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Container fleet renewal considering multiple sulfur reduction technologies and uncertain markets amidst COVID-19

Yuzhe Zhao^a, Jiajun Ye^a, Jingmiao Zhou^{a,b,*}

^a Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian, China

^b Business School, Dalian University of Foreign Languages, Dalian, China

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ABSTRACT

The onset of 2020 is marked by stricter restrictions on maritime sulfur emissions and the spread of Coronavirus Disease 2019 (COVID-19). In this background, liner companies now face the challenge to find suitable sulfur reduction technologies, make reasonable decisions on fleet renewal, and prepare stable operation plans under the highly uncertain shipping market. Considering three sulfur reduction technologies, namely, fuel-switching, scrubber, and liquefied natural gas (LNG) dual-fuel engine, this paper develops a robust optimization model based on two-stage stochastic linear programming (SLP) to formulate a decision plan for container fleet, which can deal with various uncertainties in future: freight demand, ship charter rate, fuel price, retrofit time and Sulfur Emission Control Area (SECA) ratio. The main decision contents include ship acquisition, ship retrofit, ship sale, ship charter, route assignment, and speed optimization. The effectiveness of our plan was verified through a case study on two liner routes from the Far East to Northwest America, operated by COSCO Shipping Lines. The results from SLP model show that large-capacity fuel-switching ships and their LNG dual-fuel engine retrofits should be included in the long-term investment and operation plan; slow-steaming is an important operational decision for ocean liner shipping; if the current SECA boundary is not further expanded or the sulfur emission restrictions not further tightened, the scrubber ship will have no advantage in investment cost and operation. However, considering the probabilities of more flexible scenarios, the results from the robust model suggest that it is beneficial to install scrubber on medium-capacity fuel-switching ships, and carry out more LNG dual-fuel engine retrofits for large-capacity fuel-switching ships. Compared with SLP, this robust strategy greatly reduces sulfur emissions while slightly pushing up carbon emissions.

1. Introduction

1.1. Background

The International Maritime Organization (IMO) stipulates that, starting from January 1, 2020, all ships sailing in the global seas must not use fuels with a sulfur content greater than 0.5% m/m (International Maritime Organization IMO, 2018), barring the direct use of heavy fuel oil (HFO) with a sulfur content of 3.5% in the global waters. To meet the latest regulation, shipping companies must select suitable new sulfur reduction technologies for the normal operation of their fleet (Zhao et al., 2021).

There are four sulfur reduction technologies to choose from: fuel-switching, scrubber, liquefied natural gas (LNG) dual-fuel engine, and clean energies. Fuel-switching refers to the use of marine gas oil (MGO)

with a sulfur content no more than 0.1% m/m in the Sulfur Emission Control Area (SECA), and low sulfur fuel oil (LSFO) with a sulfur content within 0.5% m/m navigating in global seas. Scrubber needs to be installed on the ship, making it possible to use HFO with a sulfur content of 3.5% m/m throughout the journey. LNG dual-fuel engine requires retrofitting of the ship, changing the power source to LNG. Clean energies, namely, methanol, can fuel ship operations, once the corresponding power equipment is in place. Among the four technologies, fuel-switching, scrubber, and LNG dual-fuel engine have gained popularity for their strong feasibility, and are considered the main technologies in this research (Fig. 1). In practice, the three technologies bring different investment and operating costs, causing shipping companies to make different plans for fleet renewal and operation. In 2021, the use of scrubbers and clean energies account for 30% and 32% of deadweight tons (dwt) ordered, respectively (Clarksons, 2021). Among clean

* Corresponding author. Collaborative Innovation Center for Transport Studies, Dalian Maritime University, Dalian, China.

E-mail addresses: zhaoyuzhe@dmlu.edu.cn (Y. Zhao), yejiajun0940@163.com (J. Ye), zhoujingmiao123@163.com (J. Zhou).

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energies, nearly 60% (59.1%) of deadweight tons are for LNG capable ships. Fuel-switching ships remain the most commonly chosen option. Therefore, it is critical for shipping companies to choose the most suitable sulfur reduction technology for the specific type of ship.

Meanwhile, the outbreak of Coronavirus Disease 2019 (COVID-19) has severely suppressed the world's container trade volume in 2020. The growth of the container trade volume is expected to slow down and even turn negative (Fig. 2). Moreover, the global container freight demand faces an uncertain future, owing to the country/regional disparity in COVID-19 control. In fact, many shipyards were completely or partially closed under COVID-19, leading to a decrease in shipbuilding capacity and an inevitably delay in the installation of ship sulfur reduction technologies (Nikos, 2020). Moreover, fuel price and charter rate have always been fluctuating over time. By contrast, the liner shipping business of shipping companies is highly certain: container ships must call at fixed ports, and collect fixed freight along fixed routes under a fixed schedule. Amidst the uncertain market of liner shipping, liner companies need to realistically control their own operational risks by identifying proper fleet size and mix and preparing a reliable and stable operation plan.

For the above reasons, this paper attempts to solve the maritime fleet renewal problem (MFRP) through the selection between multiple sulfur reduction technologies, considering the market uncertainty of liner shipping. Besides, two liner routes from the Far East to Northwest America, operated by COSCO Shipping Lines (COSCO-Liner), were chose for verification and analysis, under the background of COVID-19.

1.2. Research scope, goals, and contributions

With the emergence of more and more sulfur reduction technologies, shipping companies have the opportunity to consider various technical alternatives for the MFRP, rather than arrange a single sulfur reduction technology for ships. This requires more consideration of the investment and operating costs of different sulfur reduction technologies, and their retrofit feasibility in fleet renewal. To better reflect the reality, more

kinds of future uncertainties must be taken into account. In addition to the uncertainties of fuel price, the solving model should cover such parameters as freight demand, ship charter rate and retrofit time.

This paper makes three main contributions: (i) A two-stage stochastic linear programming (SLP) model was established to solve the MFRP; On this basis, a robust optimization model was further developed considering the probabilities of several possible scenarios. (ii) To the best of our knowledge, this is the MFRP research that addresses fleet renewal planning amidst COVID-19, under the various uncertainties in liner shipping market, e.g., maritime freight demand, ship charter rate, fuel price, and retrofit time. Based on the current situation of the liner shipping market and the actual needs of liner companies, the mathematical model also integrates the decision of container ship retrofit for multiple sulfur reduction technologies. (iii) The tools for MFRP research were verified and updated, enabling liner companies to better cope with a series of future uncertainties. In the end, the coping strategies and the associated environmental impacts was discussed for the stricter sulfur reduction restrictions, and the trend of liner shipping market under the background of COVID-19 was fully considered in the scenario construction.

Our research ruminates over the uncertainties in liner shipping market, and enriches the technical alternatives for sulfur reduction. The research results are expected to help liner companies improve their long-term investment and operation plans in the face of uncertainties, and optimize strategic and tactical decisions to form a fleet renewal plan that adapts to the changing market in the future.

The rest of this paper is organized as follows: Section 2 reviews the relevant literature; Section 3 describes the research problem, and proposes the mathematical model; Section 4 carries out the case study, and discusses the study results; Section 5 summarizes the research findings.

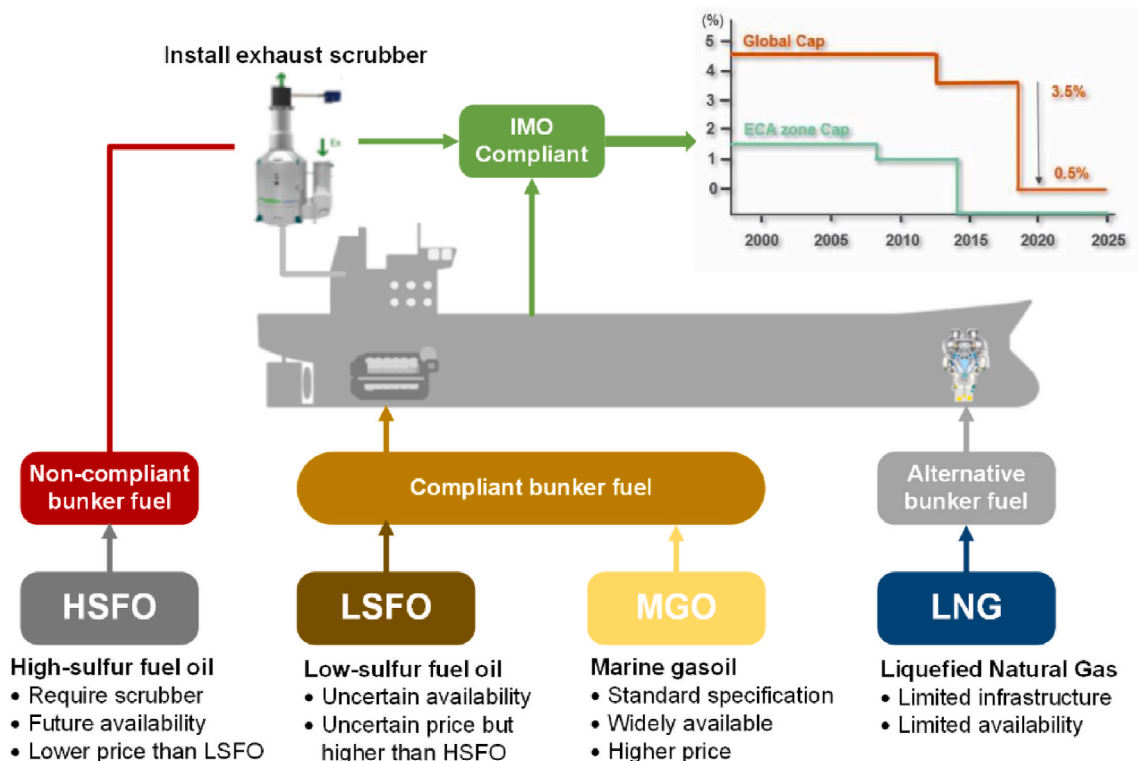


Fig. 1. Changes in sulfur emission restrictions and corresponding compliant options.

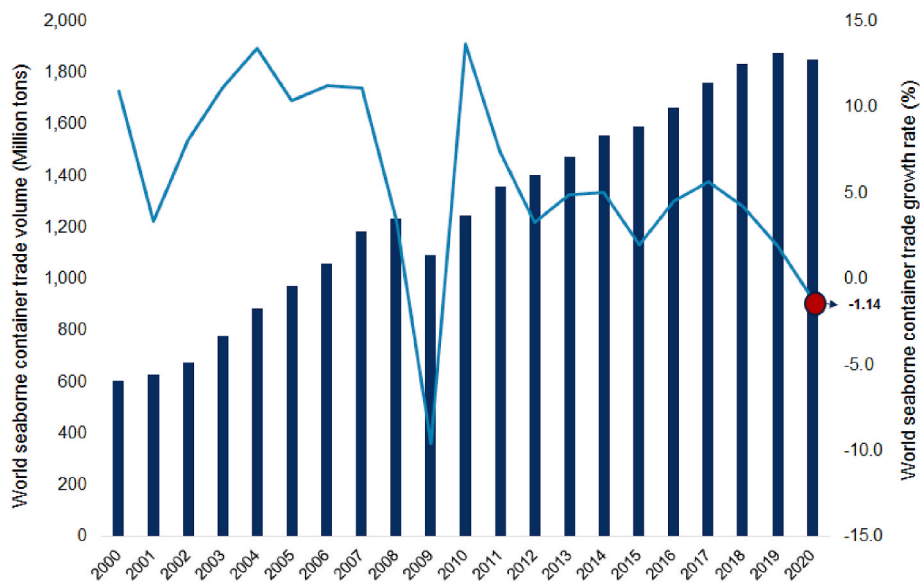


Fig. 2. Changes in global container trade volume, 2000–2020 (Source: Clarksons, 2020b).

2. Literature review

2.1. MFRP

The research on the MFRP can be traced back to the middle and late 20th century. Early on, the traditional MFRP was solved by linear programming, dynamic programming, and some simple algorithms. Nicholson and Pullen (1971) studied the problem of fleet size reduction driven by major technological changes, which aims to determine the combination between the number of ships owned and that of ships chartered based on the known fleet size, i.e., the number of ships used in each period. Wijsmuller (1979) constructed a linear programming model for ship investment and renewal, and determined the investment and renewal timing of the ships, where the fleet size can be adjusted between an upper limit and a lower limit, and the fleet combination is also adjustable. Facing the problem of liner fleet expansion, Cho and Perakis (1996) evaluated a series of treatment methods, including ship construction, acquisition, and lease, and proposed the Lagrangian relaxation method to solve this mixed integer programming problem, without carrying out any experiment. Fagerholt (1999) optimized the plan for fleet size configuration in coastal liner transport services, and the route selection of each ship. Xie et al. (2000) prepared a time-varying fleet renewal plan to meet the given freight demand: each year, ships are added to the original fleet, or idled for disposal; the fleet renewal and development was modeled through dynamic planning and solved by linear programming.

Currently, a growing attention has been paid to the uncertainties of the shipping market. As a result, MFRP researchers are more inclined to consider uncertain scenarios. Stochastic programming stands out from various methods for its effective handling of uncertainties. Meng and Wang (2010), Halvorsen-Weare and Fagerholt (2011) and Meng et al. (2012) tackled uncertainties in the short-term fleet size and mix problems. To minimize the total cost of operators, Schinas and Stefanakos (2012) proposed a SLP model to optimize the fleet combination and size under a given budget and other constraints, and tried to estimate the cost impact of environmental measures, especially the implementation of the sulfur emission restrictions specified in MARPOL Annex VI, which had pushed up the operating cost. Soundararajan and Han (2014) evaluated the impact uncertainties on ship operations, including fuel price, the availability of LNG bunkering stations, new emission equipment, and the downtime of different mechanical systems. Taking transport demand, freight, and ship prices as uncertain factors,

Bakkehaug et al. (2014) proposed a new approach of multi-stage stochastic programming, constructed a SLP model to solve the MFRP, and proved that their model does better in the uncertain case than in the deterministic case. Through stochastic programming, Patricksson et al. (2015) solved the MFRP with scrubber system, with fuel price as an uncertain factor, highlighting the huge cost savings by including emission control area (ECA) in the MFRP. Pantuso et al. (2016) put forward a stochastic planning model to handle uncertainties about future transport demand, prices of new and second-hand ships, ship charter rate, operating costs, and dismantling benefits.

After building a two-stage stochastic programming model, Wang et al. (2018) conducted an example analysis on Odjell, a leading chemical shipping company in Bergen, Norway, and drew two conclusions: a high level of detail for the MFRP improves the renewal results at a higher time cost; deterministic planning only outperforms stochastic planning under a high transport demand. Skålnes et al. (2020) derived an advanced stochastic programming model for the MFRP, with the aim to contain the bankruptcy risk induced by negative cash flow, during marine investment.

2.2. Application of sulfur reduction technologies

The industrial measures for controlling the emissions of sulfur oxides mainly include fuel-switching, ship exhaust gas cleaning system (scrubber), and LNG dual-fuel engine. Methanol and other clean energies have also been adopted to regulate sulfur emissions, but the clean energy strategy is not mature enough for application. Nielsen and Schack (2012) clarified the components of the scrubber system (the scrubber, a modified chimney, additional water tanks, additional pipes, scrubber auxiliary systems, and additional steel frames), pointing out that installing such a system could bring a maximum capacity loss of 0.3%, and a fuel consumption increment of 3%. Aesøy and Stenersen (2013) suggested that the LNG dual-fuel engines are more costly than traditional diesel engines, for the LNG fuel systems require high pressure and cold storage and may cause a 2.5% loss of capacity. Through an environmental and economic analysis of methanol dual-fuel engines, Ammar (2019) proposed to reduce the speed by 28% to lower the dual-fuel cost to the diesel fuel cost at the maximum continuous rating, and put the cost-effectiveness of the methanol dual-fuel engine in reducing NO_x, CO and CO₂ emissions at USD 385.2, 6,548, and 39.9 per ton, respectively, in light of the benefits of slow-steaming and the saved SCR costs. After life cycle assessment on the emissions of LNG and HFO

as fuel, Sharafian et al. (2019) found that, only on large ships, could low-speed LNG high-pressure dual-fuel engines significantly reduce greenhouse gas (GHG) wake emissions by 10% compared with HFO-fueled engines; the GHG reduction was not obvious on small ships. Tan et al. (2020) proposed a mixed integer programming model to study the fuel use flexibility of LNG dual-fuel engine ships with limited LNG bunkering equipment. Wang et al. (2020) performed a comparative analysis on the life cycle cost of the low-pressure gas supply system for a pure LNG-powered ship.

As sulfur reduction technologies become mature and diverse, many scholars have shifted their focus from the application of a single sulfur reduction technology to the comparison between multiple technologies. Under emission constraints of sulfur, nitrogen, and carbon, Balland et al. (2014) constructed an emission reduction technology selection model, and developed the emission reduction strategy for a self-designed mechanical system. Their results indicate that a reasonable way to reduce nitrogen and sulfur emissions is to install a low-speed diesel engine and deploy a fuel switching device. Lirn et al. (2013) discovered that the promotion of green ships directly improves corporate financial performance and environmental performance, under the joint effect of environmental policies, shipping markets, and ship suppliers, and identified the key to the improvement: encouraging shipowners to invest more in green machinery and equipment on their ships. Considering the decision to install or not install scrubber on new ships, Abadie and Goicoechea (2019) comprehensively analyzed diesel engine and LNG dual-fuel engines, and proved LNG dual-fuel engines as the better choice, which minimizes the total investment and fuel costs.

Further, the operational impact of sulfur reduction technologies has also been thrust into limelight. Based on possible emissions regulations of sulfur oxide and nitrogen oxide, Brynolf et al. (2014) performed life cycle assessments on three technical solutions, namely, HFO + SCR, MGO + SCR, and LNG, focusing on environmental impact; the results show that none of the solutions is better than the direct use of HFO, but every solution could reduce particulate matter (PM) and acid rain. Yin et al. (2013) probed into the optimal speed in liner routes, and the impact of low-speed navigation, revealing that low-speed navigation promotes environmental protection. Fagerholt et al. (2015) found that, after the introduction of ECA, ships tend to travel longer distances outside the area, thereby reducing fuel consumption within the zone; but this strategy also increases carbon emissions, with the growing transport distance. Patricksson and Erikstad (2016) proposed a two-stage SLP model to choose the best technology for sulfur reduction.

Faced by shipping operations, the various uncertainties have been researched by many scholars, and commonly solved through robust optimization. Wu et al. (2021) formulated fleet adjustment and cargo selection problem in a robust way, and presented solutions that ensure the profitability of shipping companies against fluctuating voyage costs. Fischer et al. (2016) presented a new mathematical model incorporating a set of planning strategies robust to disruptions in fleet deployment in roll-on roll-off liner shipping.

The environmental impacts of the fleet renewal problem, especially carbon and sulfur emissions, are also a global concern. For instance, Gu et al. (2019) proposed an linear programming model to study the environmental impact of fleet composition and deployment, and probed deep into the changes in carbon emission under different scenarios.

Finally, twelve representative studies were compared with our research in the following aspects: the methods and scenario elements of the MFRP; the features of sulfur reduction technologies; single or fleet retrofit (Table 1). Through thorough analysis on different sulfur reduction technologies, this paper attempts to obtain a realistic ship retrofit and operation plan for the fleet through SLP and robust optimization. This helps to understand how to cope with changes in external environment (e.g., freight demand, ship charter rate, fuel price, retrofit time and SECA ratio) based on soft and flexible fleet renewal solutions.

3. Problem description and mathematical model

3.1. Assumptions

To better understand the research problem, several assumptions were put forward:

A1: This assumption is about the initial sulfur reduction technology for the fleet. Since there were already sulfur limit restrictions before 2020, all ships in the fleet should have been equipped with compliant equipment. For convenience, it is assumed that all ships in the fleet resort to fuel-switching to meet sulfur emission restrictions. That is, the initial fleet does not include scrubber ships or LNG dual-fuel engine ships.

A2: This assumption is about ship acquisition. Our research considers two ways of ship acquisition: purchasing new ships from shipyards, and purchasing second-hand ships from the ship trading market. If new ships are purchased from shipyards, it is assumed that the acquisition has a lead time; any purchased new ship cannot join the fleet before the delivery period. If second-hand ships are purchased from the ship trading market, it is assumed that the acquisition has a lead time, which is shorter than that in new ship purchase; further, it is assumed that only fuel-switching ships are available in the second-hand ship trading market, because of the difficulty in forming a trading market for scrubber ships and LNG dual-fuel engine ships at least in the short term.

A3: This assumption is about ship prices. In this paper, ship price involves the acquisition price of new ships and that of second-hand ships. In the actual market, there is a difference between the two prices, arising from the reselling of ship assets. For convenience, this difference is neglected in this research. It is assumed that the same amount of payment is needed to purchase ships from the two ways, which equals the actual ship price. The only difference between the two ways is that the buyer can choose between more ships of more types by purchasing new ships than purchasing second-hand ships. Moreover, there exists a price difference in the cost of buying and selling ships. After querying the price data on the ship market, the cost difference between the acquisition and sale of existing ships was defined as a fixed value, and applied to different ship types with the same capacity.

A4: This assumption is about ship retrofit. It is assumed that the fuel-switching ships in the initial fleet have diverse retrofit options. These ships can be modified into other sulfur reduction technologies. However, if a ship already chooses to install a scrubber or LNG dual-fuel engines, it would be deemed as unfit for retrofit.

A5: This assumption is about LNG dual-fuel engine. The fuel cost of LNG navigation is generally 75% of that of HFO (Kong et al., 2013). In the real market, however, the price difference between fuels changes constantly with the fluctuation of fuel price. Therefore, it is assumed that, with changes in market conditions, the cost ratio of LNG to HFO could reach 80%, 70%, and 60%, corresponding to the low, medium, and high fuel market scenarios, respectively. In other words, the higher the fuel price, the greater the cost advantage of LNG. In general, ships prefer to choose LNG as the fuel for LNG dual-fuel engines. In addition, pure LNG was not treated as a technology for emission reduction, because LNG supports fewer types of ships than dual-fuel engine, and the types of pure LNG-powered ships are severely limited by the LNG bunkering stations on the route.

A6: This assumption is about LNG bunkering station. This research only considers the existing LNG bunkering stations, and those with a clear construction plan. The other LNG bunkering stations that might be constructed through the planning horizon are not considered.

A7: This assumption is about route demand. The transport demand of specific routes is involved in the case study. For convenience, the initial value of the freight demand of each route was determined in advance, making it easy to discuss the fleet renewal plan under

Table 1
Comparison against representative studies.

Literature	MFRP					Application of sulfur reduction technology							
	Deterministic linear programming	SLP	Robust optimization	Scenario Elements			Retrofit time	Single ship	Fleet	Technical feature	Solution selection	Emission reduction impact	Operation impact
				Freight demand	Charter rate	Fuel price							
Schinas and Stefanakos (2012)		✓		✓			✓		✓				
Bakkehaug et al. (2014)		✓		✓	✓	✓			✓				
Patricksson et al. (2015)		✓				✓			✓		✓		✓
Wang et al. (2018)		✓		✓	✓	✓			✓				
Skålnes et al. (2020)		✓		✓		✓			✓				
Æsøy and Stenersen (2013)	✓							✓		✓		✓	✓
Tan et al. (2020)	✓							✓		✓			✓
Balland et al. (2014)	✓							✓			✓	✓	
Abadie and Goicoechea (2019)		✓				✓	✓	✓			✓		
Patricksson and Erikstad (2016)		✓				✓		✓			✓		
Fischer et al. (2016)			✓						✓				✓
Gu et al. (2019)	✓				✓	✓			✓			✓	✓
This research		✓	✓	✓	✓	✓	✓ (scenario experiment)	✓	✓		✓	✓	✓

different initial demands. This also enables the liner companies to directly analyze its operations based on actual operating demands.

A8: This assumption is about speed optimization. The speed optimization problem, as a sub-problem of the MFRP, is a part of the actual route operation plan. For simplicity, three optional speeds were configured for each type of ship, corresponding to low, medium, and high sailing speeds, respectively.

A9: This assumption is about retrofit time. COVID-19 affects normal labor, and causes a certain time delay. The impact of the epidemic cannot be ignored, even if the demand is low or on the reference level. In these two cases, the retrofit time generally needs to be postponed (delayed by one month in this paper). If the demand is high, the global epidemic must have been effectively controlled, and no delay will occur to retrofit time.

3.2. Problem description

In this paper, the container fleet renewal problem is examined under the uncertainties in liner market (e.g., freight demand, ship charter rate, fuel price and retrofit time), with the aim to enrich sulfur reduction technologies, and support liner companies to rationalize their decision plans for fleet renewal.

Specifically, the container fleet renewal was decided mainly based on ship features (ship power, carrying capacity, etc.), investment costs (ship acquisition cost, ship sales revenue, ship retrofit cost, etc.) and operating costs (charter rate, and fuel). The decision making involves basic route, speed, and several other contents.

Based on when the decision takes shape and effect, the planning horizon was divided into several decision points and their corresponding effective points. Normally, the beginning of each period corresponds to a decision point. The decision made at that point will take effect at the beginning of the next period or one of the following periods.

Without loss of generality, the planning horizon was divided into several periods, i.e., the time interval between two subsequent time points when shipping companies make fleet renewal decisions. For example, the case study sets each period to one year, which can be adjusted by shipping companies according to the practice. The beginning of each period that divides the planning horizon is hereinafter referred to as a decision point, because it is the time for fleet renewal decision-making under our assumption. In the presence of lead time, however, fleet renewal decisions cannot change the fleet structure simultaneously after they have been made at decision points. The decision made at a decision point will take effect at the beginning of the next period or one of the following periods. As a result, the concept of effective point was introduced to represent the time when decisions take effect and really change the fleet.

Suppose several decisions are made for new ship acquisition, second-hand ship acquisition, ship sale, and ship retrofit at decision point 1. Except for new ship acquisition, all the other decisions could come into effect at the beginning of period T1. Thus, the beginning of period T1 corresponds to an effective point of decision point 1. For the acquisition of new ships, the lead time is longer. If there are two periods, then the beginning of period T2 corresponds to another effective point of decision point 1. At the start of the last period, decision point $n-1$ only corresponds to one effective point, due to the length limit of the planning horizon.

Depending on the difference in decision contents, the decision points within the planning horizon can be divided into two types: strategic decision points and tactical decision points. The former consists of decisions on new ship acquisition, second-hand ship acquisition, ship sale and ship retrofit, while the latter involves decisions on ship charter, route assignment and speed optimization. Strategic decision lays the basis of tactical decision. Thus, tactical decision is made from the second period; once made, the tactical decision will take effect within one period.

Finally, new ship undeliverable points and new ship deliverable

points were defined according to whether newly purchased ship is delivered. If the lead time of a newly purchased ship requires two periods (Fig. 3), then the beginning points of the first two periods are obviously undeliverable, and deemed as new ship undeliverable points. This division is also reflected in the construction of our model.

Our mathematical model was developed in reference to the two-stage SLP models proposed by Bakkehaug et al. (2014) and Patricksson et al. (2015), which solve the renewal problems of ro-ro ship fleet and container ship fleet, respectively. Compared with the two reference models, there are several innovative features of our model: (i) replacing the phased cost with one-time investment cost; (ii) expanding the sulfur reduction alternatives; (iii) adding uncertain parameters; (iv) developing a robust optimization model.

The minimization of MFRP costs was taken as the objective function, including ship acquisition costs (new ship/second-hand ship), ship sales revenue, ship retrofit costs (costs of retrofitting existing ships with scrubber or LNG dual-fuel engines), the cost of ship charter (charter-in cost and charter-out revenue), the operating costs through the planning horizon (fuel costs for multiple voyages on actual routes), as well as the residual value of the fleet at the end of the planning horizon.

As mentioned before, the fleet renewal decisions can be divided into strategic decisions (ship acquisition, ship retrofit, and ship sales) and tactical decisions (ship charter, route assignment, and speed optimization).

Let N^{Str} and N^{Tac} be the set of strategic decision points and tactical decision points, respectively. At a strategic decision point $n \in N^{Str}$, y_{vn} is the number of type v ships in the fleet at node n in the planning horizon, which depends on the number of type v new ships (b_{vn}^{NB}) purchased, the number of type v second-hand ships (b_{vn}^{SH}) purchased, and the number of type v ships (s_{vn}) sold at node n . Meanwhile, the number of type v scrubber retrofit ships (u_{vn}^{Scr}) and that of type v LNG dual-fuel engine retrofit ships (u_{vn}^{LNG}) at node n depend on the selection of scrubber and LNG dual-fuel engines, respectively.

The lead time for new ship acquisition was set to 2 years (Maritimemanager, 2020). If the decision to acquire a ship is made at the beginning of the first year, the new ship will be received and put into operation at the beginning of the third year. For second-hand ship acquisition, it is assumed that a second-hand ship purchased in the first year can be delivered in the next year.

For ship retrofit, the retrofit time required for different emission reduction technologies varies from 4 to 10 months (Nanjing Suntech Metal Products, 2020), depending on the ship features (ship power, container capacity, etc.). Besides, the existence of the COVID-19 will delay the normal retrofit time to a certain extent. The ship sale decision will reduce the number of the corresponding type of ships in the current period.

At the tactical decision points, the analysis was mainly unfolded around the set of fuel-switching ships V^{Fuel} , the set of scrubber ships V^{Scr} , the set of LNG dual-fuel engine ships V^{LNG} , and the number of voyages x_{visn} for type v ships to complete the route $i \in I$ at a speed $s \in S$ at node n .

The sailing speed was divided into three levels: low, medium, and high. A slow speed extends the transport time of a single voyage, but saves fuel; the inverse is also true. Thus, it is important to choose a suitable sailing speed.

Regarding route demand, the minimum transport demand of the entire route was considered by thoroughly integrating the freight demand between different pairs of origin and destination ports. This is a realistic setting, because spot demand is more unstable than contract demand. As a result, the cargo transport on a multi-port route was simplified into that between a starting port and an ending port.

In terms of uncertainties, historical data show strong volatility of freight demand, ship charter rate and fuel price. In addition, retrofit time under COVID-19 is also affected. These uncertainty factors greatly impact the cost items of the MFRP, and constrain the future operational needs of the liner company. Therefore, the four items were incorporated

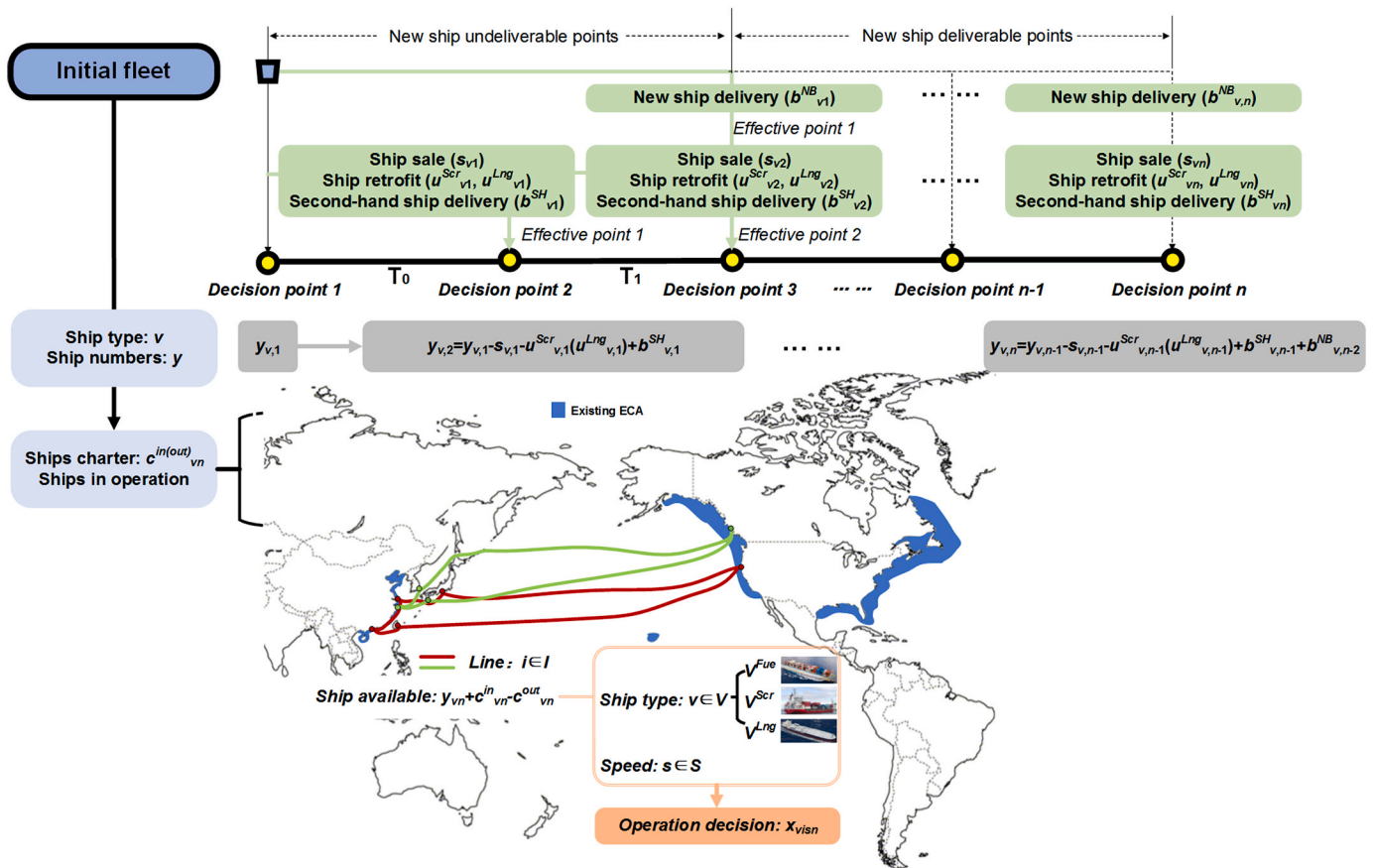


Fig. 3. Decision-making process of MFRP in the planning horizon.

into our model as random variables.

Finally, scenario tree is a key concept in the two-stage SLP model. The tree presents a clear picture of the division between certain and uncertain phases, the number of scenarios in each period of any uncertain phase, and the total number of scenarios. Fig. 4 provides the general structure of the stochastic scenario tree for the two-stage SLP model.

In Fig. 4, each node is the time point of information disclosure and decision making, marking the start of each period. In the stochastic scenario tree, every scenario is constituted by horizontal branches, and represented by a set of nodes. For example, scenario 1 is represented by nodes 0, 11, 12 and 13. Each period is described by the interval between two adjacent nodes. In fact, each scenario stands for a set of possible combinations of freight demand, ship charter rate, fuel price and retrofit

time, reflecting a potential trend of the liner shipping market.

To fully reveal the uncertainty of future sulfur reduction policies, the possibility of SECA expansion was discussed in our MFRP, in addition to the current SECA limit of 0.1% m/m on sulfur emissions. That is, the fleet renewal decision was investigated, as the sulfur emission limit was reduced to 0.1% m/m in the global waters.

3.3. Mathematical model

As stated by Patricksson et al. (2015), each node n in the stochastic scenario tree was given a probability value P_n , and the set of probabilities was fixed for all the nodes. In practice, however, it is impossible to determine the likelihood of a scenario, or finalize the set of precise probabilities. Therefore, this paper considers different candidate

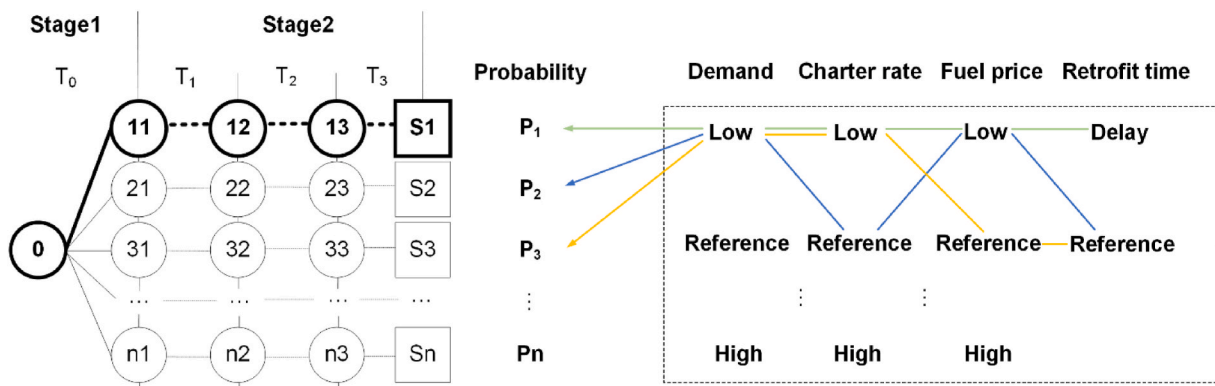


Fig. 4. General structure of the stochastic scenario tree for fleet renewal decision.

possible sets of probabilities, and constructs a robust optimization model based on two-stage SLP model.

3.3.1. Notations

Table 2 lists the sets, parameters, and their meanings in our problem.

3.3.2. Mathematical model

Firstly, a two-stage SLP model [M1-SLP] was presented, in which the probabilities of all the nodes P_n^θ are fixed as the most reasonable set. Let $P_n^{\theta^*}$ be the probabilities used in the two-stage SLP model. Meanwhile, different possible sets of probabilities belonging to collection θ are considered in the robust optimization model [M2-Robust].

Objective function:

$$\begin{aligned} \min \sum_{n \in N^{Str}} P_n^{\theta^*} & \left(\sum_{v \in V} C_{vn}^{NB} b_{vn}^{NB} + \sum_{v \in V} C_{vn}^{SH} b_{vn}^{SH} - \sum_{v \in V} B_{vn}^S s_{vn} + \sum_{v \in V^{Fue}} (C_{vn}^{Scr} u_{vn}^{Scr} + C_{vn}^{Lng} u_{vn}^{Lng}) \right) \\ + \sum_{n \in N^{Tac}} P_n^{\theta^*} & \left(\sum_{v \in V} \sum_{i \in I} \sum_{s \in S} C_{visn}^{Voy} x_{visn} + \sum_{v \in V} C_{vn}^{in} c_{vn}^{in} - \sum_{v \in V} B_{vn}^{out} c_{vn}^{out} \right) - \sum_{n \in N \setminus N^{Str}} P_n^{\theta^*} \left(\sum_{v \in V} B_{vn}^S y_{vn} \right) \end{aligned} \quad (1)$$

Transport frequency and capacity:

$$\sum_{v \in V} \sum_{s \in S} x_{visn} \geq F_{in}, i \in I, n \in N \quad (2)$$

$$\sum_{v \in V} \sum_{s \in S} Q_v x_{visn} \geq D_{in}, i \in I, n \in N \quad (3)$$

Operating time:

$$T_{vn}^{Ava} (y_{vn} + c_{vn}^{in} - c_{vn}^{out}) \geq T_{vn}^{Scr} u_{vn}^{Scr} + T_{vn}^{Lng} u_{vn}^{Lng} + \sum_{i \in I} \sum_{s \in S} T_{vis}^{Voy} x_{visn}, v \in V^{Fue}, n \in N \quad (4)$$

$$T_{vn}^{Ava} (y_{vn} + c_{vn}^{in} - c_{vn}^{out}) \geq \sum_{i \in I} \sum_{s \in S} T_{vis}^{Voy} x_{visn}, v \in V^{Scr} \cup V^{Lng}, n \in N \quad (5)$$

Number of available ships:

$$y_{v0} = Y_{v0}, v \in V \quad (6)$$

$$y_{vn} = y_{v,a(n,1)} - u_{v,a(n,1)}^{Scr} - u_{v,a(n,1)}^{Lng} - s_{v,a(n,1)} + b_{v,a(n,1)}^{SH}, v \in V^{Fue}, n \in N^{ND} \quad (7)$$

$$y_{vn} = y_{v,a(n,1)} - u_{v,a(n,1)}^{Scr} - u_{v,a(n,1)}^{Lng} - s_{v,a(n,1)} + b_{v,a(n,1)}^{SH} + b_{v,a(n,2)}^{NB}, v \in V^{Fue}, n \in N^D \quad (8)$$

$$y_{vn} = y_{v,a(n,1)} + u_{f(v),a(n,1)}^{Scr} + u_{f(v),a(n,1)}^{Lng} - s_{v,a(n,1)} + b_{v,a(n,1)}^{SH}, v \in V^{Scr} \cup V^{Lng}, n \in N^{UD} \quad (9)$$

$$y_{vn} = y_{v,a(n,1)} + u_{f(v),a(n,1)}^{Scr} + u_{f(v),a(n,1)}^{Lng} - s_{v,a(n,1)} + b_{v,a(n,1)}^{SH} + b_{v,a(n,2)}^{NB}, v \in V^{Scr} \cup V^{Lng}, n \in N^D \quad (10)$$

Number of retrofit and sold ships:

$$u_{vn}^{Scr} + u_{vn}^{Lng} + s_{vn} \leq y_{vn}, v \in V^{Fue}, n \in N \quad (11)$$

$$s_{vn} \leq y_{vn}, v \in V^{Scr} \cup V^{Lng}, n \in N \quad (12)$$

Limit on purchased, chartered, and sold ships:

$$\sum_{v \in V} b_{vn}^{NB} \leq \bar{B}_n^{NB}, n \in N \quad (13)$$

$$b_{vn}^{SH} \leq \bar{B}_{vn}^{SH}, v \in V^{Fue}, n \in N \quad (14)$$

$$\sum_{v \in V} c_{vn}^{in} \leq \bar{I}_n, n \in N \quad (15)$$

$$\sum_{v \in V} c_{vn}^{out} \leq \bar{O}_n, n \in N \quad (16)$$

$$\sum_{v \in V} s_{vn} \leq \bar{S}_n, n \in N \quad (17)$$

Decision variables:

$$x_{visn} \geq 0, v \in V, i \in I, s \in S, n \in N \quad (18)$$

$$y_{vn}, u_{vn}^{Scr}, u_{vn}^{Lng}, c_{vn}^{in}, c_{vn}^{out}, b_{vn}^{NB}, b_{vn}^{SH}, s_{vn} \geq 0, \text{ and integer}, v \in V, n \in N \quad (19)$$

Objective function (1) aims to minimize the investment costs and operating costs in certain and uncertain phases. The costs can be broken down into new ship acquisition cost, second-hand ship acquisition cost, ship sales revenue, retrofit costs of scrubber and LNG dual-fuel engine, operating cost, charter cost, charter revenue, and residual value. All the cost items were classified by strategic and tactical decisions. Constraint (2) specifies the minimum transport frequency in liner transport. Constraint (3) requires the capacity of ships operating on a route to meet the minimum transport demand on that route. Constraint (4) demands that the total available time of owned and chartered ships in the fleet must cover the retrofit time and the total voyage time of all routes. Constraint (5) stipulates that the available time of retrofitted ships in the fleet meet the total voyage time required by all routes. Constraint (6) regulates the initial size of each type of ships in the fleet. Constraints (7) and (8) define the number of fuel-switching ships at the beginning of each period according to the number of ships at the start node of the previous period, as well as the number of ships acquired, retrofit, and sold at the start node of the current period. Constraints (9) and (10) specify the number of retrofitted ships at the start node of each period. For the type of retrofit ship (scrubber, LNG dual-fuel engine), $f(v)$ represents the fuel-switch ship type corresponding to the ship type v before the retrofit, $a(n,1)$ and $a(n,2)$ respectively correspond to the preceding node which is one or two periods before node n . Constraints (11) and (12) regulate that the number of retrofitted and sold ships should not surpass the number of owned ships. Constraints (13)–(17) set the upper limit of the number of new and second-hand ships, the upper limit of the number of charter-in and charter-out ships, and the upper limit of the number of sold ships. Constraints (18) and (19) state the domain of the decision variables.

[M2-Robust].

Traditionally, the robust optimization model can be constructed as:

$$\begin{aligned} \min_{\theta \in \Theta} \max_{n \in N^{Str}} P_n^\theta & \left(\sum_{v \in V} C_{vn}^{NB} b_{vn}^{NB} + \sum_{v \in V} C_{vn}^{SH} b_{vn}^{SH} - \sum_{v \in V} B_{vn}^S s_{vn} + \sum_{v \in V^{Fue}} (C_{vn}^{Scr} u_{vn}^{Scr} + C_{vn}^{Lng} u_{vn}^{Lng}) \right) \\ & + \sum_{n \in N^{Tac}} P_n^\theta \left(\sum_{v \in V} \sum_{i \in I} \sum_{s \in S} C_{visn}^{Voy} x_{visn}^{Voy} + \sum_{v \in V} C_{vn}^{in} c_{vn}^{in} - \sum_{v \in V} B_{vn}^{out} c_{vn}^{out} \right) - \sum_{n \in N \setminus N^{Str}} P_n^\theta \left(\sum_{v \in V} B_{vn}^S y_{vn} \right) \end{aligned} \quad (20)$$

s.t. Constraints (2)–(19).

By replacing the objective function (20) with a new variable R , the model can be linearized as:

$$\min R \quad (21)$$

$$\begin{aligned} \sum_{n \in N^{Str}} P_n^\theta & \left(\sum_{v \in V} C_{vn}^{NB} b_{vn}^{NB} + \sum_{v \in V} C_{vn}^{SH} b_{vn}^{SH} - \sum_{v \in V} B_{vn}^S s_{vn} + \sum_{v \in V^{Fue}} (C_{vn}^{Scr} u_{vn}^{Scr} + C_{vn}^{Lng} u_{vn}^{Lng}) \right) \\ & + \sum_{n \in N^{Tac}} P_n^\theta \left(\sum_{v \in V} \sum_{i \in I} \sum_{s \in S} C_{visn}^{Voy} x_{visn}^{Voy} + \sum_{v \in V} C_{vn}^{in} c_{vn}^{in} - \sum_{v \in V} B_{vn}^{out} c_{vn}^{out} \right) - \sum_{n \in N \setminus N^{Str}} P_n^\theta \left(\sum_{v \in V} B_{vn}^S y_{vn} \right) \leq R, \theta \in \Theta \end{aligned} \quad (22)$$

s.t. Constraints (2)–(19).

4. Case study

4.1. Data information

Our case study focuses on COSCO-Liner, a liner company specializing in international and domestic container transport.

(1) Route

The recent trade disputes between China and the United States has drawn close attention from shipping companies. Therefore, two liner routes from COSCO-Liner Far East to Northwest America were selected, namely, the pendulum-type CPNW route and OPNW route (Fig. 5). On the CPNW route, there is an LNG bunkering station at Ningbo-Zhoushan Port. Meanwhile, the OPNW route has no LNG bunkering station. Busan port in South Korea plans to build an LNG bunkering station, which is expected to enter service in 2022. Considering the planned LNG bunkering station, this paper assumes that LNG dual-fuel engine ships can sail on the OPNW route, starting from 2022.

Table 3 presents some operating conditions of CPNW and OPNW routes. Some ship navigation data of the two routes were given separately, and used to calculate and set the sailing speed of ships at different levels on each route (Psaraftis and Kontovas, 2021).

Clarkson's Dr. Martin forecasted that, the world's container trade volume will also fluctuate greatly in the next few years, as the seaborne demand is severely impacted by COVID-19 (Clarksons, 2020a). As for the selected two liner routes, the container transport demand might follow one of three trends in future (Fig. 6).

The most optimistic expectation is the high growth trend, i.e., the high demand scenario. Under this trend, container freight demand would see a 1% decline from 2020 to 2021, followed by a high growth at the rate of 3.2% from 2022. The second-best expectation is the moderate growth trend, i.e., the reference demand scenario. Under this trend, the decline in freight demand would continue until 2023, and then be replaced by a relatively slow growth at 2.2% from 2024. The pessimistic expectation is the weak growth trend, i.e., the low demand scenario.

Under this trend, the freight demand would continue to decline till 2024 at an annual rate of 3%, and slowly resume growth at 0.7% from 2025.

With freight demand, ship charter rate, fuel price and retrofit time as uncertain factors, this paper sets up a stochastic scenario tree, including 14 scenarios (Table 4). The overall probability of low and reference

demand scenarios was set to 80%, because they are obviously more likely than high demand scenario; the remaining 20% was reserved for the probability of high demand scenario. Under the same type of demand, the likelihood of each scenario was determined based on equal probability. Table 5 shows the numerical settings of the tree.

The voyage cost of the fuel-switching ship V^{Fue} can be calculated by:

$$C_{visn}^{Voy} = t_{vis}^{Sea-Eca} \alpha_{vs} f_n^{Mgo} + (t_{vis}^{Sea-NEca} \alpha_{vs} + t_{vi}^{Port} \alpha_{v0}) f_n^{Lsfo}, v \in V^{Fue}, i \in I, s \in S, n \in N \quad (23)$$

The voyage cost of scrubber ship V^{Scr} can be calculated by:

$$C_{visn}^{Voy} = [(t_{vis}^{Sea-Eca} + t_{vis}^{Sea-NEca}) \alpha_{vs} + t_{vis}^{Port} \alpha_{v0}] f_n^{Hfo}, v \in V^{Scr}, i \in I, s \in S, n \in N \quad (24)$$

The voyage cost of LNG dual-fuel engine ship V^{Lng} can be calculated by:

$$C_{visn}^{Voy} = [(t_{vis}^{Sea-Eca} + t_{vis}^{Sea-NEca}) \alpha_{vs} + t_{vis}^{Port} \alpha_{v0}] f_n^{Lng}, v \in V^{Lng}, i \in I, s \in S, n \in N \quad (25)$$

The voyage time can be calculated by:

$$T_{vis}^{voy} = t_{vis}^{Sea-Eca} + t_{vis}^{Sea-NEca} + t_{vi}^{Port}, v \in V, i \in I, s \in S \quad (26)$$

where, $t_{vis}^{Sea-Eca}$ and $t_{vis}^{Sea-NEca}$ are the sailing time of the type v ships in and out of the ECA section of route i at speed s , respectively; t_{vi}^{Port} is the total berthing time in the port of type v ships on route i ; α_{vs} is the unit fuel consumption rate of type v ships at speed s ; α_{v0} is the unit fuel consumption rate of type v ships berthing in the port; f_n^{Hfo} , f_n^{Mgo} , f_n^{Lsfo} and f_n^{LNg} is the unit fuel consumption cost of HFO, MGO, LSFO, and LNG under different scenarios, respectively.

Following the general practice of the liner shipping market (Section 3.2), Table 6 provides the initial type and number of ships in the fleet, as well as the acquisition costs of new and second-hand ship, ship sale revenue, and upper limit of the number of ships in different situations.

The unit investment cost and ship retrofit time of scrubber and LNG dual-fuel engines on reference level, two emission reduction technologies, are shown in Table 7.

Table 2
Sets, parameters and their meanings.

Set	Meaning
$v \in V = \{V^{Fue}, V^{Scr}, V^{Lng}\}$	Ship type v ; set of ship types V , including the set of fuel-switching ships V^{Fue} , the set of scrubber ships V^{Scr} , and the set of LNG dual-fuel engine ships V^{Lng}
$i \in I$	Route i ; route set I
$s \in S$	Speed s ; speed set S
$n \in N = \{N^{ND}, N^D\}$	Period start node n ; set of period start nodes N , including the set of new ship undeliverable nodes N^{ND} and the set of new ship deliverable nodes N^D
$N^{Str} \in N, N^{Tac} \in N$	Strategic decision node set N^{Str} , tactical decision node set N^{Tac}
$\theta \in \Theta$	Set of probabilities of all the nodes $\theta = \{P_n^1, \dots, P_n^s\}$; Collection of different sets of probabilities of all the nodes Θ
Parameter	Meaning
C_{vis}^{Voy}	Voyage cost of type v ships sailing at speed s on route i at node n
C_{vn}^{NB}	New ship acquisition cost for type v ships at node n
C_{vn}^{SH}	Second-hand ship acquisition cost of type v ships at node n
B_{vn}^S	Sales revenue of type v ships at node n
C_{vn}^{Scr}	Retrofit (scrubber) cost of type v ships at node n
C_{vn}^{Lng}	Retrofit (LNG dual-fuel engine) cost of type v ships at node n
C_{vn}^{in}	Charter-in cost of type v ships at node n
B_{vn}^{out}	Charter-out revenue of type v ships at node n
F_{in}	Minimum transport frequency required for route i at node n
Q_v	Capacity of type v ships
D_{in}	Minimum transport demand required for route i at node n
T_{vis}^{Voy}	Voyage time of type v ships sailing at speed s on route i
T_{vn}^{Ava}	Available time of type v ships at node n
T_{vn}^{Scr}	Retrofit (scrubber) time of type v ships at node n
T_{vn}^{Lng}	Retrofit (LNG dual-fuel engine) time of type v ships at node n
\bar{B}_n^{NB}	Upper limit on total new ship acquisition at node n
\bar{B}_n^{SH}	Upper limit on total second-hand ship acquisition at node n
\bar{I}_n	Maximum number of total charter-in ships at node n
\bar{O}_n	Maximum number of total charter-out ships at node n
\bar{S}_n	Maximum number of ships sold at node n
Y_{v0}	Initial number of type v ships in the fleet
P_n^s	Probability of node n in set of probabilities θ
Variable	Meaning
x_{vis}	Number of voyages for type v ships to complete route i at speed s at node n
y_{vn}	Number of type v ships at node n
u_{vn}^{Scr}	Number of retrofits (scrubber) of type v ships at node n
u_{vn}^{Lng}	Number of retrofits (LNG dual-fuel engine) of type v ships at node n
c_{vn}^{in}	Number of charter-in type v ships at node n
c_{vn}^{out}	Number of charter-out type v ships at node n
b_{vn}^{NB}	Number of purchased type v new ships at node n
b_{vn}^{SH}	Number of purchased type v second-hand ships at node n
s_{vn}	Number of type v ships for sale at node n

4.2. Results and discussion

Our model was solved on CPLEX 12.6.3 to obtain the fleet renewal decisions in the current period and through the planning horizon. The computer hardware is an Intel^(R) Core^(TM) i5-9500 CPU @3.00 GHz, with a memory of 8 GB. This basically meets the needs of the model.

4.2.1. Fleet renewal decision in the current period

The most direct benefit of solving the MFRP is to guide the current investment plan of the fleet. That is why this paper discuss the fleet renewal decision in the current period first. Through calculation, the decision plan for the current period was obtained as Table 8.

According to the current fleet renewal decision plan, more ships with a large capacity of 18,000TEU should be added to the fleet in the current period, including acquiring two new LNG dual-fuel engine ships and one second-hand fuel-switching ship. The main reason is that large-capacity ships increase the volume of cargoes loaded each time, which helps to reduce the frequency of liner transport, and thus operating costs. From the angle of ship capacity and transport frequency, small container ship of 8,500TEU lacks capacity advantage. Hence, COSCO-Liner is recommended to sell two ships of this type in the current period.

The ship retrofit decision also mainly concentrates on two large container ships of 18,000TEU. Both ships need to be retrofitted into LNG dual-fuel engine ships. This not only highlights the capacity advantages of large ships, but also manifests the obvious advantage of LNG dual-fuel engines in operating cost, which arises from their relatively low fuel cost.

4.2.2. Fleet renewal decision for the planning horizon

To clarify the entire decision-making process, we then analyzed the fleet renewal decision plan throughout for the planning horizon.

From the calculation results, it can be inferred that the three types of fuel-switching ships in the fleet are all on the decline, but at different rates. In most scenarios, no 8,500TEU small-capacity ship would be retained at the end of the planning horizon (Fig. 7(a)); 4–6 13,000TEU medium-capacity ships and 4–5 18,000TEU large-capacity ships would be retained at the end of the planning horizon, that is, only 1–2 of each of the two types would be sold (Fig. 7(b)–(c)).

Even if the possibility of ship retrofit is considered, medium-to-large capacity ships boast a cost advantage among traditional fuel-switching ships, eliminating the need for substantial modification, while the small-capacity ships face a high probability of being sold through the planning horizon.

In terms of retrofit, the initial fleet of fuel-switching ships has not undergone scrubber retrofit throughout the planning horizon. In contrast, LNG dual-fuel engine ships show greater advantages; many large-capacity ships are modified to suit this sulfur reduction technology. In most scenarios, there are more than seven 18,000TEU LNG dual-fuel engine ships in the fleet. In some high-demand scenarios, that number even increases to 9–11 (Fig. 7(c)).

Judging by the operational results of route CPNW, 8,500TEU and 13,000TEU small-to-medium capacity ships are mainly used in the first half of the planning horizon, while 18,000TEU large-capacity ships are primarily used in the second half. On the selection of sulfur reduction technology, COSCO-Liner should choose LNG dual-fuel engine ships over scrubber ships to cooperate with traditional fuel-switch ships, such as to complete liner transport (Fig. 8(a)–(c)).

Specifically, in the first half of the planning horizon (1st to 3rd years), 8,500TEU and 13,000TEU fuel-switching ships are the main undertakers of liner transport, because all 18,000TEU fuel-switching ships have been retrofitted. In the second half (4th to 6th years), the LNG dual-fuel engine ships and 18,000TEU fuel-switching ships became the main players in liner transport.

Throughout the planning horizon, medium or high speed is not adopted in the liner transport on CPNW route. This means low-speed navigation is an important operational decision in liner transport of ocean routes.

There is an obvious difference in the operating status on OPNW route. The first half of the planning horizon is mainly completed by 18,000TEU fuel-switching ships. Unlike CPNW route, OPNW route cannot use LNG dual-fuel engine ships until the third year of the planning horizon. Starting from 2022, many 18,000TEU LNG dual-fuel engine ships will serve on this route (Fig. 9(a)–(c)). Throughout the planning horizon, small-capacity fuel-switching ships and scrubber ships hardly participated in the transport tasks. The 8,500TEU fuel-switching type ships in the initial fleet are basically sold, and the scrubber is not chosen, despite being a sulfur reduction technology. Like CPNW route, OPNW route sees all ships traveling at the lowest speed.

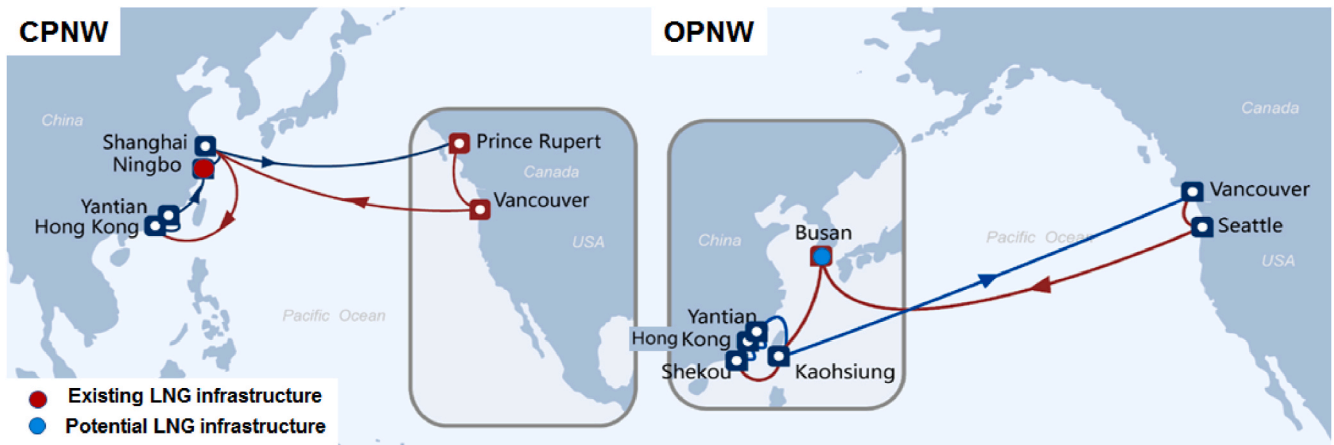


Fig. 5. Pendulum CPNW route and OPNW route (Source: COSCO, 2020).

The above results demonstrate the cost saving effect of low-speed navigation. This is because sailing at medium-to-high speeds pushes up fuel consumption, which naturally increases fuel costs, a large portion of operating costs. Moreover, no scenario witnesses the acquisition, retrofit, and use of scrubber ships. The possible reason is that the CPNW route and OPNW route are typical ocean routes, with an only a small proportion of SECA in the sailing range. If the SECA proportion increases, the scrubber ships will play a greater role in the fleet renewal decision through the planning horizon.

4.3. Experiments on SECA proportion scenario

The SECA proportion was expanded from the level of the basic case, without changing the other elements. The stringent sulfur emission policy was simulated through the SECA boundary adjustment: the sulfur emission limit was reduced to 0.1% m/m in the global seas, lower than the current limit on sulfur emissions. The adjustment is bound to affect

the fleet renewal decision of COSCO-Liner, which operates the two routes in the basic case. In this background, the fleet renewal decision plans for the current period and planning horizon were obtained again. The results for the current period are given in Table 9.

As shown in Table 9, the fleet renewal in the current period still focuses on the acquisition and retrofit of 18,000TEU large-capacity ships, including the acquisition of one 18,000TEU second-hand fuel-switching ship and two 18,000TEU new LNG dual-fuel engine ships. The decision plan also involves the retrofit of three 18,000TEU scrubber ships, and two 18,000TEU LNG dual-fuel engine ships. Hence, the ships with a large capacity of 18,000TEU are always the priority in fleet renewal. Compared with the base case, as the proportion of SECA expands to global waters, more medium-to-large-capacity ships in the fleet are modified into scrubber ships for the operation of two routes.

From the perspective of the planning horizon, the number of small-capacity 8,500TEU fuel-switching ships still decrease in most scenarios, but not as steep as that in the basic case. In the new case, 6–8

Table 3 Relevant information of CPNW and OPNW routes.

Route	Length (nm)	Departure port	Arrival port	Voyage time (day)	Frequency (times/year) F_m	SECA proportion (%)	Speed S (knot)		
							Low	Reference	High
CPNW	12,639.5	HONG KONG	PRINCE RUPERT	42	12	22	12	16	18
OPNW	12,321.7	SHEKOU	VANCOUVER	42	12	5	12	14	18

*Source: Clarksons (2020b), COSCO (2020).

(2) Freight demand, ship charter rate, fuel price and retrofit time

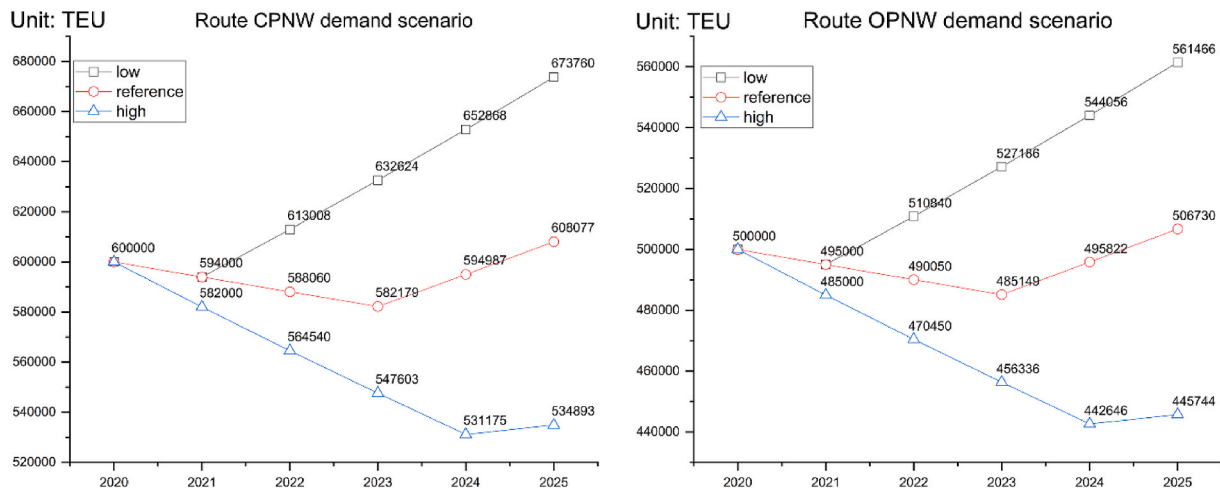


Fig. 6. Scenarios of container transport demand for CPNW and OPNW routes throughout the planning horizon.

Table 4
Stochastic scenario tree.

Scenario	Demand D_m	Ship charter rate $C_{v_n}^{in}, B_{v_n}^{out}$	Fuel price	Retrofit time $T_{v_n}^{scr}, T_{v_n}^{lng}$	Probability $P_n(\%)$
Scenario 1	Low	Low	Low	Delay	8
Scenario 2	Low	Reference	Low	Delay	8
Scenario 3	Low	Low	Reference	Delay	8
Scenario 4	Low	Reference	Reference	Delay	8
Scenario 5	Reference	Low	Low	Delay	8
Scenario 6	Reference	Reference	Low	Delay	8
Scenario 7	Reference	High	Low	Delay	8
Scenario 8	Reference	Low	Reference	Delay	8
Scenario 9	Reference	Reference	Reference	Delay	8
Scenario 10	Reference	High	Reference	Delay	8
Scenario 11	High	Reference	Reference	Reference	5
Scenario 12	High	High	Reference	Reference	5
Scenario 13	High	Reference	High	Reference	5
Scenario 14	High	High	High	Reference	5

Table 5
Numerical setting of stochastic scenario tree.

Demand (D_m)	Year	Low scenario (TEU)			Reference scenario (TEU)			High scenario (TEU)	
		CPNW	OPNW		CPNW	OPNW		CPNW	OPNW
	2020	600,000	500,000		600,000	500,000		600,000	500,000
	2021	582,000	485,000		594,000	495,000		594,000	495,000
	2022	564,540	470,450		588,060	490,050		613,008	510,840
	2023	547,604	456,337		582,179	485,150		632,624	527,187
	2024	531,176	442,646		594,987	495,823		652,868	544,057
	2025	534,894	445,745		608,077	506,731		673,760	561,467

Charter Rate ($C_{v_n}^{in}, B_{v_n}^{out}$)	Year	Low scenario (10,000 \$/day)								
		8,500Fue	13,000Fue	18,000Fue	8,500Scr	13,000Scr	18,000Scr	8,500Lng	13,000Lng	18,000Lng
	2020	0.96	1.92	2.88	1.36	2.72	3.68	1.60	3.20	4.16
	2021	1.06	1.92	2.88	1.36	2.78	3.68	1.60	3.20	4.16
	2022	1.16	1.92	2.88	1.36	2.78	3.68	1.60	3.20	4.16
	2023	1.16	2.02	2.88	1.46	2.78	3.68	1.60	3.30	4.30
	2024	1.26	2.02	2.98	1.46	2.78	3.70	1.70	3.30	4.30
	2025	1.36	2.12	3.00	1.56	2.80	3.90	1.80	3.40	4.40

Charter Rate ($C_{v_n}^{in}, B_{v_n}^{out}$)	Year	Reference scenario (10,000 \$/day)								
		8,500Fue	13,000Fue	18,000Fue	8,500Scr	13,000Scr	18,000Scr	8,500Lng	13,000Lng	18,000Lng
	2020	1.2	2.4	3.6	1.7	3.4	4.6	2.0	4.0	5.2
	2021	1.2	2.4	3.6	1.7	3.4	4.7	2.0	4.0	5.2
	2022	1.2	2.4	3.6	1.7	3.4	4.8	2.0	4.0	5.2
	2023	1.2	2.5	3.7	1.8	3.5	4.8	2.0	4.1	5.3
	2024	1.3	2.5	3.7	1.8	3.5	4.8	2.2	4.2	5.5
	2025	1.4	2.6	3.8	1.9	3.6	5.0	2.3	4.3	5.7

Charter Rate ($C_{v_n}^{in}, B_{v_n}^{out}$)	Year	High scenario (10,000 \$/day)								
		8,500Fue	13,000Fue	18,000Fue	8,500Scr	13,000Scr	18,000Scr	8,500Lng	13,000Lng	18,000Lng
	2020	1.44	2.88	4.32	2.04	4.08	5.52	2.40	4.80	6.24
	2021	1.44	2.88	4.42	2.04	4.08	5.52	2.40	4.90	6.24
	2022	1.54	2.90	4.50	2.04	4.08	5.52	2.50	4.90	6.24
	2023	1.74	2.90	4.50	2.30	4.08	5.70	2.60	4.90	6.30
	2024	1.74	3.10	4.50	2.40	4.10	5.70	2.60	5.00	6.30
	2025	1.80	3.10	4.60	2.50	4.20	5.80	2.80	5.10	6.40

Fuel Price ($f_n^{HFO}, f_n^{LSFO}, f_n^{MGO}, f_n^{LNG}$)	Year	Low scenario (10,000 \$/ton)				Reference scenario (10,000 \$/ton)				High scenario (10,000 \$/ton)			
		HFO	LSFO	MGO	LNG	HFO	LSFO	MGO	LNG	HFO	LSFO	MGO	LNG
	2020	0.0230	0.0277	0.0330	0.0184	0.0440	0.0570	0.0700	0.0308	0.0582	0.0755	0.0850	0.0349
	2021	0.0231	0.0279	0.0332	0.0185	0.0441	0.0571	0.0701	0.0310	0.0583	0.0756	0.0853	0.0353
	2022	0.0234	0.0280	0.0334	0.0188	0.0443	0.0574	0.0703	0.0311	0.0586	0.0759	0.0854	0.0355
	2023	0.0236	0.0283	0.0335	0.0191	0.0445	0.0575	0.0704	0.0314	0.0588	0.0762	0.0857	0.0358
	2024	0.0239	0.0284	0.0338	0.0192	0.0446	0.0577	0.0706	0.0315	0.0589	0.0763	0.0859	0.0361
	2025	0.0240	0.0287	0.0341	0.0194	0.0449	0.0580	0.0709	0.0317	0.0592	0.0765	0.0861	0.0365

Retrofit time ($T_{v_n}^{scr}, T_{v_n}^{lng}$)	Ship capacity (TEU)	Reference scenario (day)				Delay scenario (day)			
		Scrubber retrofit time		LNG dual-fuel engine retrofit time		Scrubber retrofit time		LNG dual-fuel engine retrofit time	
		8,500	13,000	18,000		180	210	240	
	8,500	150	210	270	180	210	240	270	300
	13,000	180	240	300	210	240	270	300	
	18,000	210	270	330	240	270	300	330	

*Data source: [Clarksons \(2020b\)](#).

*The ship charter rate also reflects the price level of chartered-in and chartered-out ships.

*The value of each element is consistent with the change trend of the corresponding scenario.

(3) Ship

Table 6
Initial information on ships of the fleet and the corresponding acquisition costs and sales revenue.

Fuel-switching ship V^{Fue}	Capacity Q_v (TEU)	New ship acquisition cost $C_{v_n}^{NB}$ (10,000 \$)	Second-hand ship acquisition cost $C_{v_n}^{SH}$ (10,000 \$)	Ship sales revenue $B_{v_n}^S$ (10,000 \$)	Number of ships in the initial fleet Y_{v_0}
1	8,500	9,166	9,166	8,700	8
2	13,000	11,251	11,251	10,700	6
3	18,000	13,924	13,924	13,500	6
Ship available time per year T_m^{Av} (day)	Upper limit on new ship acquisition \bar{E}_n^{NB}	Upper limit on second-hand ship acquisition \bar{E}_n^{SH}	Maximum number of chartered-in ships I_n	Maximum number of chartered-out ships O_n	Maximum number of sold ships S_n
300	2	1	4	4	2

*Data source: [Clarksons \(2020b\)](#).

*The upper limits on new ship acquisition and second-hand ship acquisition, as well as the maximum number of chartered-in, chartered-out, and sold ships, are applicable to all ship types.

(4) Sulfur reduction technology

small-capacity ships are retained at the end of the planning horizon in most scenarios. This is the result of the large-scale retrofit of 18,000TEU fuel-switching ships in initial fleet (the number of such ships reduces to 2 in 2021). To satisfy the route demand, it is a must to maintain a certain number of small-capacity ships (Fig. 10(a)). In addition, the renewal decision on small-capacity ships is solely selling, without any acquisition or retrofit.

Great changes take place on the medium-capacity 13,000TEU ships in the experiments on SECA proportion scenarios. Firstly, the number of such fuel-switching ships decreases less steeply than the basic case in most scenarios, in order to partly compensate for the overall lack of capacity caused by the conversion of large-capacity ships. With the expansion of the SECA proportion, the 13,000TEU fuel-switching ships in the initial fleet undergo both scrubbers retrofit (an increase of 1–3) and LNG dual-fuel engine retrofit (an increase of 2–4) (Fig. 10(b)) in some high demand scenarios. Thus, stricter sulfur reduction policy could promote the diversification of cost-efficient sulfur reduction technologies.

The large-capacity 18,000TEU ships still participate in the transport task through the planning horizon. Most of the 18,000TEU fuel-switching ships in the initial fleet are retrofitted into scrubber ships and LNG dual-fuel engine ships in the second year. With the elapse of time, compared with that of scrubber ships, the number of retrofitted LNG dual-fuel engine ships gradually rises to 5–9 (Fig. 10(c)). Nevertheless, the increase in the number of LNG dual-fuel engine ships is slower than that in the basic case, for the growing number of scrubber ships induced by the expansion of SECA proportion, to a certain extent, squeezes out the investment in LNG dual-fuel engine ships.

4.4. Experiments on robust optimization results

4.4.1. Results comparison of robust optimization and SLP in flexible scenario probabilities

To improve the generality of results, robust optimization analysis was carried out with different possible scenarios on the basis of the original model.

Until now, the world has been fighting against COVID-19, and it is still hard to estimate when the epidemic will end. This section assumes that COVID-19 impacts are stronger or weaker than the reference situation estimated by Clarkson’s Dr. Martin (the scenario tree designed in Section 4.1), and adjusts the probability of each scenario accordingly. If

Table 7
Unit investment cost and ship retrofit time for sulfur reduction technologies.

Solution	Existing ship retrofit cost (\$/kw)	New ship installation cost (\$/kw)	Retrofit time (day)		
			8,500TEU	13,000TEU	18,000TEU
Scrubber	450	250	150	180	210
LNG dual-fuel engines	800	450	210	270	300

*Source: Germanischer [Lloyd \(2013\)](#).

the COVID-19 impacts are relatively weak, e.g., limited only in short-term, the probability of the high demand scenario was upregulated to 80%, and equally divided 80% to each sub-scenario of the high demand scenario. The longer the epidemic lasts in the planning horizon, the more likely that the shipping demand will grow at a low rate. In this way, five sets of probabilities were designed (Fig. 11). Robust optimization model was introduced to compare different sets of probabilities, and find the optimal results under the worst set of probabilities.

Fig. 12 compares the ship renewal results between robust optimization (red solid lines) and the SLP (dotted lines), where all subfigures present the ship numbers of different ship types. It can be found that robust results are more stable under different future scenarios, in contrast with SLP results, where ship numbers usually fluctuate with different scenarios. Thus, the robust fleet renewal strategies were specified as follows.

For 8,500TEU small-capacity ships, no acquisition, sale, or retrofit is needed and the ship number should remain stable in the planning horizon regardless of future scenarios. For 13,000TEU medium-capacity ships, one fuel-switching ship needs to be installed with scrubbers in the current period, and the ship number should remain stable in the rest of planning horizon regardless of future scenarios. For 18,000TEU large-capacity ships, five fuel-switching ships need to be converted to LNG dual-fuel engine ships in the current period, respectively. More 18,000TEU large-capacity LNG dual-fuel engine ships are needed in the next few years, compared with the SLP results.

The comparison does not aim to prove which model performs better. The SLP can provide reliable results, as long as the scenario probabilities are estimated reasonably. But some risk-averse decision-makers prefer to solve the problem by considering more possible sets of scenarios, and

Table 8
Current fleet renewal decision plan.

Ship type v	New ship acquisition $b_{v_0}^{NB}$	Second-hand acquisition $b_{v_0}^{SH}$	Ship sales s_{v_0}	Ship retrofit $r_{v_0}^{LNG}$
8,500/ Fue	0	0	2	0
18,000/ Fue	0	1	0	2
18,000/ Lng	2	0	0	0

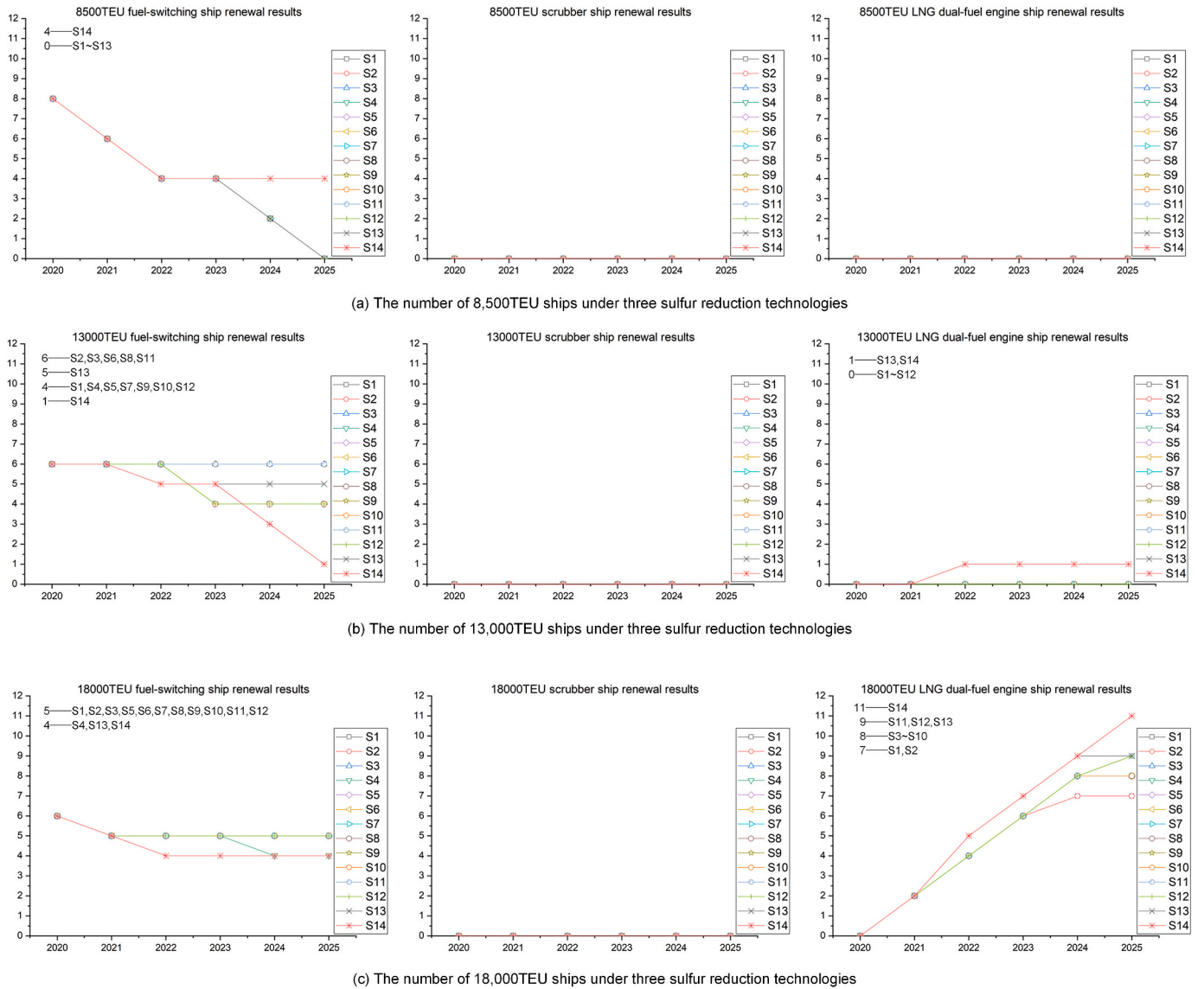


Fig. 7. Fleet renewal for three sulfur reduction technologies through the planning horizon.

pay more attention to the worst set of probabilities. It can be concluded that the robust fleet renewal strategies require the fleet to obtain more LNG dual-fuel engine ships of larger capacity through either new ship acquisition or old ship retrofit; medium-capacity ships are more suitable for scrubber installation; it may be unnecessary to add scrubber ships or LNG dual-fuel engine of smaller capacity.

4.4.2. Results comparison of robust optimization and SLP in SECA proportion scenario

The robust fleet renewal strategies also hold for SECA expansion. As shown in Fig. 13, four 18,000TEU fuel-switching ships need to be converted to LNG dual-fuel engine ships initially, three 13,000TEU fuel-switching ships need to be installed with scrubbers initially, while the 8,500TEU fuel-switching ships do not need any retrofit, with the ship number remaining at eight.

Through robust optimization, the most intuitive change of fleet renewal results is that the renewal of ship types and numbers should stabilize as soon as possible (in the first year), in order to sustain the fleet structure for the planning horizon. The stable and fleet renewal results are suitable for all the 14 proposed scenarios. Therefore, it is obvious that the fleet renewal by the cost-oriented robust optimization still focus on large-capacity LNG dual-fuel engine ships, supplemented by some

medium-capacity scrubber ships.

4.5. Results on emissions

To disclose the environmental impacts of different fleet renewal solutions, the fleet emissions were measured further during the entire planning horizon. If the shipping company chooses the fleet renewal decision derived from two-stage SLP model, then the total carbon emission E_{CO_2} and sulfur emissions E_{SO_2} of the fleet can be calculated by:

$$E_{CO_2} = \sum_{n \in N} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \sum_{m \in M} P_n^{i,v} x_{visn} FC_{vism} EF_m^{CO_2} \quad (27)$$

$$E_{SO_2} = \sum_{n \in N} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \sum_{m \in M} P_n^{i,v} x_{visn} FC_{vism} EF_m^{SO_2} \quad (28)$$

where, $P_n^{i,v}$ is the probability value of node n used in the two-stage SLP model, FC_{vism} is the fuel consumption for type v ships to complete route i at speed s of fuel type m , where $m \in M$ represents different fuel type, i.e., HFO, LSF0, MGO, LNG.

If the shipping company chooses the fleet renewal decision derived from robust optimization model, the total carbon and sulfur emissions of the fleet can be calculated by Equation (29)~(30). After obtaining the

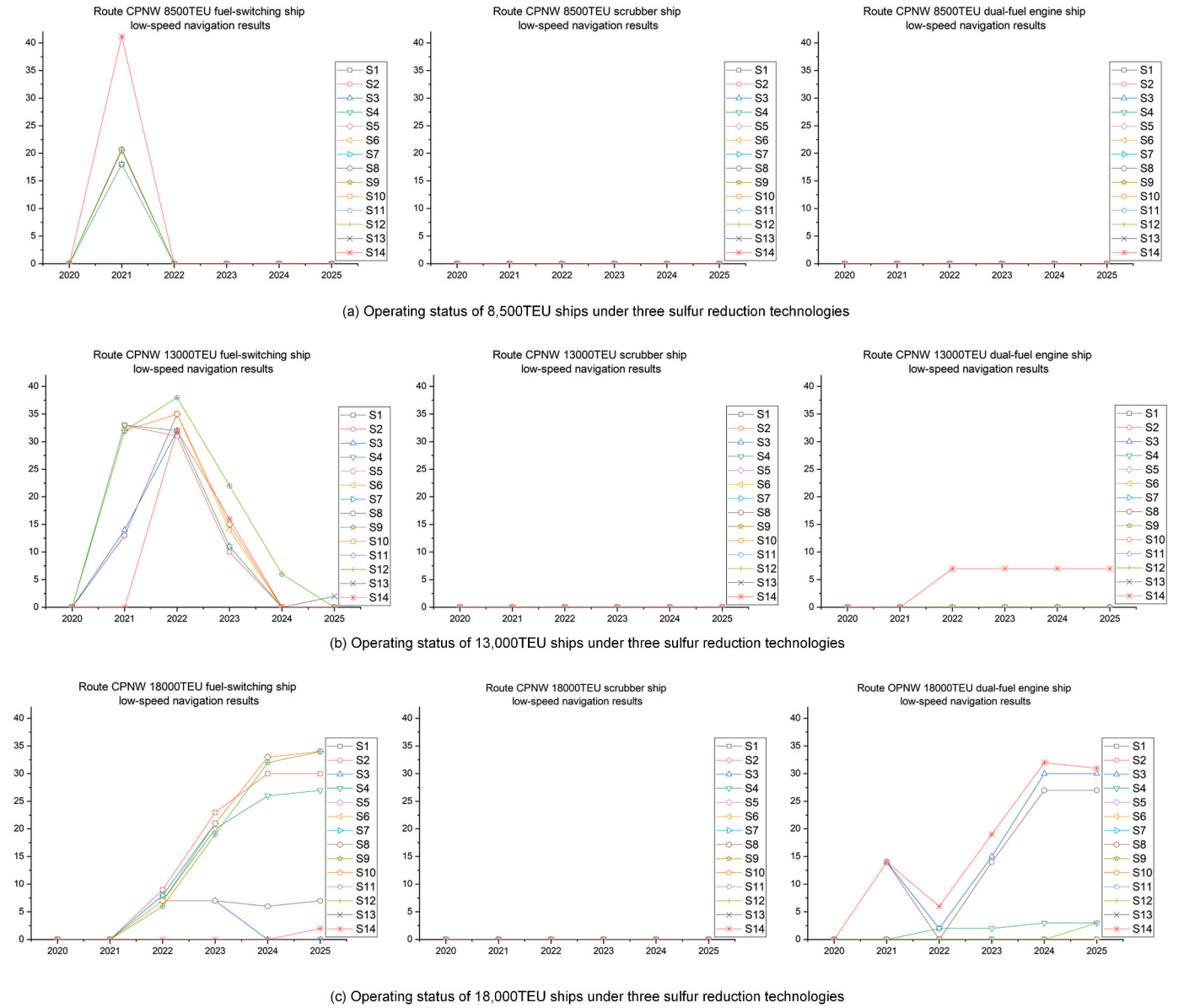


Fig. 8. Operating status of different ship types under three sulfur reduction technologies on CPNW route.

optimal solution of the robust optimization model, we identified the worst set of possibilities for the optimal solution, because the decision-makers choosing the robust strategies tend to be risk-averse and focus on the worst possible set of parameters. Then, a binary parameter z_θ was introduced: z_θ equals 1 if the corresponding θ represents the worst set of possibilities for the optimal solutions; z_θ equals 0 if otherwise.

$$E_{CO_2} = \sum_{n \in N} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \sum_{\theta \in \Theta} \sum_{m \in M} z_\theta P_n^\theta x_{visn} FC_{vism} EF_m^{CO_2} \quad (29)$$

$$E_{SO_2} = \sum_{n \in N} \sum_{v \in V} \sum_{i \in I} \sum_{s \in S} \sum_{\theta \in \Theta} \sum_{m \in M} z_\theta P_n^\theta x_{visn} FC_{vism} EF_m^{SO_2} \quad (30)$$

The carbon emission factor $EF_m^{CO_2}$ and sulfur emission factor $EF_m^{SO_2}$ of fuel type m are given in Table 10.

Tables 11 and 12 present the results about the sulfur emissions and carbon emissions of the fleet, respectively. In general, SECA expansion will significantly reduce sulfur emissions, but slightly boost carbon emissions. Hence, more stringent SECA regulations may bring unexpected side effects like boosting global warming. The result is consistent with the literature on the evaluation of SECA regulations (Lindstad et al.,

2015).

From the annual emissions, it can be observed that the sulfur emissions will gradually decrease year by year (Table 11). This is because more LNG dual-fuel engine ships or scrubber ships will appear under the SECA regulations. But the decreasing trend will slow down and even vanish in 2025. Regarding the differences between the emissions of SLP results and robust results, it can be inferred that sulfur emissions will reduce greatly if robust strategies are chosen, for these strategies require more ships to be installed with scrubbers that can reduce nearly all the sulfur emissions.

The annual carbon emissions will exhibit a convex trend: decreasing firstly and then increasing (Table 12). A possible reason is that the total ship numbers will increase with the gradual recovery of global trade in the second half of the planning horizon. Different from sulfur emissions, robust strategies may lead to slightly more carbon emissions in the coming years.

5. Conclusions

The stricter sulfur emission restrictions in global seas, coupled with

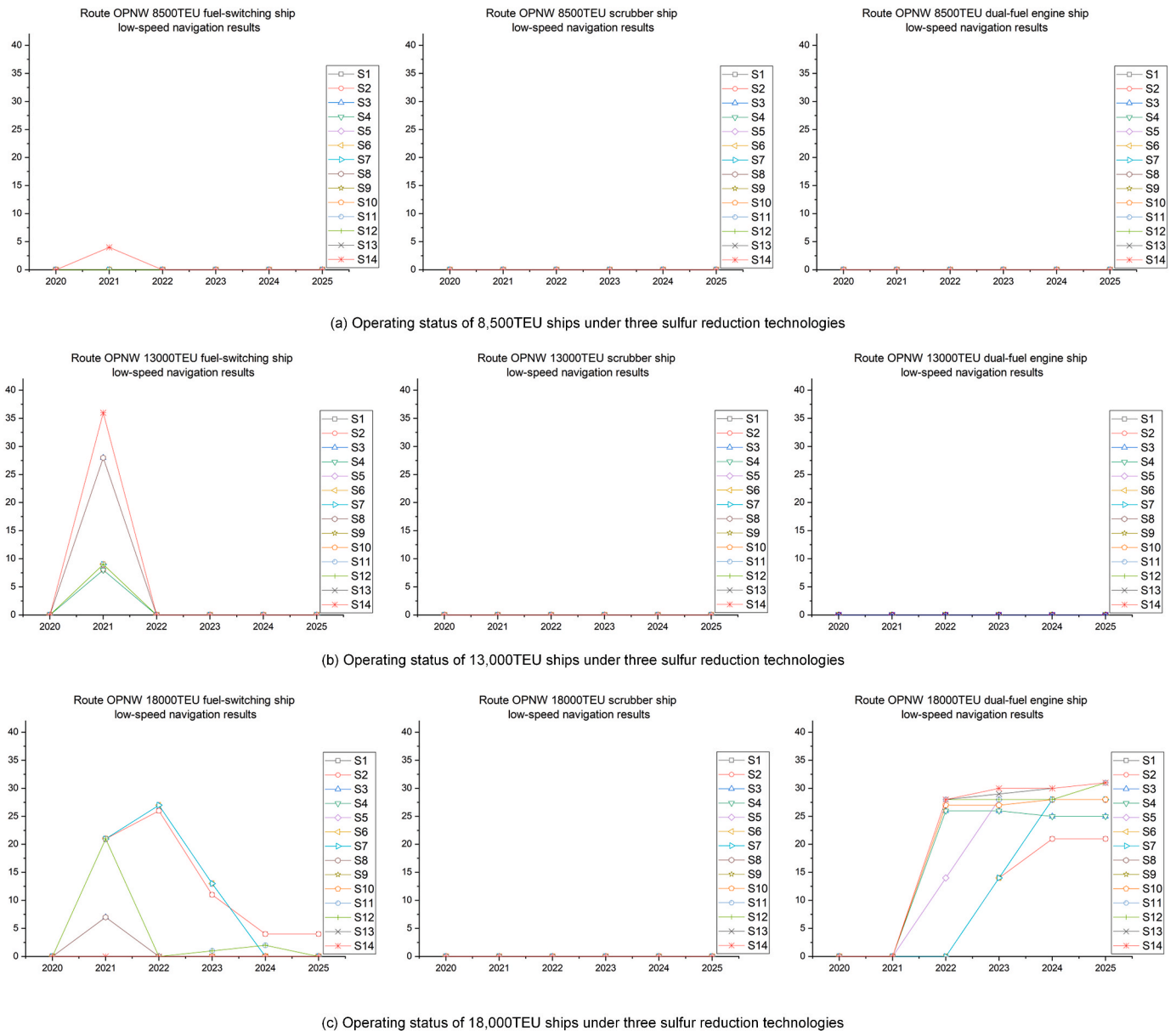


Fig. 9. Operating status of different ship types under three sulfur reduction technologies on OPNW route (The results of the medium-high speed modes not listed are all zeros.).

the emergence of various sulfur reduction technologies, motivate shipping companies to diversify their measures to meet sulfur reduction requirements. Under the influence of COVID-19, the world's container freight demand becomes highly sluggish and uncertain. Under the premise of satisfying the sulfur emission restrictions, it is a great challenge to select suitable sulfur reduction technologies, make reasonable fleet renewal decisions, and prepare stable operation plans.

To cope with the challenge, this paper proposes a robust optimization model based on two-stage SLP, which incorporates three sulfur reduction technologies: fuel-switching, scrubber, and LNG dual-fuel engines. Besides, a dazzlingly array of possible scenarios were designed based on multiple uncertainties through the planning horizon, such as maritime demand, ship charter rate, fuel price, retrofit time and SECA ratio. On this basis, we rationalized the fleet renewal decision plan, which involves ship acquisition, ship retrofit, ship sale, ship charter, route assignment, and speed optimization.

The proposed mathematical model was applied to solve a case with COSCO-Liner as the shipping company, and our decision plan was tested

under the uncertainties of the liner shipping market and the diverse sulfur reduction technologies. The results show that our decision plan provide rational strategic and tactical decisions at the same time, and can adapt to random scenarios in future. In addition, shipping companies can choose the robust strategies obtained from robust optimization model, if they are unsure about the impacts of COVID-19, and consider several different sets of possible probabilities for different scenarios.

In addition, the following findings were obtained from the case study

Table 9
Fleet renewal decision plan for the current period.

Ship type _v	New ship acquisition _{v0} ^{NB}	Second-hand ship acquisition _{v0} ^{SH}	Ship sales _{v0}	Ship retrofit _{v0} ^{Scr, Lng} , u_{v0}^{Ng}
18,000/ Fuel	0	1	0	3(Scr),2(Lng)
18,000/ Lng	2	0	0	0

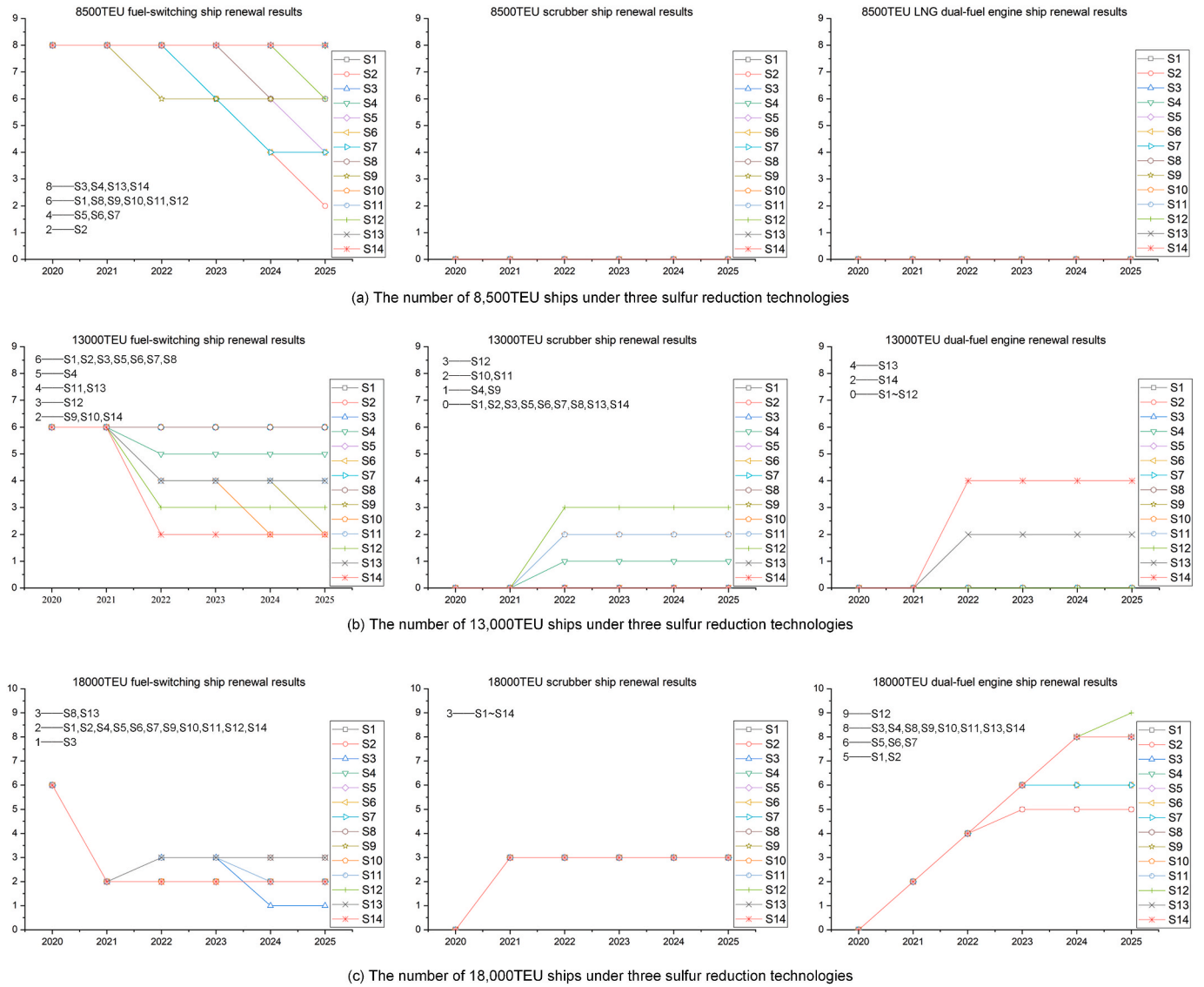


Fig. 10. Fleet renewal for three sulfur reduction technologies through the planning horizon under the expansion of SECA proportion.

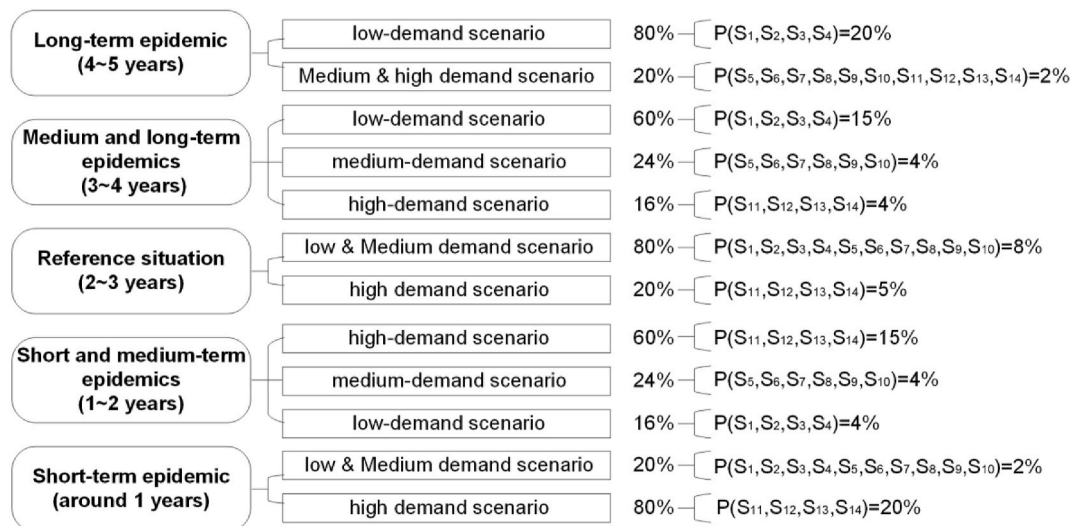


Fig. 11. Different sets of scenario probabilities.

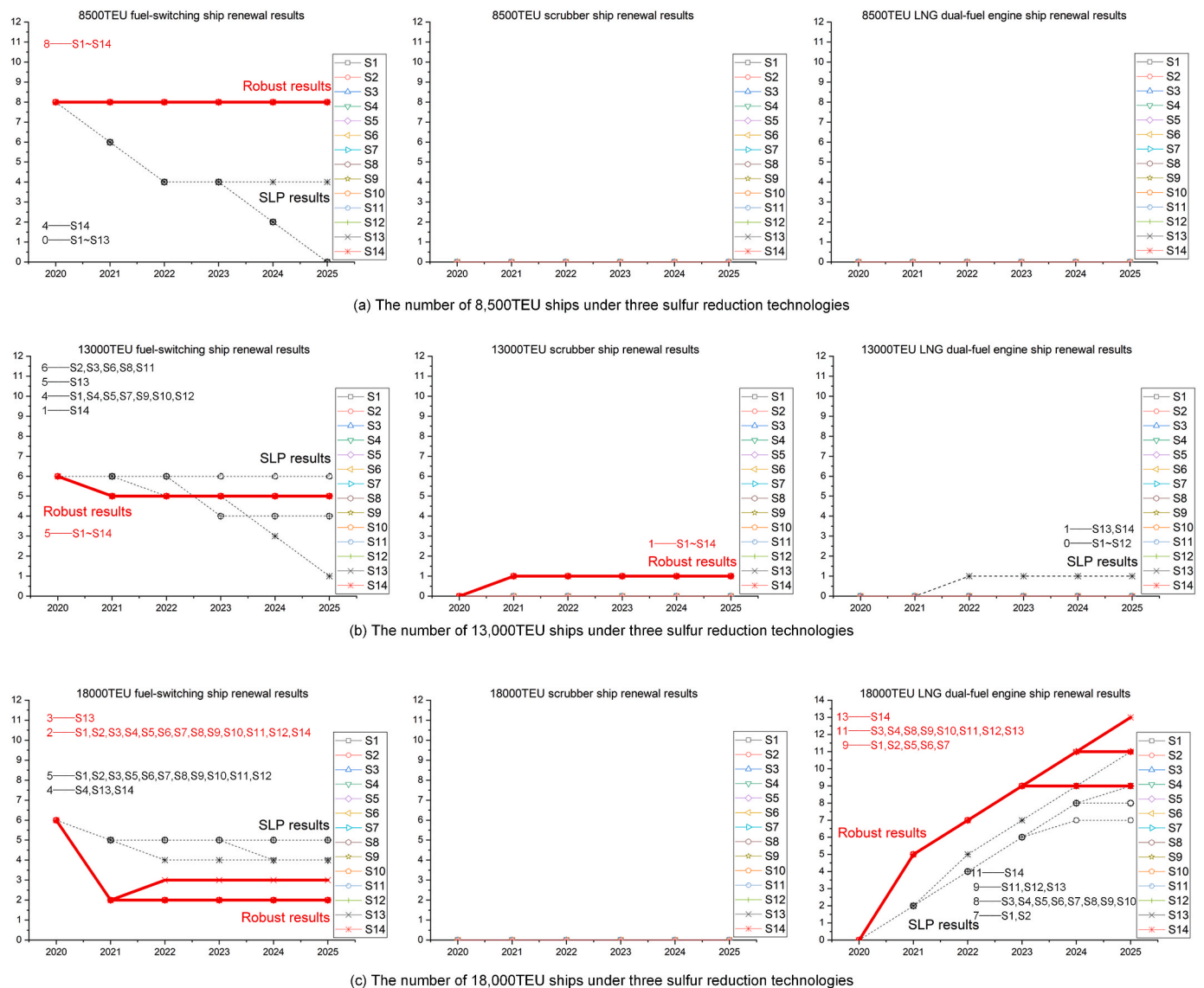


Fig. 12. Comparison of fleet renewal decisions between robust optimization and SLP.

and scenario experiments:

- (i) According to results on strategic decision through the planning horizon, whether the sulfur emission limit is maintained at the current level or further tightened, large-capacity fuel-switching ships and its LNG dual-fuel engine retrofits should be included in the long-term investment and operation plan, for their advantages of reducing investment costs, lowering operating costs, and ensuring capacity. In the short term, a certain number of medium-to-small capacity ships should be maintained to satisfy the basic transport demand. The large-capacity ships and new energy ships are unstoppable trends of shipbuilding. The application and promotion of LNG fuel in ships and ports will be a key promoter of container trade around the world (such as China-US routes).
- (ii) When it comes to the actual ship route operation plan at the level of tactical decision, all types of ships on CPNW and OPNW routes choose to operate in low-speed navigation mode. This operating mode can effectively save costs during liner transport on ocean routes.
- (iii) In any possible scenario, the sulfur reduction technology of scrubber does not have any cost advantage in investment and operation, unless the SECA boundary is expanded or the sulfur

emission limit is further straitened. Although the 0.5% m/m sulfur emission limit has been implemented since the beginning of 2020, most shipowners (DHTHoldings, Scorpio Tankers, etc.) and shipping companies (MSC, Wallenius Wilhelmsen, Stolt-Nielsen, etc.) have not immediately carried out large-scale scrubber retrofits to their ships (Scorpio Tankers, 2020).

- (iv) The robust strategies derived from robust optimization model suggest that shipping companies should be prudent to making fleet renewal plans. According to the robust strategies derived from the robust optimization model, it is necessary to add more large-capacity LNG dual engine ships and medium-capacity scrubber ships, but unnecessary to add any small-capacity LNG dual engine ships nor small-capacity scrubber ships. Compared with the SLP results, the robust strategies will remain more stable under different scenarios, and significantly reduce sulfur emissions, while slightly increasing carbon emissions.
- (v) The calculation on fleet emissions demonstrates that SECA expansion can greatly reduce sulfur emissions generated from the operating ships, but may slightly increase carbon emissions.

When it comes to the fleet renewal problem, the popular approach of stochastic programming depends heavily on the construction of the

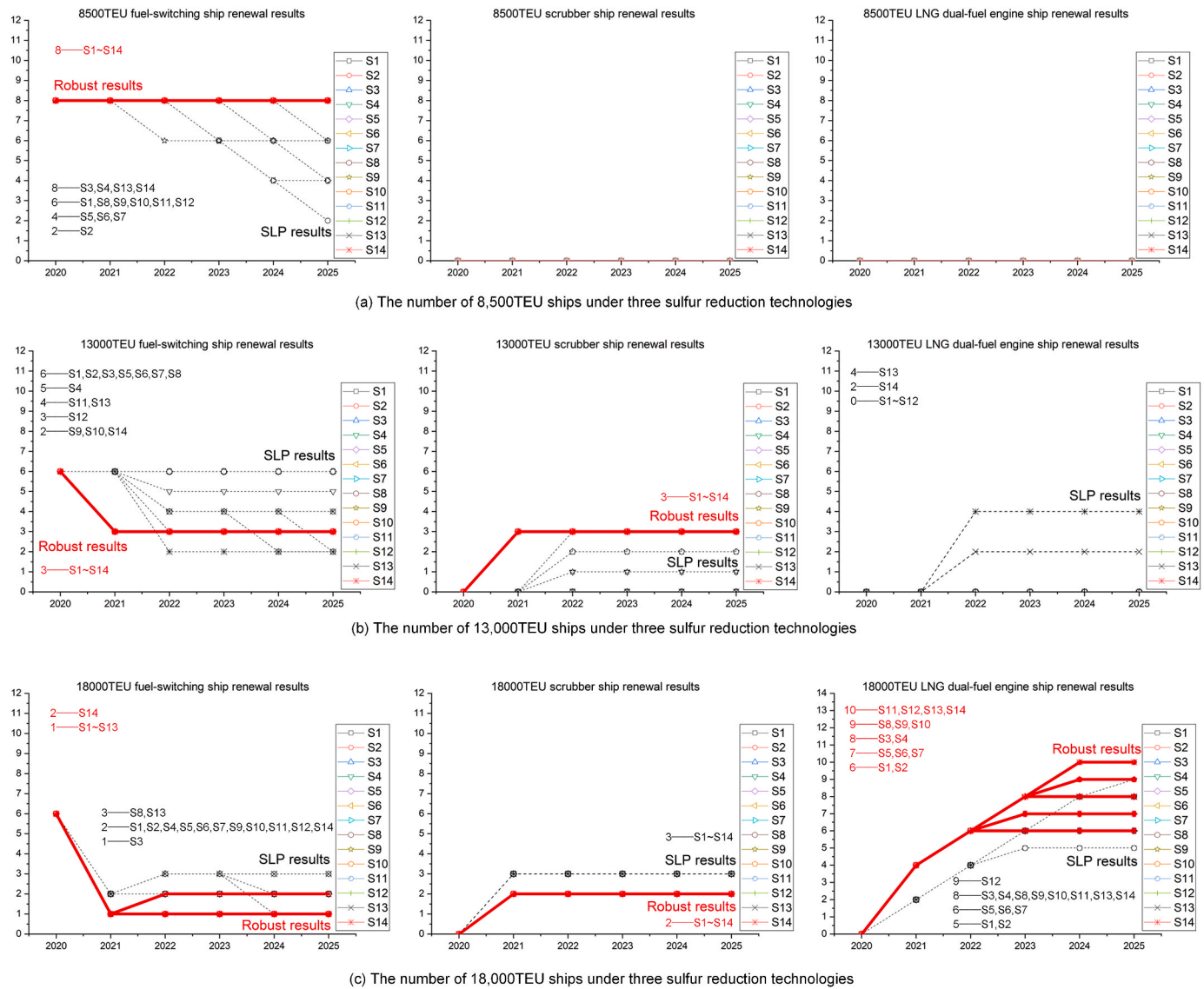


Fig. 13. Comparison of fleet renewal decisions under the expansion of SECA proportion between robust optimization and SLP.

Table 10
Emission factors (International Maritime Organization IMO, 2020)

Fuel type	Carbon emission factor (g CO ₂ /g fuel)	Sulfur emission factor (g SO ₂ /g fuel)
HFO	3.114	0.0684271
LSFO	3.114	0.0097753
MGO	3.206	0.0019551
LNG	2.750	0

scenario tree. Therefore, it is important to set up a suitable scenario tree, and assign appropriate probability (weight) to each scenario. To solve the problem, the impact of international trade and the development of sulfur reduction technologies should be considered to adapt fleet

Table 11
Sulfur emissions of the fleet.

		SO ₂ emissions (t)	2021	2022	2023	2024	2025
Before SECA expansion	SLP	4,539.81	1,572.87	1,055.35	777.03	562.64	571.91
	Robust optimization	2,649.48	1,232.74	620.17	375.52	191.72	229.33
After SECA expansion	SLP	2,442.51	1,056.67	555.53	275.89	268.91	285.51
	Robust optimization	935.08	460.33	231.56	100.96	71.11	71.11

renewal plan to the current market. However, different fleet operators face different main risks and uncertainties. The results of fleet renewal must be diversified to cope with the various uncertain factors in specific issues. Hence, the main limitation of this research is that the fleet renewal results may vary with the selected uncertain factors and the weights of their influence in the whole problem.

As for future research, some financial factors will be added to solve the MFRP. For example, it is very meaningful to study the risk management and rate of return in decision-making for the acquisition, sale and charter of new ships and second-hand ships in the ship trading market. Moreover, the increasingly diverse emission reduction technologies might be incorporated into the IMO's future policies and regulations on the emissions of SO_x, NO_x, CO₂, and CH₄, and the ECA boundaries could be further adjusted in global seas. These possible

Table 12

Carbon emissions of the fleet.

		CO ₂ emission (t)	2021	2022	2023	2024	2025
Before SECA expansion	SLP	3,040,680.47	642,043.67	609,774.53	594,477.45	591,432.44	602,952.39
	Robust optimization	3,156,684.98	644,245.23	622,399.50	619,691.72	626,646.17	643,702.37
After SECA expansion	SLP	3,066,039.53	641,701.71	609,427.49	598,288.05	602,286.63	614,335.66
	Robust optimization	3,169,200.85	636,308.70	621,648.48	624,400.83	634,575.47	652,267.38

scenarios, plus the uncertain factors in the shipping market, need to be considered to design a set of more rigorous and realistic scenarios, which helps to renovate the modeling and solution to the MFRP.

CRedit authorship contribution statement

Yuzhe Zhao: Conceptualization, Methodology, Validation, Formal analysis, Supervision, Funding acquisition. **Jiajun Ye:** Software, Resources, Data curation, Writing – original draft, Visualization. **Jingmiao Zhou:** Investigation, Writing – review & editing, Project administration.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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