the decreasing allowance quota and market carbon price. Although

Table 3.6: Results of the case that heterogeneous fleet is deployed

Content	Period 1	Period 2	Period 3	Period 4	Period 5	Sum
Total Cost (USD)	81,751,756	80,244,268	83,697,740	69,715,853	67,327,998	382,737,614
Chartering Cost (USD)	45,500,000	45,500,000	42,900,000	46,800,000	45,500,000	226,200,000
Bunker cost (USD)	20,989,166	20,989,166	27,971,487	16,927,410	20,989,166	107,866,397
Carbon cost (USD)	15,262,590	13,755,102	12,826,252	5,988,443	838,831	48,671,218
Ship deployment	Ty2-2, Ty3-1	Ty2-2, Ty3-1	Ty1-1, Ty2-2	Ty3-3	Ty2-2, Ty3-1	NA
Emission volume (ton)	4,497,825	4,497,825	4,423,124	4,607,506	4,497,825	22,524,107
α_m^{Auc} (ton)	0	0	0	0	0	0
α_m^{Pur} (ton)	2,424,448	2,839,123	3,179,098	3,778,155	4,083,150	16,303,973
α_m^{Sold} (ton)	0	0	0	0	0	0
α_m^{Sur} (ton)	4,497,825	4,497,825	4,423,124	4,607,506	4,497,825	22,524,107
α_m^{W} (ton)	0	0	0	0	0	NA

a heterogeneous fleet is preferable only in certain cases, this finding is enlightening because a homogeneous fleet is recommended in most studies of ship deployment.

3.7 Conclusions

In this chapter, we investigated the ship operation and allowance management problem in liner shipping under the maritime emission trading system. Different from existing papers, this is the first to consider the management problem faced by a liner shipping route operator that takes the ship deployment and sailing speed optimization into account. The characteristics of the METS are also well integrated into our model, including various carbon allowance sources (free, auctioned, open carbon market), penalties for not surrendering enough allowances to cover the emissions from the route, and the decreasing rate of free allowances from the competent authority. A stochastic model considering the uncertainty in the market carbon price is originally developed to identify a ship operation and allowance management plan that minimizes the total operating cost. Based on the structure of the problem, we convert the model into a deterministic linear form, after which abundant numerical experiments were conducted to demonstrate the necessity for this study.

The results of various cases offer insightful managerial insights. First, the initial market carbon price and the changing pattern of the market price significantly influence the route operating cost. When the free allowance rate is high, for example in the initial stage of the METS, the route operator tends to sell the carbon allowance for extra revenue. Thus, it is possible to achieve a very low or even negative route operating cost. A higher initial carbon price combined with an increasing changing pattern always leads to a lower total cost in this case. However, when the allowance quotas decrease to a very low level, as could occur in the later stage, the influence of the carbon price becomes more complicated. Constraints on delivery time increase the total cost but the optimal objective function value is still very low if the free or auctioned allowance quotas are set at a high level. Moreover, a heterogeneous fleet should be deployed by the shipping company in certain cases to balance the bunker costs, chartering costs, and carbon costs, which is a conclusion not commonly seen in existing papers on ship deployment on a liner shipping route.

Chapter 4

Ship Deployment Problem in Liner Shipping Under Operational Sailing Speed Limits

4.1 Introduction

Confronted with the profound impact of the COVID-19 pandemic, the international maritime trade volume decreases by 3.8% in 2020, but it returns to growth and increases by 4.3% in 2021, according to the Review of Maritime Transportation by the United Nations Conference on Trade and Development (UNCTAD 2021). Considering the recovery of international maritime trade, maritime transport still remains pivotal in the interdependent world in the long term. Given the growing trend, the greenhouse gas (GHG) emissions from shipping keep increasing and make up 2.89% of the global anthropogenic emissions in 2018, as shown in the report led by the International Maritime Organization (IMO) (Faber et al. 2020). Besides, the sustainability development and low-carbon targets will keep playing an important role and attracting wide attention from both the academia and industry (UNCTAD 2020). The International Maritime Organization (IMO) has set the target to peak and then reduce GHG emissions from international shipping in the near future; the total annual GHG emissions should drop by at least 50% by 2050 compared to 2008 (International Maritime Organization 2018). In view of the general growing trend of international maritime trade volume in recent decades (UNCTAD 2020), a larger decline in carbon intensity of international shipping is required to achieve this goal. As a result, the International Maritime Organization has been pursuing efforts towards a 70% decrease of the average CO_2 (carbon dioxide) emissions per international maritime transport work by 2050 (International Maritime Organization 2018). Trying to achieve this goal, multiple measures, including compulsory regulations and market based measures (MBMs), have been enacted by the IMO and governments of various countries and areas to control carbon emissions from shipping. Compared with other emission reduction measures, ship operational speed limits are directive and requires only operational adjustment.

For the ship operators, sailing speed optimization is a critical operation decision, because bunker costs comprises up to 60% of a carrier's total operating costs and 35% of the total freight rate, which can be attest by academic research and experts in the shipping industry (UNCTAD 2012, Gusti et al. 2019, Han and Wang 2021, Bhonsle 2022). In maritime sector, container ships, together with bulk carriers and oil tankers, make up the top three largest fuel consumers and emitters (Corbett et al. 2009, Maloni et al. 2013, Psaraftis 2019b, Faber et al. 2020). According to the official proposal of sailing speed limit submitted by the Clean Shipping Coalition (CSC) to IMO, the speed limits would be implemented as maximum average operational speeds on an annual basis for vessels (International Maritime Organization 2019b). Considering the rigid service requirement and the deployment plan lasting three to six months (Wang and Meng 2012), sailing speed limit will have significant impact on the operation of liner shipping routes, including ship deployment and speed optimization. Thus, it is necessary to investigate ship deployment and sailing speed optimization problem in liner shipping with operational sailing speed limit. However, the current literature has not covered the problem, and therefore this paper aims to fill this research gap and study the ship deployment problem in liner shipping under operational speed limits.

The remainder of this paper is organized as follows: Section 4.2 reviews literature related to this study. Detailed problem description and model formulation are given in Section 4.3.2. Section 4.4 demonstrates how the model is solved. Numerical experiments and analyses are in Section 4.5. Lastly, the paper closes with conclusions in Section 4.6.

4.2 Literature Review

In this section, three streams of literature are reviewed, namely studies on ship deployment in section 4.2.1, sailing speed limit in section 4.2.2, and papers on similar topics in section 4.2.3.

4.2.1 Ship Deployment

Ship deployment is a critical operation problem in liner shipping, which includes the determination of vessel type and number assigned to liner shipping routes, usually with the aim of profit maximization or cost minimization (Christiansen et al. 2013, Ng 2017). Following the very first studies on ship deployment by Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991), abundant papers investigated the problem under various scenarios and assumptions.

The fist extension is to consider uncertainties in the problem, mainly the shipping demand uncertainty (Meng and Wang 2010, Meng et al. 2012, Wang et al. 2013, Ng 2014, 2015, Chen et al. 2021, Tan et al. 2021, Lai et al. 2022). This extension relaxes the assumption of known shipping demand and makes the problem more realistic. The next extension is to investigate the problem in conjunction with other decisions in liner shipping, including but not limited to liner shipping network design (Brouer et al. 2014, Huang et al. 2015, Mulder and Dekker 2014, Wang et al. 2021b) and sailing speed optimization (Andersson et al. 2015, Wang and Wang 2021, Wang et al. 2021b). Besides, problems considering additional elements related to ship deployment have attracted extensive attention. Due to the imbalanced shipping volume in difference direction liner shipping routes, empty container repositioning is one of the most investigated issues (Song and Dong 2013, Huang et al. 2015, Wu et al. 2020). Meanwhile, various regulations have been implemented for the emission reduction target of IMO and impact operation of container ships, thus studies on ship deployment problem considering such regulations become another branch of the literature (Wang and Meng 2017, Rodriguez et al. 2022). Specifically, ship deployment problems with ECA (Wang et al. 2021b, Zhen et al. 2020), METS (Xing et al. 2019, Zhu et al. 2018), and carbon tax (Wang and Chen 2017, Xing et al. 2019) have been discussed by scholars.

However, ship deployment under sailing speed limit has been seldom investigated. The main differences between this paper and existing studies on similar topics are stated in section 4.2.3.

4.2.2 Sailing Speed Limit

Sailing speed limit was officially proposed by the Clean Shipping Coalition (CSC) to IMO at the 74th session of Marine Environment Protection Committee as an immediate GHG reduction measure to deliver the IMO 2030 target, and regulatory pathways were given together with the proposal (International Maritime Organization 2019b). Although the speed limit regulation has not been implemented, discussion about it continues.

Wada et al. (2021) develop systematic dynamic models to predict GHG emissions from shipping with various emission reduction measures, including slow steaming. Impact of ship operation speed on ship building and demolishing market is taken into account. Results show that linearly decreasing ship operation speed will lead to GHG emission reduction despite the larger fleet volume required. However, the operation decisions of ships are not considered, it is simply assumed that all ships sail at the predetermined average speed. And the study focuses on bulk carrier, which has very different operation model from that of container ship. Zis and Psaraftis (2022) analyze the impacts of several short-term decarbonization measures by IMO, including the sailing speed limit approach, on perishable cargoes. It is concluded that the efficacy of sailing speed limit depends on the specific speed upper bound for ships. Meanwhile, due to the longer transit time resulted from a strict speed limit, more expensive perishable cargoes will shift to air transportation, which leads to a higher total GHG emission. Maloni et al. (2013) focus on the benefits brought by slow steaming and its spread across different stakeholders in the maritime industry. Taking a high volume Asia–North America container trade lane as an example, Maloni et al. (2013) explain how shippers and carriers' will benefit from slow steaming under different sailing speeds.

Eide et al. (2009) assess cost-effectiveness of CO_2 reduction measures in maritime transportation by an originally proposed criterion named the Cost of Averting a Tonne of CO_2-eq Heating (CATCH), and speed limit is recommended as a promising method. Taking the freight income into account, Corbett et al. (2009) estimate the marginal abatement cost (MAC) of CO_2 reductions when speed limit is mandated. It is shown that MAC increases with the speed limit getting stricter. Marques et al. (2023) estimate the CO_2 emission volume of the world fleet and the cost per reduced ton of CO_2 under various speed reduction scenarios. According to the study, speed reduction is more effective than power reduction and approximately 30% reduction in sailing speed would be sufficient to achieve the IMO's decarbonization goal.

Ng (2022) focus on the operation of liner shipping route under sailing speed limit. Results show that due to the rigid service frequency requirement, strict sailing speed limit might be infeasible for liner shipping under extreme circumstances. It also turns out that the influence of port times on ship scheduling will be magnify by strict speed limits. Taking two container liner services for example, Cariou and Cheaitou (2012) analyze the effectiveness of a unilateral sailing speed limit regulation in Europe. To maintain the weekly service frequency, route operators speed up outside the speed limit zoom, which requires higher operating costs and leads to increased emission volume from the whole route.

Besides being considered as the method to reduce ship emission, ship sailing speed limit is also adopted for other maritime issues. Nielsen et al. (2016), He et al. (2017), Theocharis et al. (2021) and Browne et al. (2022) take sailing speed limit as a measure to guarantee shipping safety considering various geographical situations and sailing conditions. Lott (2022) and Guzman et al. (2020) on the other hand, focuses on speed limit's positive effect on the protection of marine wildlife. Wang et al. (2020)

adopt Automatic Identification System (AIS) data to evaluate the performance of shipping traffic with speed limits for safety considerations. The results indicate that the speed limit regulation performs well and is complied by most of the vessels in the Shanghai section of Yangtze River.

4.2.3 Similar Topic

In existing literature, three studies share multiple issues with our paper. The main differences will be stated in this subsection and prove that our paper is essentially different from them.

Nielsen et al. (2016) investigate the sailing speed and bunkering plan optimization problem with speed limits due to geographical reasons. There are three main differences between Nielsen et al. (2016) and our paper. First, the route operation problems investigated are different. Nielsen et al. (2016) consider a single route served by one vessel, and the sailing speed, the port for fuel bunkering, and the bunkering amounts are to be optimized. Our paper, distinguishing from Nielsen et al. (2016), considers multiple routes and takes ship deployment, sailing speed optimization as the main decisions. The second distinction is the sailing speed limits taken into account. In the study of Nielsen et al. (2016), sailing speed limits are due to the geographical condition along the route, which are absolute upper bounds of ship sailing speed. Meanwhile, in our paper, the speed limits are implemented as an annual average limit. These two differences make the mathematical models developed essentially distinguishable from each other. Third is the solution method. Nielsen et al. (2016) propose a heuristic algorithm to solve its problem, whereas a tailored optimization solution method is proposed to solve our model.

He et al. (2017) investigate a speed optimization problem of a sailing route with heterogeneous speed limits and bunker costs due to marine conditions and service time-windows across arcs. Like the study of Nielsen et al. (2016), the paper by He et al. (2017) has different problem structure and speed limits from ours, and does not cover ship deployment. As a result, the mathematical model we developed is also essentially different from that in He et al. (2017). Besides, both He et al. (2017)

and Nielsen et al. (2016) only consider bunker costs in their objective functions, whilst we also take ship chartering costs into account.

Tan et al. (2022) covers the speed limit set for emission reduction targets and discuss about the impact of annual average speed limit on liner shipping. However, in Tan et al. (2022), the annual average speed limit is not integrated into the optimization model as an constraint, but evaluated by the speed allowance accumulation rate, which indicates the deviation from the average speed limit. In our paper, multiple shipping routes are considered, and the ship deployment shifts in the middle of each year. The average speeds of deployed vessels are constrained to be no higher than the limits given by the authority. Thus, the optimization model we develop is essentially different from that in Tan et al. (2022).

Given the literature, the main academic contribution of this chapter is threefold.

- First, we investigate the ship deployment problem with sailing speed optimization under the limit on annual average operational speed. The two ship deployment periods in one calendar year for multiple shipping routes were considered simultaneously to adapt to the annual average operational speed limits.
- Second, a mixed-integer nonlinear model is originally developed to describe the problem. Unlike previous studies, we integrate ship deployment, sailing speed optimization, and annual average sailing speed limit constraint into our model. Some assumptions in traditional ship deployment problems are loosen in this paper for optimality.
- Third, based on the problem structure, we develop a tailored method to solve the model, and the solution method we developed is essentially different from those in previous papers. Besides, numerical experiments were conducted to validate the model and solution method developed. Results indicate the necessity of this study and the superiority of our model in various transport demand scenarios.

4.3 Model Formulation

In this section, a mixed-integer nonlinear model is developed to describe the problem faced by a liner shipping company operating multiple routes. The annual average operational speed limits are integrated into the model as hard constraints.

4.3.1 Problem Description

In this study, we consider a liner shipping company that operates a set of liner routes, denoted by $\mathcal{R}$. To accomplish a round trip of route $i \in \mathcal{R}$, a ship needs to sail h_i nautical miles (nm). Considering the fluctuation of trade volume, we split a calendar year into two periods, and each of them consists of 26 weeks. At the beginning of each period, the shipping company makes the ship deployment plan. The shipping demand of route i in period 1 and period 2 are denoted by w_i^1 and w_i^2 respectively. The total berthing time of a round trip along route i, which is closely related to the shipping demand, is different in the two periods, denoted by t_i^1 and t_i^2 respectively. The shipping company charters in container ships at an annual contract and deploy them on the routes to provide liner shipping service in a weekly frequency for the two periods.

To record the annual average speed of each vessel, we denote the set of container ship available on the ship chartering market by $\mathcal{S}$, which are from various ship types $\mathcal{V}$. The binary parameter $n_{kj}, k \in \mathcal{S}, j \in \mathcal{V}$ indicates the type of vessel k, and it equals 1 if vessel k is from type j, 0 otherwise. A vessel from type j has a capacity of c_j and consumes the bunker fuel at the price of p. To charter such a vessel, an annual chartering cost of b_j will be incurred.

Vessels are chartered on an annual basis, which is denoted by α_k. If vessel k is chartered, namely $\alpha_k = 1$, it will be operated by the shipping company for the whole year. Meanwhile, the chartered vessels will be deployed twice in a year, at the beginnings of period 1 and period 2 to provide liner service at a weekly frequency. The deployment of vessel k in period 1 (period 2) is denote by $\alpha_k^1 i$ ($\alpha_k^2 i$), equals 1 when vessel k is deployed on route k, 0 otherwise. During each period, the deployed vessels sail according to a fixed schedule.

For chartered vessels from type j, there are a set of speed limits. First are the upper and lower limits of the absolute operating speed, denoted by $\bar{\pi}$ and $\underline{\pi}$, which are due to the ship design or economical reasons. Besides, in this paper we also consider the limit of annual average operating speed for each ship type, denoted by $\hat{\pi}_j$, which is implemented for the emission reduction purpose.

Considering the multiple speed limits on vessels and two deployment periods in a year, we lose the assumption of homogeneous fleet in traditional ship deployment problem. In this paper, vessels from different ship types can be deployed on the same route. In addition, it is assumed that a large vessel can be substituted with several small vessels that have the equivalent total capacity. For example, a ship with 4,000 TEU capacity can be replaced by two ships with 2,000 TEU capacity. Thus, in each period, ships are deployed and operated in groups, which refers to one ship or a team of ships that are not necessarily from the same type. The groups that have the same ship combination, namely the numbers of vessels from each ship type are the same, are defined as one group type. The number of ships from ship type j in group type l is denoted by GV_{lj}. The set of group types considered in this paper are denoted by $\mathcal{G}$. Meanwhile, GS_{il}^1 and GS_{il}^2 are binary parameters that indicate whether group type l is suitable for route i in period 1 and period 2, respectively. The groups should have enough capacities and no redundant vessels. To provide liner shipping service, GN_{il}^1 (GN_{il}^2) of vessel groups from type l are deployed on route i at period 1 (period 2), thus $\sum_{l\in\mathcal{G}_{il}^1} GN_{il}^1$ ($\sum_{l\in\mathcal{G}_{il}^2} GN_{il}^2$) ship groups are deployed on route i in period 1 (period 2) in total.

To maintain the weekly service frequency, ship groups deployed on route i in period 1 (period 2) sail at the speed of π_i^{R1} (π_i^{R2}). For ship k if it is deployed on route i in period 1 (period 2), namely $\alpha_{ki}^1 = 1$ ($\alpha_{ki}^2 = 1$), its sailing speed at period 1 (period 2) equals π_i^{R1} (π_i^{R2}). When deployed, a vessel from ship type j consumes $g^j(\pi)$ ton of bunker fuel for sailing 1 nm at the speed of π. The auxiliary engines consume g'^j tons of bunker fuel each year.

The shipping company, aims to minimize the total annual operating costs consisting of bunker costs and ship chartering costs.

4.3.2 Mathematical Model

We list the notations that will be used before presenting the specific mathematical model.

Sets and parameters

$\mathcal{R}$	the set of liner routes operated by the shipping company, $\mathcal{R} = \{1, 2, ..., \lvert\mathcal{R}\rvert\}$, indexed by i;
$\mathcal{V}$	the set of ship types considered, $\mathcal{V} = \{1, 2, ..., \lvert\mathcal{V}\rvert\}$, indexed by j;
$\mathcal{S}$	the set of ships available on the market, $\mathcal{S} = \{1, 2, ..., \lvert\mathcal{S}\rvert\}$, indexed by k;
$\mathcal{G}$	the set of vessel group types, $\mathcal{G} = \{1, 2, ..., \lvert\mathcal{G}\rvert\}$, indexed by l;
GS^1_{il}	binary parameter, equal to 1 if group type l is suitable for route i in period 1, 0 otherwise, $\forall l \in \mathcal{G}, \forall i \in \mathcal{R}$;
GS^2_{il}	binary parameter, equal to 1 if group type l is suitable for route i in period 2, 0 otherwise, $\forall l \in \mathcal{G}, \forall i \in \mathcal{R}$;
GV_{lj}	the number of vessels from ship type j in group type l, $\forall l \in \mathcal{G}, \forall j \in \mathcal{V}$;
h_i	the total sailing distance (nm) of a round trip along route $i, \forall i \in \mathcal{R}$;
t^1_i	the total berthing time (hour) of round trip along route i in period 1, $\forall i \in \mathcal{R}$;
t^2_i	the total berthing time (hour) of round trip along route i in period 2, $\forall i \in \mathcal{R}$;
w^1_i	the ship capacity (TEU) required by route i for a vessel group during period 1, $\forall i \in \mathcal{R}$;
w^2_i	the ship capacity (TEU) required by route i for a vessel group during period 2, $\forall i \in \mathcal{R}$;
p	the price (USD/ton) of bunker fuel consumed by ships;
c_j	the capacity (TEU) of ship type j, $\forall j \in \mathcal{V}$;
b_j	the annual chartering price (USD/year) of ships from type j, $\forall j \in \mathcal{V}$;
$\bar{\pi}$	the upper limit (knot) on absolute operating speed of ships;
$\underline{\pi}$	the lower limit (knot) on absolute operating speed of ships;
$\hat{\pi}_j$	the upper limit (knot) on annual average operating speed of ships from type j, $\forall j \in \mathcal{V}$;

n_{kj} binary parameter, equal to 1 if ship k is from ship type j, 0 otherwise, $\forall k \in \mathcal{S}, \forall j \in \mathcal{V}$.

g'^j auxiliary engine fuel consumption (ton/year) of ships from type j, $\forall j \in \mathcal{V}$.

M a number that is large enough.

Decision variables

α_k binary variable, equal to 1 when ship k is chartered, 0 otherwise, $\forall k \in \mathcal{S}$;

α_{ki}^1 binary variable, equal to 1 when ship k is deployed on route i in period 1, 0 otherwise, $\forall k \in \mathcal{S}, \forall i \in \mathcal{R}$;

α_{ki}^2 binary variable, equal to 1 when ship k is deployed on route i in period 2, 0 otherwise, $\forall k \in \mathcal{S}, \forall i \in \mathcal{R}$;

GN_{il}^1 the number of vessel groups from group type l deployed on route i in period 1, $GN_{il}^1 \in \mathbb{N}$, $\forall i \in \mathcal{R}, \forall l \in \mathcal{G}$;

GN_{il}^2 the number of vessel groups from group type l deployed on route i in period 2, $GN_{il}^1 \in \mathbb{N}$, $\forall i \in \mathcal{R}, \forall l \in \mathcal{G}$;

π_k^1 the sailing speed (knot) of ship k in period 1, $\forall k \in \mathcal{S}$;

π_k^2 the sailing speed (knot) of ship k in period 2, $\forall k \in \mathcal{S}$;

π_i^{R1} the sailing speed (knot) of ships deployed on route i in period 1, $\forall i \in \mathcal{R}$;

π_i^{R2} the sailing speed (knot) of ships deployed on route i in period 2, $\forall i \in \mathcal{R}$;

$g^j(\pi)$ fuel consumption rate (ton/nm) of ships from type j while sailing at the speed of π, $\forall j \in \mathcal{V}$;

The problem faced by the shipping company can be described in the following minx-integer nonlinear optimization model $[M1]$:

$$[\boldsymbol{M1}] \quad \text{minimize} \sum_{k \in \mathcal{S}} \sum_{j \in \mathcal{V}} n_{kj} \left(b_j + g'^j p_j \right) \alpha_k + \sum_{i \in \mathcal{R}} \sum_{l \in \mathcal{G}} \frac{26 \sum_{j \in \mathcal{V}} GV_{lj} g^j(\pi_i^{\text{R1}}) h_i p_j GN_{il}^1}{\frac{t_i + \frac{h_i}{\pi_i^{\text{R1}}}}{168}}$$
$$+ \sum_{i \in \mathcal{R}} \sum_{l \in \mathcal{G}} \frac{26 \sum_{j \in \mathcal{V}} GV_{lj} g^j(\pi_i^{\text{R2}}) h_i p_j GN_{il}^2}{\frac{t_i + \frac{h_i}{\pi_i^{\text{R2}}}}{168}} \tag{4.1}$$

subject to

$$\alpha_{ki}^1 \leq \alpha_k, \forall k \in \mathcal{S} \tag{4.2}$$

$$\alpha_{ki}^2 \leq \alpha_k, \forall k \in \mathcal{S} \tag{4.3}$$

$$\sum_{i \in \mathcal{R}} \alpha_{ki}^1 \leq 1, \forall k \in \mathcal{S} \tag{4.4}$$

$$\sum_{i \in \mathcal{R}} \alpha_{ki}^2 \leq 1, \forall k \in \mathcal{S} \tag{4.5}$$

$$\pi_k^1 = \sum_{i \in \mathcal{R}} \alpha_{ki}^1 \pi_i^{\mathrm{R1}}, \forall k \in \mathcal{S} \tag{4.6}$$

$$\pi_k^2 = \sum_{i \in \mathcal{R}} \alpha_{ki}^2 \pi_i^{\mathrm{R1}}, \forall k \in \mathcal{S} \tag{4.7}$$

$$\frac{\frac{26 \times 168 \sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\pi_k^1} + t_i} + \frac{26 \times 168 \sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\pi_k^1} + t_i}}{26 \left(\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\pi_k^1} + t_i + \frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\pi_k^2} + t_i \right)} \leq \sum_{j \in \mathcal{V}} n_{kj} \hat{\pi}_j, \forall k \in S \tag{4.8}$$

$$168 \sum_{l \in \mathcal{G}} GN_{il}^1 \geq \frac{h_i}{\pi_i^{R1}} + t_i^1, \forall i \in \mathcal{R} \tag{4.9}$$

$$168 \sum_{l \in \mathcal{G}} GN_{il}^2 \geq \frac{h_i}{\pi_i^{R2}} + t_i^2, \forall i \in \mathcal{R} \tag{4.10}$$

$$GN_{il}^1 \leq GS_{il}^1 M, \forall i \in \mathcal{R}, \forall l \in \mathcal{G} \tag{4.11}$$

$$GN_{il}^2 \leq GS_{il}^2 M, \forall i \in \mathcal{R}, \forall l \in \mathcal{G} \tag{4.12}$$

$$\sum_{k \in \mathcal{S}} n_{kj} \alpha_{ki}^1 = \sum_{i \in \mathcal{R}} \sum_{l \in \mathcal{G}} GV_{lj} GN_{il}^1, \forall j \in \mathcal{V} \tag{4.13}$$

$$\sum_{k \in \mathcal{S}} n_{kj} \alpha_{ki}^2 = \sum_{i \in \mathcal{R}} \sum_{l \in \mathcal{G}} GV_{lj} GN_{il}^2, \forall j \in \mathcal{V} \tag{4.14}$$

$$\underline{\pi} \leq \pi_k^1 \leq \bar{\pi}, \forall k \in \mathcal{S} \tag{4.15}$$

$$\underline{\pi} \leq \pi_k^2 \leq \bar{\pi}, \forall k \in \mathcal{S} \tag{4.16}$$

$$\alpha_k, \alpha_{ki}^1, \alpha_{ki}^2 = 0, 1, \forall i \in \mathcal{R}, \forall k \in \mathcal{S} \tag{4.17}$$

$$GN_{il}^1, GN_{il}^2 \in \mathbb{N}, \forall i \in \mathcal{R}, \forall l \in \mathcal{G} \tag{4.18}$$

$$\pi_k^1, \pi_k^2, \pi_i^{\mathrm{R1}}, \pi_i^{\mathrm{R2}} \geq 0, \forall i \in \mathcal{R}, \forall k \in \mathcal{S} \tag{4.19}$$

The objective function (4.1) minimizes the total annual operating costs, which are equivalent to ship chartering costs in the whole year plus bunker costs of liner routes in the two periods. Constraints (4.2) and (4.3) indicate that only chartered ships can be deployed. Constraints (4.4) and (4.5) show that a ship can be deployed on at most one route in a period. Constraints (4.6) and (4.7) explain the relationship between route speed and ship speed. Constraints (4.8) guarantee the annual average sailing speeds of all chartered ships do not exceed the limits. Constraints (4.9) and (4.10) assure that each route has enough vessel groups to provide the weekly service frequency. Constraints (4.11) and (4.12) indicate that routes can only adopt vessel groups suitable for the transporting demand. Constraints (4.13) and (4.14) indicate that enough vessels are deployed to make up the vessel groups on each route. Constraints (4.15) and (4.16) are the limits on absolute ship operating speed. Constraints (4.17)–(4.19) are decision variable domains.

4.4 Solution Method

To solve the mixed-integer nonlinear model $[M1]$, the main difficulties lie in the large number of available ships on market and the nonlinear part in the model. In this section, we show how to handle these two barriers.

First, we introduce a different way to describe the ship chartering decisions and reduce the problem scale. Instead of taking all the available ships into consideration, we introduce a set of ships that will be chartered $\mathcal{S}'$ but with the vessel types to be determined. Without the loss of generality, we have $|\mathcal{S}'|$ equals to the upper limit of ships deployed. Meanwhile, we introduce a new ship type set $\mathcal{V}'$ which consists of all types in the original set $\mathcal{V}$ and a virtual type indicating the corresponding vessel is not chartered in practice. Before the new model, we list set, parameters, and decision variables that will be used in it.

Sets and parameters

$\mathcal{S}'$	the set of ships chartered, $\mathcal{S}' = \{1, 2, ..., \lvert\mathcal{S}'\rvert\}$, indexed by k;
$\mathcal{V}'$	the set of ship types, $\mathcal{V} = \{0, 1, 2, ..., \lvert\mathcal{V}'\rvert - 1\}$, indexed by j, $j = 0$ refers to the virtual type indicating the corresponding ship is not chartered in practice;
c_0	the capacity (TEU) of the virtual vessel type 0, equals 0;
b_0	the annual chartering price (USD/year) of ships from the virtual type 0, equals 0;
$\hat{\pi}_0$	the upper limit (knot) on annual average operating speed of ships from the virtual type 0, equals 0;
g'^0	the annual auxiliary engine fuel consumption (ton/year) of ships from the virtual type 0, equals 0;
GV_{0l}	the number of vessels from the virtual ship type 0 in group type l, equals 0, $\forall l \in \mathcal{G}$;

Decision variables

ω_{kj}	binary variable, equal to 1 when we select ship k from vessel type j, 0 otherwise, $\forall k \in \mathcal{S}', \forall j \in \mathcal{V}'$;

Then the original model $[M1]$ can be rewritten as follows.

$$[\boldsymbol{M2}] \quad \text{minimize} \sum_{k\in\mathcal{S}'}\sum_{j\in\mathcal{V}'}\left(b_j + g'^j p_j\right)\omega_{kj} + \sum_{i\in\mathcal{R}}\sum_{l\in\mathcal{G}} \frac{26\sum_{j\in\mathcal{V}'} GV_{lj} g^j(\pi_i^{\text{R1}}) h_i p_j GN_{il}^1}{\frac{t_i + \frac{h_i}{\pi_i^{\text{R1}}}}{168}} + \sum_{i\in\mathcal{R}}\sum_{l\in\mathcal{G}} \frac{26\sum_{j\in\mathcal{V}'} GV_{lj} g^j(\pi_i^{\text{R2}}) h_i p_j GN_{il}^2}{\frac{t_i + \frac{h_i}{\pi_i^{\text{R2}}}}{168}} \tag{4.20}$$

subject to constraints (4.9), (4.10), (4.11), (4.12), and (4.18),

$$\sum_{j\in\mathcal{V}'} \omega_{kj} = 1, \forall k \in \mathcal{S}' \tag{4.21}$$

$$\sum_{i \in \mathcal{R}} \alpha_{ki}^1 \leq 1, \forall k \in \mathcal{S}' \tag{4.22}$$

$$\sum_{i \in \mathcal{R}} \alpha_{ki}^2 \leq 1, \forall k \in \mathcal{S}' \tag{4.23}$$

$$\pi_k^1 = \sum_{i \in \mathcal{R}} \alpha_{ki}^1 \pi_i^{\text{R1}}, \forall k \in \mathcal{S}' \tag{4.24}$$

$$\pi_k^2 = \sum_{i \in \mathcal{R}} \alpha_{ki}^2 \pi_i^{\text{R2}}, \forall k \in \mathcal{S}' \tag{4.25}$$

$$\frac{\frac{26 \times 168 \sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\pi_k^1} + t_i} + \frac{26 \times 168 \sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\pi_k^1} + t_i}}{26 \left(\frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^1}{\pi_k^1} + t_i + \frac{\sum_{i \in \mathcal{R}} h_i \alpha_{ki}^2}{\pi_k^2} + t_i \right)} \leq \sum_{j \in \mathcal{V}'} \omega_{kj} \hat{\pi}_j, \forall k \in S' \tag{4.26}$$

$$\sum_{k \in \mathcal{S}'} \omega_{kj} \alpha_{ki}^1 = \sum_{l \in \mathcal{G}} GV_{lj} GN_{il}^1, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}' \tag{4.27}$$

$$\sum_{k \in \mathcal{S}'} \omega_{kj} \alpha_{ki}^2 = \sum_{l \in \mathcal{G}} GV_{lj} GN_{il}^2, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}' \tag{4.28}$$

$$\underline{\pi} \leq \pi_k^1 \leq \bar{\pi}, \forall k \in \mathcal{S}' \tag{4.29}$$

$$\underline{\pi} \leq \pi_k^2 \leq \bar{\pi}, \forall k \in \mathcal{S}' \tag{4.30}$$

$$\alpha_{ki}^1, \alpha_{ki}^2 = 0, 1, \forall i \in \mathcal{R}, \forall k \in \mathcal{S}' \tag{4.31}$$

$$\pi_k^1, \pi_k^2, \pi_i^{\text{R1}}, \pi_i^{\text{R2}} \geq 0, \forall i \in \mathcal{R}, \forall k \in \mathcal{S}' \tag{4.32}$$

In the model $[M2]$, constraints (4.21) assures that only one type for each chartered ship. Besides, the parameters about the virtual vessel type guarantee that ships from it are not deployed or incur any costs, which is equivalent to not chartered in practice. However, $[M2]$ is still difficult to solve due to the nonlinear elements. The crux of matter are the nonlinear relationship between ship sailing speed and fuel consumption rate, denoted by $g^j(\pi)$, and constraint (4.26) indicating the annual average operating speed limit in this paper. Next, we show how to handle it by introducing Property 4.1.

Property 4.1. In the optimal solution, for each route in each period, at least one of the two conditions must be satisfied: 1). weekly service frequency constraint is tight, namely $168\sum_{l\in\mathcal{G}} GN_{il}^1 = \frac{h_i}{\pi_i^{R1}} + t_i$ ($168\sum_{l\in\mathcal{G}} GN_{il}^2 = \frac{h_i}{\pi_i^{R2}} + t_i$); 2). or the sailing speed is at the absolute lower bound, namely $\pi_i^{R1} = \underline{\pi}$ ($\pi_i^{R2} = \underline{\pi}$).

Proof. *Suppose that we have the optimal solution denoted by* Opt^**, with the optimal objective value denoted by* $ObjVal^*$*.*

If in Opt^* *we have* $168\sum_{l\in\mathcal{G}} GN_{il}^{1*} > \frac{h_i}{\pi_i^{R1*}} + t_i, \pi_i^{R1*} > \underline{\pi}, \exists i \in \mathcal{R}$*. Then we can obtain a new solution, denoted by* $\tilde{Opt}$*, by replacing* π_i^{R1*} *by* $\tilde{\pi}_i^{R1}$*, which meets the conditions: i)* $\tilde{\pi}_i^{R1} < \pi_i^{R1*}$*, ii)* $\frac{h_i}{168\sum_{l\in\mathcal{G}} GN_{il}^{1*} - t_i} \leq \tilde{\pi}_i^{R1}$*, and iii)* $\underline{\pi} \leq \tilde{\pi}_i^{R1}$*.*

Step 1: Proof that the new solution $\tilde{Opt}$ *is feasible. For constraint* (4.9)*, from condition ii)* $\frac{h_i}{168\sum_{l\in\mathcal{G}} GN_{il}^{1*} - t_i} \leq \tilde{\pi}_i^{R1}$ *we can easily obtain* $168\sum_{l\in\mathcal{G}} GN_{il}^1 \geq \frac{h_i}{\pi_i^{R1}} + t_i, \forall i \in \mathcal{R}$*, namely constraint* (4.9) *is still valid. For constraint* (4.26)*, the first-order derivative of the left-hand side*

$$\frac{Part1 - Part2}{26\left(\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\pi_k^1} + t_i + \frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^2}{\pi_k^2} + t_i\right)^2}\left(\frac{-\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{{\pi_k^1}^2}\right) \geq 0,$$

in which

$$Part1 = \frac{26\times 168\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\pi_k^1} + t_i}\left[-\frac{1}{\left(\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\pi_k^1} + t_i\right)^2}\right]\left(\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\pi_k^1} + t_i + \frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^2}{\pi_k^2} + t_i\right)$$

and

$$Part2 = \left(\frac{26\times 168\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^1}{\pi_k^1} + t_i} + \frac{26\times 168\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^2}{\frac{\sum_{i\in\mathcal{R}} h_i\alpha_{ki}^2}{\pi_k^1} + t_i}\right).$$

Therefore, from condition i) we can obtain that the left-hand side value with $\tilde{\pi}_i^{\mathrm{R1}}$*, denoted by* $\tilde{LHS}$*, is no larger than the value with* $\pi_i^{\mathrm{R1}*}$*, denoted by* LHS^**. Namely, we have* $\tilde{LHS} \leq LHS^* \leq \sum_{j\in\mathcal{V}'} \omega_{kj}\hat{\pi}_j$ *and constraint* (4.26) *is valid with the new solution. As a result, the new solution* $\tilde{Opt}$ *with* $\tilde{\pi}_i^{\mathrm{R1}}$ *is a feasible solution.*

Step 2: Proof $Ob\tilde{j}Val < ObjVal^*$, in which $Ob\tilde{j}Val$ refers to the objective value of the new solution $\tilde{Opt}$. In $[M2]$, the first-order derivative of the objective function is definitely positive, namely

$$\frac{\left(26 \times 168 GV_{lj} \left[g^j(\pi_i^{\mathrm{R1}})\right]' h_i p_j GN_{il}^1\right)\left(t_i + \frac{h_i}{\pi_i^{\mathrm{R1}}}\right) - \left(26 \times 168 GV_{lj} g^j(\pi_i^{\mathrm{R1}}) h_i\right) p_j GN_{il}^1 \frac{-h_i}{\left(\pi_i^{\mathrm{R1}}\right)^2}}{\left(t_i + \frac{h_i}{\pi_i^{\mathrm{R1}}}\right)^2} > 0,$$

in which $\left[g^j(\pi_i^{\mathrm{R1}})\right]' (> 0)$ is the first-order derivative of $g^j(\pi_i^{\mathrm{R1}})$. Therefore, from condition i) $\tilde{\pi}_i^{R1} < \pi_i^{R1*}$, we can obtain that $Ob\tilde{j}Val < ObjVal^*$.

As a result, we can obtain a new feasible solution $\tilde{Opt}$ with lower objective value than that of Opt^*, which violates the assumption that Opt^* is the optimal solution.

Else, if in Opt^* we have $168 \sum_{l \in \mathcal{G}} GN_{il}^{2*} > \frac{h_i}{\pi_i^{R2*}} + t_i, \pi_i^{R2*} > \underline{\pi}, \exists i \in \mathcal{R}$. The proof is as above due to the symmetry of $[M2]$.

Combining Property 4.1 and the absolute ship operating speed limit $[\underline{\pi}, \bar{\pi}]$, we can enumerate the feasible numbers of deployed vessel groups for each route and the corresponding optimal sailing speeds, which are defined as candidate ship schedule profiles. Thus, ship deployment can be replaced by ship schedule profile selection, avoiding the nonlinear elements of bunker fuel consumption rates and annual average speed limits. Then, model $[M2]$ can be rewritten into $[M3]$, and the parameters and decision variables needed are listed before the specific model.

Sets and parameters

- $Sech_i^1$ the set of candidate ship schedule profiles of route i in period 1, $Sech_i = 1, ..., |Sech^i|$, indexed by u;
- $Sech_i^2$ the set of candidate ship schedule profiles of route i in period 2, $Sech_i = 1, ..., |Sech^i|$, indexed by u;
- $GNumS_{iu}^1$ the total number of vessel groups deployed in profile u of route i in period 1, $\forall u \in Sech_i, \forall i \in \mathcal{R}$;
- $GNumS_{iu}^2$ the total number of vessel groups deployed in profile u of route i in period 2, $\forall u \in Sech_i, \forall i \in \mathcal{R}$;
- πS_{iu}^1 the sailing speed (knot) of ships deployed on route i when profile u is adopted in period 1, $\forall u \in Sech_i, \forall i \in \mathcal{R}$;

πS_{iu}^2 — the sailing speed (knot) of ships deployed on route i when profile u is adopted in period 2, $\forall u \in Sech_i, \forall i \in \mathcal{R}$;

g_{jiu}^1 — the bunker fuel consumption rate (ton/nm) of vessels from ship type j deployed on route i when profile u is adopted in period 1, $\forall j \in \mathcal{V}', \forall u \in Sech_i, \forall i \in \mathcal{R}$;

g_{jiu}^2 — the bunker fuel consumption rate (ton/nm) of vessels from ship type j deployed on route i when profile u is adopted in period 2, $\forall j \in \mathcal{V}', \forall u \in Sech_i, \forall i \in \mathcal{R}$;

Decision variables

ξ_{iu}^1 — binary variable, equal to 1 when profile n is adopted on route i in period 1, 0 otherwise, $\forall i \in \mathcal{R}, \forall u \in Sech_i$;

ξ_{iu}^2 — binary variable, equal to 1 when profile n is adopted on route i in period 2, 0 otherwise, $\forall i \in \mathcal{R}, \forall u \in Sech_i$;

The nonlinear model $[M2]$ can be rewritten as follows.

$$[\boldsymbol{M3}] \text{ minimize } \sum_{k \in \mathcal{S}'} \sum_{j \in \mathcal{V}'} \left(b_j + g'^j p_j\right) \omega_{kj} + \sum_{i \in \mathcal{R}} \sum_{u \in Sech_i^1} \xi_{iu}^1 \sum_{l \in \mathcal{G}} 26 \sum_{j \in \mathcal{V}'} \frac{GV_{lj} g_{jiu}^1 h_i p_j GN_{il}^1}{GNumS_{iu}^1} + \sum_{i \in \mathcal{R}} \sum_{u \in Sech_i^2} \xi_{iu}^2 \sum_{l \in \mathcal{G}} 26 \sum_{j \in \mathcal{V}'} \frac{GV_{lj} g_{jiu}^2 h_i p_j GN_{il}^2}{GNumS_{iu}^2} \tag{4.33}$$

subject to constraints (4.11), (4.12), (4.18), (4.21), (4.22), (4.23), (4.27), (4.28), (4.31), (4.32), and

$$\pi_k^1 = \sum_{i \in \mathcal{R}} \alpha_{ki}^1 \sum_{u \in Sech_i^1} \xi_{iu}^1 \pi S_{iu}^1, \forall k \in \mathcal{S}' \tag{4.34}$$

$$\pi_k^2 = \sum_{i \in \mathcal{R}} \alpha_{ki}^2 \sum_{u \in Sech_i^2} \xi_{iu}^2 \pi S_{iu}^2, \forall k \in \mathcal{S}' \tag{4.35}$$

$$\sum_{u \in Sech_i^1} \xi_{iu}^1 = 1, \forall i \in \mathcal{R} \tag{4.36}$$

$$\sum_{u \in Sech_i^2} \xi_{iu}^2 = 1, \forall i \in \mathcal{R} \tag{4.37}$$

$$\frac{\sum_{i\in\mathcal{R}} \sum_{u\in Sech_i^1} \frac{26}{GNnmS_{iu}^1} h_i \alpha_{ki}^1 \xi_{iu}^1 + \sum_{i\in\mathcal{R}} \sum_{u\in Sech_i^2} \frac{26}{GNnmS_{iu}^2} h_i \alpha_{ki}^2 \xi_{iu}^2}{\sum_{i\in\mathcal{R}} \sum_{u\in Sech_i^1} \frac{26}{GNumS_{iu}^1} \frac{h_i}{\pi S_{iu}^1} \alpha_{ki}^1 \xi_{iu}^1 + \sum_{i\in\mathcal{R}} \sum_{u\in Sech_i^2} \frac{26}{GNumS_u^i} \frac{h_i}{\pi S_{iu}^2} \alpha_{ki}^2 \xi_{iu}^2} \le \sum_{j\in\mathcal{V}'} \hat{\pi}_j \omega_{kj}, \quad \forall k \in S' \tag{4.38}$$

$$\sum_{l\in\mathcal{G}} GN_{il}^1 = \sum_{u\in Sech_i^1} \xi_{iu}^1 GNumS_{iu}^1, \forall i \in \mathcal{R} \tag{4.39}$$

$$\sum_{l\in\mathcal{G}} GN_{il}^2 = \sum_{u\in Sech_i^2} \xi_{iu}^2 GNumS_{iu}^2, \forall i \in \mathcal{R} \tag{4.40}$$

$$\xi_{iu}^1, \xi_{iu}^2 = 0, 1, \forall u \in Sech_i^1, Sech_i^2, \forall i \in \mathcal{R} \tag{4.41}$$

The model $[M3]$ still have nonlinear elements, namely products of decision variables, which can be linearized through a standard process. For the linearization details and the linear model $[M4]$ that finally obtained, please see Appendix E.

4.5 Numerical Experiments

Multiple numerical experiments were conducted to validate the model and the algorithm. The algorithm was programmed in C++ with Visual Studio 2021, and we used CPLEX 20.10 to solve $[M4]$ under various scenarios. Analysis on the impact of the shipping demand scenarios was also carried out. Computational experiments were conducted on a HP ENVY x360 Convertible 15-dr1xxx laptop with i7-10510U CPU, 2.30 GHz processing speed and 16 GB of memory.

4.5.1 Parameter Settings

In this section, we considered five different container shipping routes operated by the same shipping company. The sailing distances of each route are randomly generated between 3,000 and 8,000 nm. We consider the transporting demands, namely the largest capacity required along the round trip of a route, are different in two periods for the same route, ranging from 1,000 to 6,000 TEU. To meet the demands, three types of ships are available, namely vessels with the capacities of 2,000, 4,000, and 6,000 TEU. For the specific data, please refer to Appendix B. Following CSC's proposal for the speed limits, the annual average operating speed limits were set at 90% of the average operational speeds in 2015 (International Maritime Organization 2019b).

4.5.2 Results and Sensitivity Analysis

In the basic case, seven candidate vessel group types were enumerated to be deployed, and the detailed information is listed in Table 4.1.

Table 4.1: Candidate vessel groups in the basic case

Group No.	Capacity (TEU)	Number of ships			GS_{il}^1					GS_{il}^2				
		T1	T2	T3	R1	R2	R3	R4	R5	R1	R2	R3	R4	R5
1	6000	0	0	1	1	1	1	1	1	1	1	1	1	1
2	4000	0	1	0	0	1	1	1	0	1	0	0	1	1
3	8000	0	2	0	1	0	0	0	1	0	1	1	0	0
4	2000	1	0	0	0	1	0	0	0	0	0	0	1	1
5	6000	1	1	0	1	0	0	0	1	0	1	1	0	0
6	4000	2	0	0	0	0	1	1	0	1	0	0	0	0
7	6000	3	0	0	1	0	0	0	1	0	1	1	0	0

T1, T2, T3: The first, second, and third vessel type.
R1, R2, R3, R4, R5: The first to the fifth sailing route.

Given the groups in Table 4.1, numerical experiment of the basic case was conducted. It turns out that 23 ships are chartered to satisfy the shipping demands of the five routes, including fifteen ships from type 1, one ship from type 2, and seven ships from type 3, and the annual operating costs of 800,444,288 USD are incurred. Table 4.2 and Table 4.3 show the operation plans for different routes and deployment of chartered ships, respectively. Table 4.2 reveals that the deployment of vessel groups from different types are preferred under the regulation on annual average operational speed limit, which reflects the necessity of taking heterogeneous fleet into consideration. It is also shown in Table 4.3 that 20 out of 23 ships chartered are deployed on different routes in Perid 1 and Period 2. Besides, 13 ships sail faster than the annual average operational speed limit at one period, which indicates that the speed limit can be avoided by considering multiple deployment periods simultaneously.

Table 4.2: Operation plans for routes

Period	Route (i)	$GN_{il}^{1(2)}$							$\sum_{l\in\mathcal{G}} GN_{il}^{1(2)}$
		G1	G2	G3	G4	G5	G6	G7	
1	1	2	0	0	0	0	0	1	3
	2	0	0	0	5	0	0	0	5
	3	1	0	0	0	0	2	0	3
	4	1	1	0	0	0	1	0	3
	5	3	0	0	0	0	0	0	3
2	1	0	1	0	0	0	2	0	3
	2	5	0	0	0	0	0	0	5
	3	2	0	0	0	0	0	2	4
	4	0	0	0	3	0	0	0	3
	5	0	0	0	2	0	0	0	2

G1, G2, G3, G4, G5, G6, G7: The first to the seventh vessel group type.

For comparison, the ship deployment problem was also solved in a traditional method. For each period, the problem is equivalent to a traditional ship deployment with a sailing speed limit. The specific models for Period 1 and Period 2 and the solution method are displayed in Appendix E. The traditional method yielded an annual operating costs of $93, 8347, 456$ USD, which is 17.2% higher than that of the solution method developed in this paper. For the whole year, 22 ships are required, including six ships from Type 1, seven ships from Type 2, and nine ships from Type 3. Detailed ship deployment plan for each route of the traditional method are displayed in Table 4.4.

In practice, the seasonal changing pattern of transport demands depends on the area covered by a shipping route. For the shipping company that operate multiple routes, the gap between the total transport demand influences the ship chartering and deployment decisions. Thus, numerical experiments with different shipping demands were conducted to show the effectiveness of our model and solution method under

Table 4.3: Deployment situation of chartered ships

Ship (k)	Type (j)	Deployment 1	Deployment 2	π_k^1 (knot)	π_k^2 (knot)	Average speed (knot)
1	T1	R3	R4	13.35	9.47	11.34
2	T1	R2	R5	9.53	14.65	12.02
3	T1	R1	R4	14.51	9.47	11.32
4	T1	R4	R3	13.01	11.52	12.23
5	T1	R3	R1	13.35	9.88	11.70
6	T1	R4	R3	13.01	11.52	12.23
7	T1	R2	R5	9.53	14.65	12.02
8	T1	R1	R1	14.51	9.88	11.76
9	T1	R1	R1	14.51	9.88	11.76
10	T1	R2	R3	9.53	11.52	10.40
11	T1	R3	R1	13.35	9.88	11.70
12	T1	R3	R4	13.35	9.47	11.34
13	T1	N.A.	R3	N.A.	11.52	11.52
14	T1	R2	R3	9.53	11.52	10.40
15	T1	R2	R3	9.53	11.52	10.40
16	T2	R4	R1	13.01	9.88	11.33
17	T3	R3	R2	13.35	13.43	13.38
18	T3	R1	R3	14.51	11.52	12.77
19	T3	R1	R3	14.51	11.52	12.77
20	T3	R4	R2	13.01	13.43	13.22
21	T3	R5	R2	13.73	13.43	13.57
22	T3	R5	R2	13.73	13.43	13.57
23	T3	R5	R2	13.73	13.43	13.57

T1, T2, T3: The first, second, and third vessel type.
R1, R2, R3, R4, R5: The first to the fifth route.

Table 4.4: Operation plans for routes

Period	Route (i)	$GN_{il}^{1(2)}$							$\sum_{l \in \mathcal{G}} GN_{il}^{1(2)}$
		G1	G2	G3	G4	G5	G6	G7	
1	1	4	0	0	0	0	0	0	4
	2	0	0	0	4	0	0	0	4
	3	0	4	0	0	0	0	0	4
	4	0	2	0	0	0	0	0	2
	5	3	0	0	0	0	0	0	3
2	1	4	0	0	0	0	0	0	4
	2	0	0	0	4	0	0	0	4
	3	0	4	0	0	0	0	0	4
	4	0	2	0	0	0	0	0	2
	5	3	0	0	0	0	0	0	3

G1, G2, G3, G4, G5, G6, G7: The first to the seventh vessel group type.

various conditions. The specific demands considered are displayed in Table 4.5. In CBasic, Route 1, Route 4, and Route 5 have higher transportation demands in Period 2, and Route 2 and Route 3 are busier in Period 2. In Cw1, only Route 3 has higher demand in Period 2. In Cw2, all routes have higher demands in Period 2, making the total demands quite uneven between two periods. Results of these three cases are listed in Table 4.6 and Table 4.7.

Table 4.5: Transport demands in different cases

Case	Route (i)	w_i^1 (TEU)	t_i^1 (hour)	w_i^2 (TEU)	t_i^2 (hour)
CBasic	R1	5082	236.96	2356	111.84
	R2	1083	25.47	5879	261.65
	R3	2825	73.59	4650	173.37
	R4	3574	166.36	1440	40.29
	R5	4547	175.04	1041	27.65
Cw1	R1	4402	256.16	2016	51.74
	R2	4871	157.37	2188	103.63
	R3	2407	63.30	3286	150.10
	R4	3187	185.15	1368	46.09
	R5	5859	270.90	2581	107.40
Cw2	R1	5563	213.15	1078	74.88
	R2	3087	233.23	1695	113.46
	R3	5400	168.13	2802	122.77
	R4	4349	216.61	2396	41.26
	R5	3527	273.09	2981	68.65

R1, R2, R3, R4, R5: The first to the fifth route.
CBasic, Cw1, Cw2: The basic case, case with demand situation 1, and case with demand situation 2.

Table 4.6: Ship chartering plans of CBasic, Cw1, Cw2

Case	Our method					Traditional method					Gap
	Total costs (USD)	Chartered ships				Total costs (USD)	Chartered ships				
		T1	T2	T3	Total		T1	T2	T3	Total	
Cbasic	800,444,288	15	1	7	23	938,347,456	6	7	9	22	17.2%
Cw1	851,115,648	3	6	9	18	1,261,005,568	3	12	13	28	48.2%
Cw2	880,560,640	6	4	10	20	1,187,379,456	8	10	11	29	34.8%

T1, T2, T3: The first, second, and third ship type.

Table 4.7: Sailing speeds of ships in Cw1 and Cw2

Ship (k)	Cw1			Cw2		
	π_k^1 (knot)	π_k^2 (knot)	Average speed (knot)	π_k^1 (knot)	π_k^2 (knot)	Average speed (knot)
1	15.64	9.59	11.72	19.56	8	12.13
2	15.64	9.59	11.72	19.56	8	12.13
3	15.64	9.59	11.72	19.56	8	12.13
4	13.04	11.01	12.08	19.56	8	12.13
5	13.04	11.01	12.08	19.56	8	12.13
6	13.78	11.39	12.45	19.56	8	12.13
7	13.78	11.01	12.25	17.70	8.01	12.21
8	13.78	11.39	12.45	17.70	8.01	12.21
9	13.04	11.39	12.26	17.70	9.49	12.90
10	19.37	8.57	12.24	17.70	8.00	12.28
11	15.64	11.01	12.80	13.33	10.37	11.56
12	19.37	10.54	13.59	13.33	8.01	10.15
13	15.09	10.54	12.66	15.29	8.01	10.92
14	15.09	10.54	12.66	15.29	10.37	12.33
15	19.37	10.54	13.59	11.40	8.01	9.60
16	15.64	10.54	12.38	13.33	9.49	10.97
17	15.09	8.57	11.57	15.29	9.49	11.71
18	15.09	8.57	11.57	11.40	14.84	13.15
19	N.A.	N.A.	N.A.	11.40	14.84	13.15
20	N.A.	N.A.	N.A.	11.40	10.37	10.85

T1, T2, T3: The first, second, and third vessel type.
R1, R2, R3, R4, R5: The first to the fifth route.

Combining Table 4.6 and Table 4.7, we can see that there are two ways how our model and method further reduce the operating costs. The first way is replacing ship of larger capacity with multiple ships with smaller capacity, which are more flexible to deploy. In CBasic, for example, six ships from type 2 and two ships from type 3 are substituted by nine ships from type 1. By deploying these ships wisely, less ships are idling. In CBasic, only one ship is idling in Period 1 and all ships are deployed in Period 2. Meanwhile, in Cw1, three ships from type 1 and two ships from type 3 are idling in Period 1, and four ships from type 2 are idling in Period 2. Thus, chartering ships with smaller capacities avoids ship idling, and therefore reduces the total costs. The second way is deploying ships at different speeds to lower the total costs while obeying the annual average operational speed limits. In Cw1 and Cw2, as demonstrated in Table 4.7, ships are deployed at speeds higher than the annual average limits in one of the period, which lower the operational costs. Whilst, the lower sailing speed in the other period assures that the annual average operational speed does not exceeds the upper limit.

4.6 Conclusions

Environmental issues have been recognized as one of the priorities for the maritime industry. IMO aims high and sets the target to reduce the total GHG emissions from shipping by 50% on or before 2050, compared to 2008 levels. However, without more effective measures, the number is going to reach 90-130% in 2050, depending on economic and energy scenarios. Given the close relationship between operational speed and fuel consumption, slow steaming is one plausible breakthrough point. Sailing speed limit has been officially proposed to IMO as an immediate GHG emission reduction method that would contribute to the achievement of the IMO decarbonization target. From the ship operators' perspective, operational speed is a critical decision in ship operation, impacting greatly the total operation costs. Therefore, in this chapter, we originally investigate the ship deployment problem in liner shipping under annual average sailing speed limits.

In this study, a mixed-integer nonlinear programming model was proposed to describe the problem. Taking account of characteristics of liner shipping and the annual average speed limits, several commonly-seen assumptions were loosen, and a calendar year was separated into two periods in this model. Solution method based on the problem structure was proposed to handle the nonlinear parts and make the model computationally feasible. Numerical experiments were conducted to validate the model and solution method. Comparison between results yielded by our method and traditional method shows the necessity of this study. Detailed analysis was also conducted to show the effectiveness of our model under different transport demand situations.

Chapter 5

Summary and Future Research

5.1 Conclusions

This thesis focuses on the ship emission reduction measures, namely promoting LNG as alternative marine fuel, METS, and ship sailing speed limits. Problems confronting both the government and the shipping industry are explored. The main part of the thesis is comprised of three studies.

The first study investigated the government subsidy optimization problem for promoting LNG as marine fuel, in which subsidy amount for ports and shipping companies are decided. Two-stage subsidy methods were originally proposed in this study, namely giving subsidy to port or ship at first and then subsidize the other party. Different from existing papers, the analytical solution to the problem was obtained to better demonstrate the logic between the subsidy plan the LNG promotion outcome. Based on the results, we also explore the optimal LNG bunkering price that can maximize the promotion effect. Influence of the LNG purchasing price for ports and the MDO bunkering price on the optimal LNG bunkering price were also analyzed. It is revealed that the analytical analyses and the logic intuition corroborate each other.

In the second study, the ship operation and allowance management problem in liner shipping under the maritime emission trading system was investigated. Sailing speed optimization and the characteristics of the METS were well-integrated into the model, including various carbon allowance sources (free, auctioned, open carbon market), penalties for not surrendering enough allowances to cover the emissions from the route, and the decreasing rate of free allowances from the competent authority. A stochastic model considering uncertain market carbon price is originally developed to obtain a ship operation and allowance management plan that minimizes the total operating costs. Based on the structure of the problem, the model was converted into a deterministic linear form, after which abundant numerical experiments were conducted to validate the model solution method. Results demonstrate the necessity of this study and analyses provide insightful managerial insights. Impacts of the initial market carbon price and the changing pattern of the market price were demonstrated, and the influences become more complicated when the allowance quotas decrease to a very low level. Besides, heterogeneous fleets are preferred to balance the bunker costs, chartering costs, and carbon cost sunder certain scenarios, which is uncommon in traditional ship deployment problems.

In the third study, the ship deployment problem in liner shipping under annual average sailing speed limits was studied. Different from previous papers on this topic, this study focuses on the ship deployment problem of a liner shipping company in two consecutive periods that compose a calendar year. Adapting to the annual average operational speed limits, some assumptions commonly-seen in ship deployment problems were loosen in the mixed-integer nonlinear programming model we originally proposed. Based on the problem structure, a solution method was developed to handle the nonlinear elements and make the model computationally feasible. Numerical experiments conducted validate the model and solution method. Comparison between results yielded by our method and traditional method validates out model and indicates the necessity of this study. Sensitive analysis regarding transport demand situation was also conducted to show the superiority of our model under various scenarios.

Overall, this thesis provides solutions to management problems faced by the government and ship operators in the implementation of three critical shipping emission reduction measures. Ship operators are provided with managerial insights under the emission reduction trend. The government, on the other hand, obtains suggestions on how to design the specific details of those measures. Together, this thesis gives suggestions on emission reduction measure implementation and estimation of the shipping industry's reactions.

5.2 Future Research

Given the three studies in the thesis, there are several future research directions that can be explored.

In the first study, we consider two-stage subsidy plan, and in further research, more flexible subsidy plans could be considered to better reflect the interrelationship between ports and ships in LNG promotion and further reduce the total subsidy amount. Moreover, the LNG supply chain can be extended. For example, in practice, the refueling of LNG storage tanks and the construction of other infrastructure facilities at port side are closely related to the promotion effect, and these factors can be integrated into the model.

For the second study, the following directions could be followed. First, the uncertainty of the market carbon price could be better captured and analyzed. Second, in this study, we considered one liner shipping route. The problem faced by shipping companies operating multiple routes or even shipping alliances would be interesting to investigate. Third, other uncertain elements, for example the stochastic freight rate, can be considered, too. Fourth, this study was conducted with an open carbon market, and METS design considering the reactions of all shipping companies in a closed carbon market can provide constructive managerial insights for the competent department.

In the third study, we did not include the influence of sailing speed on the liner shipping service level and transportation demand. In future research, these impacts can be integrated into the problem. Besides, a calendar year was divided into two periods in this study, but ships might be redeployed three or four times in a year in practice. Thus, ship deployment optimization for more periods can be investigated. Lastly, this study did not consider liner ship routing, which is also a critical management problem in liner shipping. Models integrating ship deployment and routing problem worth in depth research.

In addition to the measures discussed in this thesis, other emission reduction measures are also worth investigation. Hydrogen, for example, is a clean energy source to be adopted as alternative fuel in maritime, which can almost eliminate the problem of ship emissions once implemented. Besides, electric ships are promising solution to the air pollution of shipping. Studies regarding these measures and technologies will make a breakthrough in ship emission reduction.

Appendix A

Linearization of model $[M2]$ in Chapter 3

Model $[M2]$ can be linearized with the help of following new decision variables and parameters.

Decision variable

ϕ_{ms}	the total cost in period m under scenario s, $m = 1, ..., M$, $\forall s \in S_\eta$.
β_{ms}^{Auc}	the product of $\alpha_{ms}^{\text{Auc}}$and ξ_{ms} $m = 1, ..., M, \forall s \in S_\eta$;
β_{ms}^{Pur}	the product of $\alpha_{ms}^{\text{Pur}}$and ξ_{ms} $m = 1, ..., M, \forall s \in S_\eta$;
β_{ms}^{Sold}	the product of $\alpha_{ms}^{\text{Sold}}$and ξ_{ms} $m = 1, ..., M, \forall s \in S_\eta$;
β_{ms}^{Sur}	the product of $\alpha_{ms}^{\text{Sur}}$and ξ_{ms} $m = 1, ..., M, \forall s \in S_\eta$;
β_{ms}^{W}	the product of $\alpha_{ms}^{\text{W}}$and ξ_{ms} $m = 1, ..., M, \forall s \in S_\eta$.

Parameter

$\bar{c}^{\text{Ch}}$	the largest value of c_j^{Ch};
$\bar{c}^{\text{Bun}}$	the largest value of c_j^{Bun};
$\bar{q}(\pi_s^*)$	the largest value of $q^j(\pi)$ when solution s is adopted, $\forall s \in S_\eta$;
$\bar{g}(\pi_s^*)$	the largest value of $g^j(\pi)$ when solution s is adopted, $\forall s \in S_\eta$;

Max_s^{E} parameter that is large enough, the specific value equals

$$52\bar{g}\left(\pi_s^*\right)\sum_{i\in\mathcal{P}} l_i$$

$\forall s \in S_\eta$;

Max_s^{TC} the upper bound of total cost in a period;

Min_s^{TC} the lower bound of total cost in a period;

Max_{ms}^{Auc} the upper bound of $\beta\mathrm{Auc}_{ms}$;

Max_{ms}^{Pur} the upper bound of $\beta\mathrm{Pur}_{ms}$;

Max_{ms}^{Sold} the upper bound of $\beta\mathrm{Sold}_{ms}$;

Max_{ms}^{Sur} the upper bound of $\beta\mathrm{Sur}_{ms}$;

Max_{ms}^{W} the upper bound of $\beta\mathrm{W}_{ms}$.

$$[\boldsymbol{M2'}] \ \text{minimize} \sum_{m=1}^{M}\sum_{s\in S_\eta}\phi_{ms} \tag{A.1}$$

subject to constraints (3.3), (3.4), (3.7), (3.9)–(3.22) and

$$52\frac{\sum_{j\in\mathcal{V}}\eta_{ms}^j g^j\left(\pi_s^*\right)\sum_{i\in\mathcal{P}} l_i}{\eta_s^*} \geq \alpha_{ms}^{\mathrm{Sur}} - \left(1-\xi_{ms}\right) Max_s^{\mathrm{E}} \tag{A.2}$$

$$Min_s^{\mathrm{TC}} \leq \xi_{ms}\phi_{ms} \leq Max_s^{\mathrm{TC}}\xi_{ms}, m = 1, ..., M, \forall s \in S_\eta \tag{A.3}$$

$$\begin{aligned}\phi_{ms} \leq \sum_{j\in\mathcal{V}} 52\left[c_j^{\mathrm{Ch}}\eta_{ms}^j + \frac{c_j^{\mathrm{Bun}}\eta_{ms}^j q^j\left(\pi_s^*\right)\sum_{i\in\mathcal{P}} l_i}{\eta_s^*}\right] + k^{\mathrm{U}}\alpha_{ms}^{\mathrm{Auc}} + \tilde{k}_m^{\mathrm{Mar}}\left(\alpha_{ms}^{\mathrm{Pur}} - \alpha_{ms}^{\mathrm{Sold}}\right)\\ + Pen\left(52\frac{\sum_{j\in\mathcal{V}}\eta_{ms}^j g^j\left(\pi_s^*\right)\sum_{i\in\mathcal{P}} l_i}{\eta_s^*} - \alpha_{ms}^{\mathrm{Sur}}\right), m = 1, ..., M, \forall s \in S_\eta\end{aligned} \tag{A.4}$$

$$\phi_{ms} \geq \sum_{j\in\mathcal{V}} 52\left[c_j^{\mathrm{Ch}}\eta_{ms}^j + \frac{c_j^{\mathrm{Bun}}\eta_m^j q^j\left(\pi_s^*\right)\sum_{i\in\mathcal{P}} l_i}{\eta_s^*}\right] + k^{\mathrm{U}}\alpha_{ms}^{\mathrm{Auc}} + \tilde{k}_m^{\mathrm{Mar}}\left(\alpha_{ms}^{\mathrm{Pur}} - \alpha_{ms}^{\mathrm{Sold}}\right)$$

$$+Pen\left(52\frac{\sum_{j\in\mathcal{V}}\eta_{ms}^{j}g^{j}(\pi_s^*)\sum_{i\in\mathcal{P}}l_i}{\eta_s^*}-\alpha_{ms}^{\text{Sur}}\right)-Max_s^{\text{TC}}\left(1-\xi_{ms}\right), m=1,...,M, \forall s\in S_\eta \tag{A.5}$$

$$\beta_{ms}^{\text{Auc}}\leq Max_{ms}^{\text{Auc}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.6}$$

$$\beta_{ms}^{\text{Auc}}\leq \alpha_{ms}^{\text{Auc}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.7}$$

$$\beta_{ms}^{\text{Auc}}\geq \alpha_{ms}^{\text{Auc}}-Max_{ms}^{\text{Auc}}\left(1-\xi_{ms}\right)\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.8}$$

$$0\leq\beta_{ms}^{\text{Auc}}\leq Max_{ms}^{\text{Auc}}, m=1,...,M, \forall s\in S_\eta \tag{A.9}$$

$$\beta_{ms}^{\text{Pur}}\leq Max_{ms}^{\text{Pur}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.10}$$

$$\beta_{ms}^{\text{Pur}}\leq \alpha_{ms}^{\text{Pur}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.11}$$

$$\beta_{ms}^{\text{Pur}}\geq \alpha_{ms}^{\text{Pur}}-Max_{ms}^{\text{Pur}}\left(1-\xi_{ms}\right)\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.12}$$

$$0\leq\beta_{ms}^{\text{Pur}}\leq Max_{ms}^{\text{Pur}}, m=1,...,M, \forall s\in S_\eta \tag{A.13}$$

$$\beta_{ms}^{\text{Sold}}\leq Max_{ms}^{\text{Sold}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.14}$$

$$\beta_{ms}^{\text{Sold}}\leq \alpha_{ms}^{\text{Sold}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.15}$$

$$\beta_{ms}^{\text{Sold}}\geq \alpha_{ms}^{\text{Sold}}-Max_{ms}^{\text{Sold}}\left(1-\xi_{ms}\right)\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.16}$$

$$0\leq\beta_{ms}^{\text{Sold}}\leq Max_{ms}^{\text{Sold}}, m=1,...,M, \forall s\in S_\eta \tag{A.17}$$

$$\beta_{ms}^{\text{Sur}}\leq Max_{ms}^{\text{Sur}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.18}$$

$$\beta_{ms}^{\text{Sur}}\leq \alpha_{ms}^{\text{Sur}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.19}$$

$$\beta_{ms}^{\text{Sur}}\geq \alpha_{ms}^{\text{Sur}}-Max_{ms}^{\text{Sur}}\left(1-\xi_{ms}\right)\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.20}$$

$$0\leq\beta_{ms}^{\text{Sur}}\leq Max_{ms}^{\text{Sur}}, m=1,...,M, \forall s\in S_\eta \tag{A.21}$$

$$\beta_{ms}^{\text{W}}\leq Max_{ms}^{\text{W}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.22}$$

$$\beta_{ms}^{\text{W}}\leq \alpha_{ms}^{\text{W}}\xi_{ms}, m=1,...,M, \forall s\in S_\eta \tag{A.23}$$

$$\beta_{ms}^{\mathrm{W}} \geq \alpha_{ms}^{\mathrm{W}} - Max_{ms}^{\mathrm{W}} \left(1 - \xi_{ms}\right) \xi_{ms}, m = 1, ..., M, \forall s \in S_{\eta} \tag{A.24}$$

$$0 \leq \beta_{ms}^{\mathrm{W}} \leq Max_{ms}^{\mathrm{W}}, m = 1, ..., M, \forall s \in S_{\eta} \tag{A.25}$$

$$0 \leq \phi_{ms} \leq Max_{s}^{\mathrm{TC}}, m = 1, ..., M, \forall s \in S_{\eta}. \tag{A.26}$$

Appendix B

The model of $CWithout$ in Chapter 3

$$[\boldsymbol{MW}] \;\; \text{minimize} \sum_{s \in S_\eta} \xi_s \sum_{j \in \mathcal{V}} 52 \left[c_j^{\text{Ch}} \eta_s^j + \frac{c_j^{\text{Bun}} \eta_s^j q^j(\pi_s^*) \sum_{i \in \mathcal{P}} l_i}{\eta_s^*} \right] \tag{B.1}$$

subject to

$$\sum_{s \in S_\eta} \xi_m = 1, \tag{B.2}$$

$$\eta_s^* = \sum_{j \in \mathcal{V}} \eta_{ms}^j, \forall s \in S_\eta \tag{B.3}$$

$$\eta_s^j = 0, 1, \forall j \in \mathcal{V}, \forall s \in S_\eta \tag{B.4}$$

$$\xi_s = 0, 1, \forall s \in S_\eta. \tag{B.5}$$

Appendix C

Model linearization of $[M3]$ in Chapter 4

The nonlinear elements exist in both the objective function and constraints of $[M3]$, namely $\xi^1_{iu} \times GN^1_{il}$ and $\xi^2_{iu} \times GN^2_{il}$ in the objective function (4.33), $\alpha^1_{ki} \times \xi^1_{iu}$ and $\alpha^2_{ki} \times \xi^2_{iu}$ in constraints (4.34) (4.35) (**??**) and (**??**), and $\alpha^1_{ki} \times \xi^1_{iu} \times \omega_{kj}$ and $\alpha^2_{ki} \times \xi^2_{iu} \times \omega_{kj}$ in constraints (4.38). The following variables are introduced to linearize the model.

Parameters

$M^{\max 1}_i$	the upper bound of GN^1_{il}, equals $\lceil \frac{h_i}{168\pi} + \frac{t^1_i}{168} \rceil, \forall i \in \mathcal{P}, \forall l \in \mathcal{G}$;
$M^{\max 2}_i$	the upper bound of GN^2_{il}, equals $\lceil \frac{h_i}{168\pi} + \frac{t^2_i}{168} \rceil, \forall i \in \mathcal{P}, \forall l \in \mathcal{G}$;

Decision variables

β^1_{iul}	variable introduced to linearize the objective function (4.33), $\beta^1_{iul} = GN^1_{il}\xi^1_{iu}, \forall i \in \mathcal{S}', \forall u \in Sech_i, \forall l \in \mathcal{G}$;
β^2_{iul}	variable introduced to linearize the objective function (4.33), $\beta^2_{iul} = GN^2_{il}\xi^2_{iu}, \forall i \in \mathcal{S}', \forall u \in Sech_i, \forall l \in \mathcal{G}$;
γ^1_{kiu}	binary variable introduced to linearize constraints (4.34) (**??**) and (4.38), $\gamma^1_{kiu} = \alpha^1_{ki}\xi^1_{iu}, \forall k \in \mathcal{S}', \forall i \in \mathcal{R}, \forall u \in Sech_i$;
γ^2_{kiu}	binary variable introduced to linearize constraints (4.35) (**??**) and (4.38), $\gamma^2_{kiu} = \alpha^2_{ki}\xi^2_{iu}, \forall k \in \mathcal{S}', \forall i \in \mathcal{R}, \forall u \in Sech_i$;

δ^1_{ijk} binary variable introduced to linearize constraints (4.27), $\delta^1_{ijk} = \omega_{kj}\alpha^1_{ki}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}'$;

δ^2_{ijk} binary variable introduced to linearize constraints (4.28), $\delta^2_{ijk} = \omega_{kj}\alpha^2_{ki}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}'$;

ϕ^1_{ijku} binary variable introduced to linearize constraints (4.38), $\phi^1_{ijku} = \alpha^1_{ki}\xi^1_{iu}\omega^1_{kj}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech_i$;

ϕ^2_{ijku} binary variable introduced to linearize constraints (4.38), $\phi^2_{ijku} = \alpha^2_{ki}\xi^2_{iu}\omega^2_{kj}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech_i$;

Then, $[M3]$ can be rewritten into a linear model as follows.

$$[\boldsymbol{M4}] \text{ minimize } \sum_{k\in\mathcal{S}'}\sum_{j\in\mathcal{V}'}\left(b_j + g'^j p_j\right)\omega_{kj} + \sum_{i\in\mathcal{R}}\sum_{u\in Sech^1_i}\sum_{l\in\mathcal{G}} 26 \sum_{j\in\mathcal{V}'} \frac{GV_{lj}g^1_{jiu}h_i p_j \beta^1_{iul}}{GNumS^1_{iu}} + \sum_{i\in\mathcal{R}}\sum_{u\in Sech^2_i}\sum_{l\in\mathcal{G}} 26 \sum_{j\in\mathcal{V}'} \frac{GV_{lj}g^2_{jiu}h_i p_j \beta^2_{iul}}{GNumS^2_{iu}} \tag{C.1}$$

subject to constraints (4.11), (4.12), (4.18), (4.21), (4.22), (4.23), (4.31), (4.32), (4.36), (4.37), (4.39), (4.40), (4.41) and

$$\pi^1_k = \sum_{i\in\mathcal{R}}\sum_{u\in Sech^1_i} \gamma^1_{kiu}\pi S^1_{iu}, \forall k \in \mathcal{S}' \tag{C.2}$$

$$\pi^2_k = \sum_{i\in\mathcal{R}}\sum_{u\in Sech^2_i} \gamma^2_{kiu}\pi S^2_{iu}, \forall k \in \mathcal{S}' \tag{C.3}$$

$$\sum_{k\in\mathcal{S}'}\delta^1_{ijk} = \sum_{l\in\mathcal{G}} GV_{lj}GN^1_{il}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}' \tag{C.4}$$

$$\sum_{k\in\mathcal{S}'}\delta^2_{ijk} = \sum_{l\in\mathcal{G}} GV_{lj}GN^2_{il}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}' \tag{C.5}$$

$$\sum_{i\in\mathcal{R}}\sum_{u\in Sech^1_i}\frac{26}{GNnmS^1_{iu}}h_i\gamma^1_{kiu} + \sum_{i\in\mathcal{R}}\sum_{u\in Sech^2_i}\frac{26}{GNnmS^2_{iu}}h_i\gamma^2_{kiu}$$

$$-\left(\sum_{j\in\mathcal{V}'}\sum_{i\in\mathcal{R}}\sum_{u\in Sech_i^1}\frac{26}{GNumS_{iu}^1}\frac{h_i}{\pi S_{iu}^1}\hat{\pi}_j\phi_{ijku}^1+\sum_{j\in\mathcal{V}'}\sum_{i\in\mathcal{R}}\sum_{u\in Sech_i^2}\frac{26}{GNumS_{iu}^2}\frac{h_i}{\pi S_{iu}^2}\hat{\pi}_j\phi_{ijku}^2\right)\leq 0,$$

$$\forall k\in\mathcal{S}' \tag{C.6}$$

$$\beta_{iul}^1\leq GN_{il}^1,\forall i\in\mathcal{R},\forall u\in Sech_i^1,\forall l\in\mathcal{G} \tag{C.7}$$

$$\beta_{iul}^1\geq GN_{il}^1-M_i^{\max 1}\left(1-\xi_{iu}^1\right),\forall i\in\mathcal{R},\forall u\in Sech_i^1,\forall l\in\mathcal{G} \tag{C.8}$$

$$0\leq\beta_{iul}^1\leq M_i^{\max 1}\xi_{iu}^1,\forall i\in\mathcal{R},\forall u\in Sech_i^2,\forall l\in\mathcal{G} \tag{C.9}$$

$$\beta_{iul}^2\leq GN_{il}^2,\forall i\in\mathcal{R},\forall u\in Sech_i^2,\forall l\in\mathcal{G} \tag{C.10}$$

$$\beta_{iul}^2\geq GN_{il}^2-M_i^{\max 2}\left(1-\xi_{iu}^2\right),\forall i\in\mathcal{R},\forall u\in Sech_i^2,\forall l\in\mathcal{G} \tag{C.11}$$

$$0\leq\beta_{iul}^2\leq M_i^{\max 2}\xi_{iu}^2,\forall i\in\mathcal{R},\forall u\in Sech_i^2,\forall l\in\mathcal{G} \tag{C.12}$$

$$\gamma_{kiu}^1\leq\alpha_{ki}^1,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^1 \tag{C.13}$$

$$\gamma_{kiu}^1\leq\xi_{iu}^1,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^1 \tag{C.14}$$

$$\gamma_{kiu}^1\geq\alpha_{ki}^1+\xi_{iu}^1-1,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^1 \tag{C.15}$$

$$\gamma_{kiu}^2\leq\alpha_{ki}^2,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^2 \tag{C.16}$$

$$\gamma_{kiu}^2\leq\xi_{iu}^2,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^2 \tag{C.17}$$

$$\gamma_{kiu}^2\geq\alpha_{ki}^2+\xi_{iu}^2-1,\forall k\in\mathcal{S}',\forall i\in\mathcal{R},\forall u\in Sech_i^2 \tag{C.18}$$

$$\delta_{ijk}^1\leq\omega_{kj},\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.19}$$

$$\delta_{ijk}^1\leq\alpha_{ki}^1,\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.20}$$

$$\delta_{ijk}^1\geq\omega_{kj}+\alpha_{ki}^1-1,\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.21}$$

$$\delta_{ijk}^2\leq\omega_{kj},\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.22}$$

$$\delta_{ijk}^2\leq\alpha_{ki}^2,\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.23}$$

$$\delta_{ijk}^2\geq\omega_{kj}+\alpha_{ki}^2-1,\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}' \tag{C.24}$$

$$\phi_{ijku}^1\leq\alpha_{ki}^1,\forall i\in\mathcal{R},\forall j\in\mathcal{V}',\forall k\in\mathcal{S}',\forall u\in Sech_i^1 \tag{C.25}$$

$$\phi^1_{ijku} \leq \xi^1_{iu}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^1_i \tag{C.26}$$

$$\phi^1_{ijku} \leq \omega^1_{kj}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^1_i \tag{C.27}$$

$$\phi^1_{ijku} \geq \alpha^1_{ki} + \xi^1_{iu} + \omega^1_{kj} - 2, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^1_i \tag{C.28}$$

$$\phi^2_{ijku} \leq \alpha^2_{ki}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^2_i \tag{C.29}$$

$$\phi^2_{ijku} \leq \xi^2_{iu}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^2_i \tag{C.30}$$

$$\phi^2_{ijku} \leq \omega^2_{kj}, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^2_i \tag{C.31}$$

$$\phi^2_{ijku} \geq \alpha^2_{ki} + \xi^2_{iu} + \omega^2_{kj} - 2, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall u \in Sech^2_i \tag{C.32}$$

$$\gamma^1_{kiu}, \gamma^2_{kiu}, \phi^1_{ijkl}, \phi^2_{ijkl} = 0, 1, \forall i \in \mathcal{R}, \forall j \in \mathcal{V}', \forall k \in \mathcal{S}', \forall l \in \mathcal{G}, \forall u \in Sech^1_i, Sech^2_i. \tag{C.33}$$

Appendix D

Parameters in the Basic Numerical Experiment in Chapter 4

Table D.1: Parameters regarding sailing routes

Route No. (i)	h_i (mn)	W_i^1 (TEU)	W_i^2 (TEU)	t_i^1 (hour)	t_i^2 (hour)	t_i^2 (hour)
1	3876	5082	2356	236.96	111.84	
2	7765	1083	5879	25.47	261.65	
3	5746	2825	4650	73.59	173.37	
4	4393	3574	1440	166.36	40.29	
5	4516	4547	1041	175.04	27.65	

T1, T2, T3: The first, second, and third vessel type.
R1, R2, R3, R4, R5: The first to the fifth sailing route.

Table D.2: Parameters regarding ship types

Type No. (j)	c_j (TEU)	b_j (USD/year)	$\hat{\pi}_j$ (knot)	g'^j (ton/year)	p_j^{ref} (kWh)	v_j^{ref} (knot)
1	2,000	21,900,000	12.24	962.21	12083	21.1
2	4,000	40,150,000	13.32	1,202.31	34559	23.55
3	6,000	47,450,000	13.752	1,452.27	48064.25	24.3

T1, T2, T3: The first, second, and third vessel type.
R1, R2, R3, R4, R5: The first to the fifth sailing route.

Appendix E

Model for Single Period of the Ship Deployment Problem in Chapter 4

The model for Period 1, denoted as $[MT1]$, is listed as follows.

$$[\boldsymbol{MT1}] \quad \text{minimize} \sum_{k\in\mathcal{S}'}\sum_{j\in\mathcal{V}'}\left(b_j + g'^j p_j\right)\omega_{kj} + \sum_{i\in\mathcal{R}}\sum_{u\in Sech_i^1}\sum_{l\in\mathcal{G}} 52 \sum_{j\in\mathcal{V}'} \frac{GV_{lj} g_{jiu}^1 h_i p_j \beta_{iul}^1}{GNumS_{iu}^1} \tag{E.1}$$

subject to constraints (4.11), (4.18), (4.21), (4.22), (4.31), (4.32), (4.36), (4.39), (4.41), (C.2), (C.4), (C.7), (C.8), (C.9), (C.13), (C.14), (C.15), (C.20), (C.21), (C.25), (C.26), (C.27), (C.28), (C.33) and

$$\pi_k^1 \le \sum_{j\in\mathcal{V}'} \hat{\pi}_j \omega_{kj}, \forall k \in \mathcal{S}'. \tag{E.2}$$

The model for Period 2, denoted by $[MT2]$, is similar to $[MT1]$.

Before the specific solution method are some notations that will be used for better understanding.

Parameters

$FixedC_j$	the annual fixed costs of a ship from type j, $\forall j \in \mathcal{V}$, equals the ship chartering costs and auxiliary engine costs;

Decision variables

$OptValT$	the optimal objective value(USD);
$ObjValT^1$	the optimal objective value of $[MT1]$ (USD);
$ObjValT^2$	the optimal objective value of $[MT2]$ (USD);
$MECost^1$	the main engine costs of Period 1 (USD);
$MECost^2$	the main engine costs of Period 2 (USD);
$ShipN_j$	number of chartered ships from type j, $\forall j \in \mathcal{V}$;
$ShipN_j^1$	number of deployed ships from type j in period 1, $\forall j \in \mathcal{V}$;
$ShipN_j^2$	number of deployed ships from type j in period 2, $\forall j \in \mathcal{V}$;

Algorithm 1 Solving the problem without combing Period 1 and Period 2

Output: $OptValT$, $ShipN_j$;

1: Initialization: initial variables $ShipN_j^1, ShipN_j^2 = 0, j = 1, ..., |\mathcal{V}|$, initial solution $OptValT, ObjValT^1, ObjValT^2 = 0$, $ShipN_j, j = 1, ..., |\mathcal{V}|$.

2: Solve $[MT1]$, obtain $ObjValT^1$, $ShipN_j^1$, and $MECost^1 = ObjValT^1 - \sum_{j\in\mathcal{V}} FixedC_j ShipN_j^1$.

3: Solve $[MT2]$, obtain $ObjValT^2$, $ShipN_j^2$, and $MECost^2 = ObjValT^2 - \sum_{j\in\mathcal{V}} FixedC_j ShipN_j^2$.

4: Calculate the optimal solution: $ShipN_j = \max\left\{ShipN_j^1, ShipN_j^2\right\}, j = 1, ..., |\mathcal{V}|$, $OptValT = \frac{MECost^1 + MECost^2}{2} + \sum_{j\in\mathcal{V}} FixedC_j ShipN_j$.

5: **return** $OptValT$ and $ShipN_j$.

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