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Research Article

Incorporating Sulfur and CO_2 Emission Reduction Options into the Container Fleet Capacity Renewal Alternatives for a Shipping Operator in the Post-COVID-19 Era

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In this article, a cost-benefit decision framework is proposed to analyze the three alternative options of the container fleet capacity renewal for a ship operator. In this decision framework, the ship operator can trade off the following factors: MGO fuel or LNG option vessels, carbon neutrality, and other investment factors. The following variables are considered: the distance of the round trip, the prices of LNG and MGO, the freight rates of each option, and the initial investment ratios of new vessels. It was found that (1) the retrofitted vessels were more stable and suitable in an uncertain shipping market and have better investment potential. (2) The MGO option was the best option before the epidemic of COVID-19. In the postepidemic era, under the double carbon (carbon neutral and carbon peaking) policy, the advantage of low fuel consumption for the LNG ships disappeared due to the increase in LNG prices, and the NPV advantage of MGO ships becomes significant.

1. Introduction

In the post-COVID-19 era, according to the forecasting of Clarkson study [1], the global seaborne trade exceeded 12.2 billion tonnes by 2022, with a steadier growth of 3.6% in TEU. This dramatic increase on seaborne trade led to a severe imbalance between the supply and demand. To alleviate this imbalanced situation, the ship operators were building new or retrofitting existing container ships [2]. Until 5 March 2021, 147 box ships (most of which are in the largest size category) had been ordered since October 2020, compared to only 40 ordered between January and September 2020. The order book had reached more than 360 vessels, representing 12% of the deployed capacity [2].

For a shipping operator, there are several challenges in the decision to build new or retrofit existing container ships. Firstly, from 1 January 2020, stricter regulations on sulfur emissions from ships are implemented [3]. Secondly, the introduction and implementation of the carbon neutral/peaking policy require reducing CO_2 emissions. Thirdly, shipping markets are more complex due to the impact of the COVID-19 pandemic. The ship operator faces more uncertainties in their investment decisions in the post-COVID-19 era.

For the ship operator, while building new or retrofitting existing ships, the sulfur reduction regulations should be taken into account. The sulfur emissions from shipping operations can lead to ocean acidification [4]. The sulfur emissions also have a range of negative impacts on air quality and human health, including causing asthma and premature abnormal death [5, 6]. The International Maritime Organization (IMO) established emission control areas (ECAs) and included ECA regulations in Annex VI of the International Convention for the Prevention of Pollution from Ships (MARPOL). This regulation requires ships to use fuel with a sulfur content of no more than 0.1% in the regulated area [7].

In order to meet the requirements on sulfur emissions, some sulfur reduction options have been proposed. The first option is fuel switching. Under this option, the ship can operate with high-sulfur heavy fuel oil outside the emission control area (ECA) and low sulfur heavy fuel oil, MDO, or MGO inside the ECA. However, this option increases the operative risk, especially for vessels that frequently enter or operate within the ECA [8].

The second option is liquid natural gas (LNG) vessels. This LNG vessel can use clean LNG as fuel. The number of LNG vessels is rapidly growing. Until December 2019, there were 172 LNG vessels operating worldwide, an increase of 20.3% compared to 2018 [9]. It was concluded that the use of LNG was becoming mainstream and provided a 20% to 30% reduction in CO_2, while minimizing SOx and other emissions [10].

The third option is the installation of scrubbers. The scrubber is highly efficient in reducing sulfur and particulate emissions. Specifically, the scrubbers were optimally profitable with the high price differential between heavy fuel oil (HFO) and MGO [11]. However, the wastewater from scrubbers had a negative effect on the marine environment. As a result, many countries such as China, Singapore, and Germany banned the use of open-loop scrubbers in ECA [12].

For the ship operator, while building new or retrofitting existing ships, carbon neutrality should be taken into account. According to the IMO estimation, shipping accounted for 2.9% of global greenhouse gas emissions [13]. It was projected that CO_2 emissions from shipping will continue to grow by 50 percent to 250 percent in the period to 2050, due to the projected growth in demand for maritime transport services [14]. If left unmitigated, ship emissions were expected to account for nearly 17% of global CO_2 emissions by 2050 [10]. The international community has been concerned about the pollution caused by exhaust emissions from ships. Climate change due to increased greenhouse gas emissions has become increasingly prominent in recent decades, and countries around the world were collaborating to address this global challenge [15]. Carbon neutrality had become a global issue and will also be a future national development strategy for China and several other countries [16, 17]. In August 2020, the Fourth Greenhouse Gas Study of the IMO set the main goal for the shipping industry to reduce greenhouse gas emissions by 50% by 2050, compared to 2008 [13].

For the ship operator, while building new or retrofitting existing ships, the COVID-19 pandemic should also be considered. The COVID-19 pandemic had a major influence on globalization and the shipping industry [18, 19]. The COVID-19 pandemic led to the difficulty in finding containers for import and export foreign trade orders between China and the USA [20]. According to the Clarkson Intelligence Network's Global Shipping Index (GSI), GSI for March 2021 was already higher than the prepandemic level. The COVID-19 pandemic inevitably affected freight rates, fuel prices, revenues, and earnings, as well as the utilization of facilities and human resources [21].

Compared with the previous studies, the effects of the post-COVID-19 era are taken into account in this article. As for the alternatives of building new and retrofitting ships, we trade off several factors, including extra investment on new ships, negative cash flows of the ship operator, retrofitting fees for retrofitted ships, and the investment decisions on capacity. Container shipping is a capital-intensive industry. Asset management of the fleet is a key component of the profitability of container shipping companies [22]. Extra investment in new ships can lead to economic losses and loss of market share and jeopardize the long-term competitive position of shipping companies. Over investment on new ships may lead to negative cash flows, due to extreme financial costs [23].

In this article, a cost-benefit decision framework is proposed for the ship operator to make a decision on building new or retrofitting existing container ships. The following questions are explored: Which sulfur reduction options should be chosen for the ship operator? Which sulfur reduction option is better to reduce carbon emissions?

The article is organized as follows. Section 2 reviews the literature on building new and retrofitted vessels. Section 3 describes the methodology and model. Section 4 presents a case study, with sensitivity analysis on key parameters for the ship operator. Section 5 concludes this article with some remarks and further studies.

2. Literature Review

As shown in Table 1, we compare the related research on building new and retrofitted vessels for a ship operator with respect to three dimensions, namely, sulfur emission reduction technology, variables for container fleet capacity expansion, and the post-COVID-19 era.

To reduce emissions from ships, IMO has established four ECAs to reduce emissions from ships, including the Baltic Sea, the North Sea and the English Channel, the North American coast, and the US Caribbean coast. Within these ECAs, sulfur emissions are stricter controls, with a limit of 0.1% sulfur in marine fuels [39, 40]. In 2018, the Chinese government designated all 12 nautical miles of China's coast as an ECA. From 1 January 2019, ships entering the ECA should use marine fuels with a sulfur content of no more than 0.5% m/m. From 1 January 2022, marine vessels entering Hainan's coastal control zone should use marine fuel oil with a sulfur content of no more than 0.1% m/m [41].

There are three common technologies for sulfur reduction: fuel switching, scrubbers, and LNG. Under the influence of the IMO, fuel switching from heavy oil to low-sulfur fuel has significantly reduced pollutant emissions from engines [24, 42, 43]. The use of fuel switching options was found to have a positive impact on air quality in the study area through the monitoring of air quality in the port area [44]. MGO was considered to be a fuel that reduces sulfur emissions in the shipping industry today [8, 25]. By installing a sulfur scrubber, it was possible to keep using the cheaper high-sulfur fuel, and sulfur emissions were reduced by 98% [26]. Retrofitting scrubbers on the existing ships was an economically viable option considering the balance between the private costs to ship owners and the social and environmental benefits of emission reduction. The option of ship retrofitting scrubbers was not appropriate when the remaining life of the old ship was less than four years [11]. In

Table 1: Literature review with respect to sulfur emission reduction technology, variables for container fleet capacity expansion, and the post-COVID-19 era.

Citations	Sulfur emission reduction technology				Variables for container fleet capacity expansion				Post-COVID-19 era
	LNG	Scrubber	MGO	Fuel switching	Distance of the round trip	Fuel price	The freight rates	Initial investment ratios of new vessels	
[24]			√						
[25]			√	√		√		√	
[26]		√				√		√	
[27]							√	√	
[11]						√			
[28]		√		√		√		√	
[29]						√		√	
[30]	√		√			√			
[5]			√						
[31]	√	√	√						√
[32]	√								
[10]	√	√	√						
[19]	√								
[33]			√						√
[34]	√	√	√						√
[35]	√	√		√		√		√	√
[36]	√					√			
[37]				√	√		√	√	√
[38]									√
This research	√		√		√	√	√	√	√

order for LNG abatement schemes to be competitive, LNG prices must be lower than HFO [45]. Many ships in Norway used LNG to reduce sulfur emissions and several studies focusing on SOx and NOx reduction strategies for ships had concluded that LNG can be effective in reducing pollutant emissions from alternative fuels [46, 47]. Sharafian et al. [32] found that LNG dual-fuel engines can reduce SOx emissions by 95–98% and particulate emissions by 97–98% compared to conventional HFO. They suggested using LNG instead of HFO to reduce SOx and NOx emissions. Abadie et al. [31] concluded that the LNG was the best option for minimizing investment and fuel costs. Considering environmental concerns, LNG was the best alternative fuel [36].

For the ship operator, they can increase the container fleet capacity by building new or retrofitting existing vessels. Ship operators usually chose to build larger vessels to increase their capacity, while nimble operators tended to use second-hand vessels to increase their capacity [27]. Players in the market should consider retrofitting older vessels to improve fuel economy during economic downturns and using new fuel-efficient vessels for capacity expansion during market upturns. The random variable costs and random fuel price factors should be considered in investment models, while making investment decisions for capacity upgrades to obtain better evaluation and selection results [29, 30]. The main decision factors for retrofitting LNG vessels included fuel prices, retrofit capital costs, and investment time [28]. Factors affecting shipowners' decisions for new building included freight and fuel costs, but these factors had little impact on the choice of abatement solutions for new ships [34]. Shipping companies faced higher investment costs in the post-COVID-19 era, as they will have to invest in their fleets to comply with new emission reduction standards and the urgent demand for capacity in the shipping market [21]. In the post-COVID-19 era, shipping capacity will be increased mainly through new vessels, in contrast to the trend towards "withdrawal" of shipping capacity from the main trade channels, during the extremes of the pandemic [33].

In the post-COVID-19 era, the ship operator is facing greater difficulties in making investment decisions. Since January 2020, weekly ship calls at Shanghai seaports had decreased by 20% [48–50]. In the United States, Los Angeles handled 9.46 million TEUs in 2018, with trade volumes down by more than 22% since the pandemic [51]. Similarly, in Long Beach, which handles over 8 million TEUs, imports were reported to be down by 17% [51–53]. Changes in container freight rates will have a negative impact on the cash flow of shipping companies [54, 55]. The COVID-19 pandemic has resulted in a decrease in effective transport capacity and cargo handling efficiency, and a sharp increase in freight rates. Freight rates on the China-North America route could rise nearly threefold by early 2020 [37, 56, 57].

Several researchers have studied the impact of the COVID-19 pandemic on emission reduction plans and responses in the transport sector [35, 38, 58–60]. These studies have examined the application of sulfur abatement programs in the context of the massive spread of COVID-19 and marine sulfur emissions to future long-term investment and operational plans. However, there is still little advice on investment decisions for container fleet capacity expansion in the uncertain shipping market in the post-COVID-19 era.

In contrast to the previous studies, a cost-benefit model is proposed for a ship operator with the consideration of sulfur and carbon emission reduction options in the post-COVID-19 era. Sensitivity analysis is conducted on fuel prices, container freight rates, and initial investment ratios. An example of China-Europe container liner shipping is presented to show the application of our model.

3. Research Methodology and Model Formulation

For better presentation, without loss of generality, the following assumptions are made.

3.1. Assumptions

A1 The voyage time of a liner shipping route is T_{voyage}. The time for the ship at berth in the port T_{port} is the ship's departure interval of one week, and then, the number of ships in the fleet can be written as $k = T_{\text{voyage}} + T_{\text{port}}/168$.

A2 According to the [13] global environmental regulations, LNG is used as the main engine fuel and MGO as the ignition fuel throughout the entire process while using a dual-fuel engine as the main engine. While using MGO fuel, only MGO fuel is used throughout.

A3 The average speed of the ship between ports of call on the route is used to calculate the fuel consumption of the ship, ignoring the fuel consumption at ports of call.

3.2. Cost of Each Ship Compliance Option. For the ship compliance option $i = (1, 2)$, where 1 is the use of MGO and 2 is the use of LNG; $j = (a, b)$ where a represents the retrofit compliance option and b represents a newly built ship. According to the conditional assumptions, the number of round trips of ships on the research route is set to K and the number of ships arranged on the route k. The loading factor of the ships is set as $w = 80\%$. The freight rate on the route is set to p (\$/TEU). The annual operating time of the ship is set to 350 days, and the operating cycle of the ship's route is T (days), and then, $K = 350/T$. Q is the loading capacity of the ship (TEU), and the income of the ship's freight can be set as $E_{ij}^{re} = 2KkQwp$.

The total cost in a year C_{ij} is the sum of the daily sailing cost in a year. The total cost of the ship studied in this article mainly includes three parts: the fuel cost C_{ij}^{FC}, the annual maintenance cost of option C_{ij}^{OC}, and the cost incurred while calling at ports C_{ij}^{PC}:

$$C_{ij} = C_{ij}^{FC} + C_{ij}^{OC} + C_{ij}^{PC}. \quad (1)$$

The fuel costs for ships using low sulfur oil, MGO, include the fuel costs of the main engine C_{1a}^{M} and the fuel costs of the auxiliary engines C_{1a}^{A}:

$$C_{1a}^{FC} = C_{1a}^{M} + C_{1a}^{A}. \quad (2)$$

The fuel consumption cost of the main and auxiliary engines using the MGO is calculated as [61]

$$C_{ia}^{FC} = \left[F_{1j}^{M} \frac{DV_S^2}{V_0^3} + F_{1j}^{A} \frac{D}{V_S} \right] P^{MGO},$$

$$F_{1j}^{M} = \frac{SFOC^{M} EL^{M} PS^{M}}{10^6}, \quad (3)$$

$$F_{1j}^{A} = \frac{SFOC^{A} EL^{A} PS^{A}}{10^6},$$

where F_{1j}^{M} is the fuel consumption of the main engine, $SFOC^{M}$ is the unit time fuel consumption of the main engine, and $SFOC^{A}$ is the unit time fuel consumption of the ship's auxiliary engine. EL^{M} is the load of the ship's engine, EL^{A} is the load of the ship's auxiliary engine (%), PS is the power of the engine, M is the main engine, and A stands for the auxiliary engine. P^{MGO} stands for the price of MGO fuel, and T_{port} is the time spent at port. According to Corbett et al. [62] and Doudnikoff and Lacoste [61], $SFOC^{M} = 206$(g/kwh), $EL^{M} = 0.8$, $SFOC^{A} = 221$(g/kwh), $EL^{A} = 0.5$.

The main dual-fuel engines on the market can be divided into three types, namely, medium speed 4-stroke low-pressure dual-fuel (MS-LPDF) engines, low-pressure dual-fuel 2-stroke (LPDF 2-stroke) engines, and low-speed high-pressure dual-fuel 2-stroke (LS-HPDF) engines. The main operating principles of dual-fuel engines using LNG are the direct in-cylinder high-pressure injection type represented by MAN and the low-pressure in-cylinder injection type represented by Wärtsilä [32]. The natural gas is injected at high pressure into the cylinder so that it burns with the energy released by the ignition of a small amount of ignition oil. The high-pressure in-cylinder direct injection type uses a high-pressure gas supply system, which consumes a certain amount of energy and leads to an increase in overall fuel consumption throughout the ship. LS-HPDF engines, in contrast, have been found to have almost no methane slip (about 0.01%). Low-pressure gas engines, due to the diesel cycle operating gas mode, mix natural gas, and air by injecting natural gas into the cylinder at low pressure after the piston has closed the sweeping port. When the piston reaches the upper stop, a small amount of ignition oil is injected into the cylinder and the ignition energy of the ignition coil is used to ignite the mixture of gas and air in the cylinder, thus burning the fuel and completing the work process. As the gas is injected into the inlet of the cylinder, the incompletely burned methane is expelled with the exhaust gas, increasing the amount of methane slippage.

A dual-fuel engine with in-cylinder low-pressure injection 2 strokes is used. The Wartsila DF engine with an ignition oil consumption rate of $SFOC^{MGO}$ is approximately 1.5 (g/kwh), a fuel consumption factor of $SFOC^{MLNG}$ is 147.6 (g/kwh) for liquefied natural gas (LNG), and a load factor of DF engine EL^{M} is 0.8. Auxiliary unit gas consumption (50% load) $SFOC^{\text{ALNG}}$ is 215.04 (g/kwh). Auxiliary ignition oil consumption (50% load) is 4.97 (g/kwh). The slip of the LNG dual-fuel engine methane slip CH_4 is 2.5 (g/kwh) [63]. This allows the calculation of the fuel costs for the use of LNG DF:

$$C_{ib}^{FC} = \left[F_{2j}^{M} \frac{DV_S^2}{V_0^3} + F_{2j}^{msLNG} \frac{D}{V_S} \right] P^{LNG}$$

$$+ \left[F_{2j}^{MGO} \frac{DV_S^2}{V_0^3} + \left(F_{2j}^{A2} + F_{2j}^{A1} \right) \frac{D}{V_S} \right] P^{MGO},$$

$$F_{2j}^{MGO} = \frac{SFOC^{MGO} PS^M EL^M}{10^6},$$

$$F_{2j}^{M} = \frac{SFOC^{MLNG} PS^M EL^M}{10^6}, \quad (4)$$

$$F_{2j}^{A1} = \frac{SFOC^{ALNG} PS^A EL^A}{10^6},$$

$$F_{2j}^{A2} = \frac{SFOC^{AMGO} PS^A EL^A}{10^6},$$

$$F_{2j}^{msLNG} = \frac{SFOC^{msLNG} PS^M EL^M}{10^6}.$$

3.3. Depreciation Costs of Retrofitted Vessels. The current financial system in China stipulates that the maximum depreciation period for transport vessels is 18 years. The average age of ships sold worldwide is mostly between 20 and 25 years [64]. Due to the large value of shipping assets, taking into account the payback period and investment risk factors, the depreciation period calculated in this article is 10 years. The annual average method is used for the depreciation calculation of the large hull ships. The net residual value rate is generally 3%–5%. In this article, the net salvage value at the end of the period is 5% of the original value [65]. The cost of conversion of a converted ship includes the cost of construction of the ship and the cost of conversion for depreciation C_{ij}^{ICnb}. P_{ij}^{ship} is the cost of the ship, and N_{ij}^{s} is the number of years of depreciation. C_{ij}^{ICnb} is the depreciated cost of a new ship, and C_{ij}^{ICre} is the depreciated cost of a retrofitted ship:

$$C_{ij}^{ICre} = \frac{P_{ij}^{re}}{N_{ij}^{s}},$$

$$C_{ij}^{ICnb} = \frac{P_{ij}^{\text{ship}}}{N_{ij}^{s}}. \quad (5)$$

3.4. Expenditure on Ship Loans. As ships are larger fixed assets, ship operators usually take out loans for purchase. Loan costs are mainly made up of repayment principal and interest incurred on the loan, for new ships fitted with LNG dual-fuel engine systems and new MGO ships. Due to the large initial cost of new ships, shipping finance loans are considered to address the financial problems of ship operators. Typical financing terms in the international shipbuilding market are used, similar to the OECD "Export Credit Understanding" terms [65]. C_{ij}^{IC} is the initial investment cost of the sulfur reduction option, β is the loan interest rate, m is the repayment period of the vessel, and X_{ij} is the annual repayment amount. Without the loss of generality, the interest rate on the loan is 4% and the loan term is 10 years in this study:

$$X_{ij} = \frac{C_{ij}^{IC} \beta (1+\beta)^m}{(1+\beta)^m - 1}. \quad (6)$$

Table 2: Emission factors used in this study.

	Emission factors (g/g of fuel)	
	SOx	CO_2
HFO	0.054881	3.114
LNG	0.00002	2.75
MGO	0.001955	3.206

Data source: [66].

3.5. NPV Model. NPV is the difference between the present value of future financial inflows and the present value of future financial flows. C_{ij}^{IC} is the initial investment cost of the sulfur reduction programme, and the investment cost of a new ship consists mainly of the construction price of the new ship. The cost of retrofitting a ship consists mainly of the cost of retrofitting the sulfur reduction programme. A_{ij} is the difference between the total revenue (E_{ij}^{re}) and the total cost for each year of the voyage; that is, $A_{ij} = E_{ij}^{re} - C_{ij}$. While the NPV is greater than or equal to zero, the economic effect of the programme investment is considered to have exceeded or met the predetermined rate of return requirement and the programme is economically feasible; otherwise, it is not a feasible solution. Among the options with a NPV greater than zero, the larger value is preferred:

$$NPV_{ij} = -C_{ij}^{IC} + \sum_{k=0}^{n-1} \frac{A_{ij}}{(1+\varphi)^k}. \quad (7)$$

3.6. Cost-Return Model. The benefit-to-cost ratio is the ratio of the total revenue of the ship to the total cost of the ship over the planning period. Generally, the higher the rate of return on cost, the more efficient the operation of the enterprise and better reflects the effect of the return on the cost of investment. The total revenue of the ship is E_{ij}^{re}, $CT_{ij}^{FC} + CT_{ij}^{OC} + CT_{ij}^{IC}$ is the total cost of the ship, and the discount rate is chosen as $\varphi = 10\%$ in this study:

$$BCR_{ij} = \frac{\sum_{k=1}^{n} E_{ij}^{re} / (1+\varphi)^k}{\sum_{k=1}^{n} CT_{ij}^{FC} + CT_{ij}^{OC} + CT_{ij}^{JC} / (1+\varphi)^k}. \quad (8)$$

4. Case Study

The SOx and CO_2 of different marine sulfur reduction options are calculated based on the emission factors in Table 2.

We selected a container service between Tianjin port (China) and Hamburg port (Germany), which is a major route from China to Europe. The data for the container service were obtained from the company website and our interview, and the vessel information was taken from Clarksons Research [1]. Table 3 presents detailed information on the route and ships involved in the case study.

Marine sulfur reduction programmes using low sulfur oils have the advantage of lower initial investment costs and shorter retrofit cycles. The initial investment cost of using low sulfur oil is derived from surveys and data regression analysis. In this article, we have selected prices from the Clarkson Intelligence website for new building vessels. The cost of a new building vessel using low sulfur oil was 148 million $. The LNG dual-fuel engine ship conversion costs are mainly related to the ship's LNG storage and supply system, dual-fuel engine, and auxiliary electrical system. According to a previous study, the cost of retrofitting a ship with an LNG two-stroke dual-fuel system was 700 ($/KW) [68]. According to the International Ship Network (http://www.eworldship.com/), the initial investment cost of a new LNG DF system is approximately 30% higher than the cost of a new ship using low sulfur oil. In this study, the fixed cost of the vessel is 8,280$/day [39]. The maintenance costs are 0.01725 ($/kWh) for liquefied natural gas (LNG) vessels and 0.0161 ($/kWh) for vessels using MGO [67]. The LNG price is 1795.45 $/ton, and the MGO price is 1,105.94 $/ton. The prices are selected from the Clarkson Intelligence.

We compare the operator's compliance option between LNG fuel and MGO fuel on a specific container route using NPV, BCR, and pollutant gas emission analysis under the following scenarios: (1) current shipping market base conditions; (2) scenarios for different distances; (3) scenarios for fuel price differences; (4) scenarios for different freight rates; and (5) scenarios for different loan ratio.

According to a survey of data from shipping companies, there are currently 11 container vessels deployed on the route. The sailing cycle of the route is maintained at a weekly frequency, and sailing information for the vessels is obtained from the schedule published by the shipping companies. The sailing speed was calculated by selecting the average sailing speed on the different legs of the route.

4.1. Benchmark. According to the information provided by the major shipping company in China, there are currently 11 container ships on the route. To maintain a weekly frequency, the sailing speed V_S should be the average speed of different segments in the actual voyage obtained by ijingzhun (http://www.ijingzhun.com). Figure 1 illustrates the shipping route for a round trip (23573.6 nm).

Figure 2 illustrates the NPV trends of LNG fuel and MGO fuel during the lifespan of the new builds and retrofit vessels in this study for the current benchmark scenario, as well as the NPV at the end of the study period. The use of shipping finance options for new builds vessels has been taken into account in this study, making the difference in initial investment costs between new builds vessels and retrofitting vessels insignificant. In the benchmark case, MGO has a price advantage. The current LNG fuel price is 85.7% higher than before the outbreak of COVID-19, while the MGO price has risen by 36%. This gives the abatement option using MGO fuel of retrofit vessel a clear NPV advantage among the four options on the Central European route. It is obvious that the NPV of the LNG fuel option is always lower.

Table 3: Characteristics of the route and container ships.

The service information	
Vessel capacity (TEU)(1)	19150
Main engine power (kW)(1)	54950
Auxiliary engine power (kW)(1)	8200
Design speed (knots)(1)	22.5
Round-trip distance (nm)	23573.6
Number of trips for a vessel(4)	4
Freight rate(2)	7282.3
Freight rate(2)	615
Number of calls in the round trip (day)(2)	74.15972222
Number of vessels for the service(2)	11
MGO maintenance and servicing (USD/kWh)(3)	0.014
LNG DF maintenance and servicing (USD/kWh)(3)	0.015
Operating costs (USD/day)(4)	8280

(1)Clarksons, World Fleet Register. [1], (2)from our interview with the shipping company. (3)Trivyza et al. [67]. (4)The daily cost refers to [61].

Figure 3 illustrates the BCR at the end of the study period of LNG and MGO during the lifespan of the new builds and retrofit vessels for the current benchmark scenario. In the benchmark case, using MGO fuel of retrofit vessel shows a clear NPV advantage among the four options on the Central European route. It is obvious that the BCR of the new building vessel option is always lower.

Figure 4 illustrates the pollutant emissions of LNG, MGO, and HFO fuel options during the lifespan. We calculated their pollutant emissions based on the fuel emission factors in Table 2, multiplied by the fuel consumption during the study period for the abatement options. The annual CO_2 and SOx emissions from LNG fuel during the study period were 739,203 tons and 15 tons, while the emissions from MGO fuel were 1,067,258 tons and 651 tons. The emissions from HFO were 1,036,632 tons and 17,572 tons. The MGO has a higher CO_2 emission, because the MGO has a higher carbon content compared to the HFO (see Table 2). The MGO also has lower SOx emissions, because it has lower sulfur content compared to the HFO (see Table 2). Compared to MGO, LNG reduces CO_2 and SOx emissions by 98% and 31%, respectively. Thus, although the MGO fuel option has a higher NPV and BCR, it also has higher CO_2 and SOx emissions.

4.2. Scenarios for Different Distances. Under the current situation of the China-Europe container liner route selected in the above study, there will be certain variations in the distance travelled by ship as the ship will use charts to plan the route during the actual voyage according to the actual sea and weather conditions. In addition, due to the impact of the pandemic, in order to ensure that the ships arrive at the destination port on schedule, the increase in ship speed will lead to an increase in fuel consumption, which to a certain

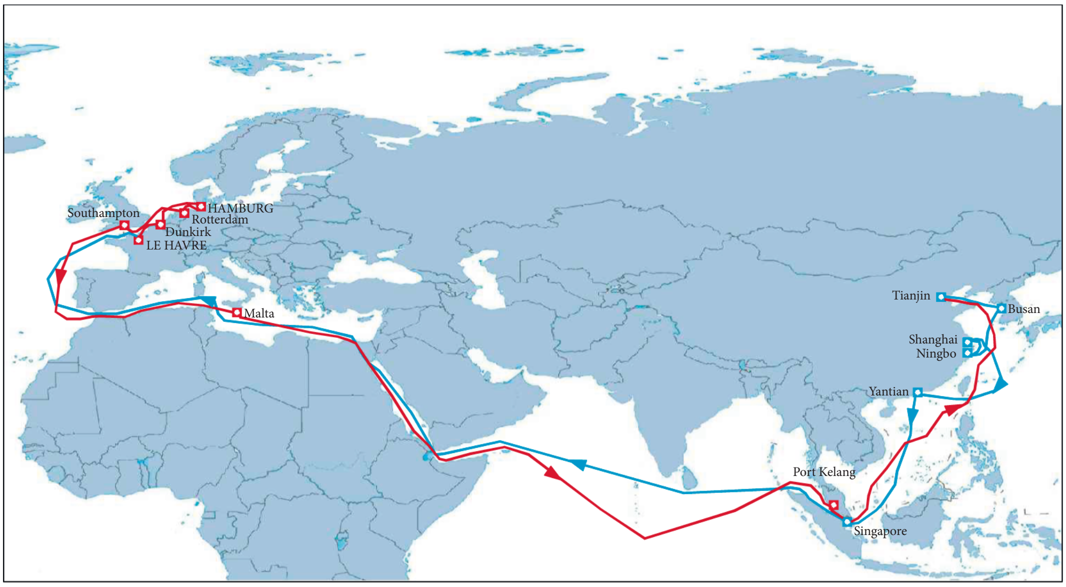

Figure 1: The route of this case study (data source: COSCO SHIPPING Lines (coscon.com)).

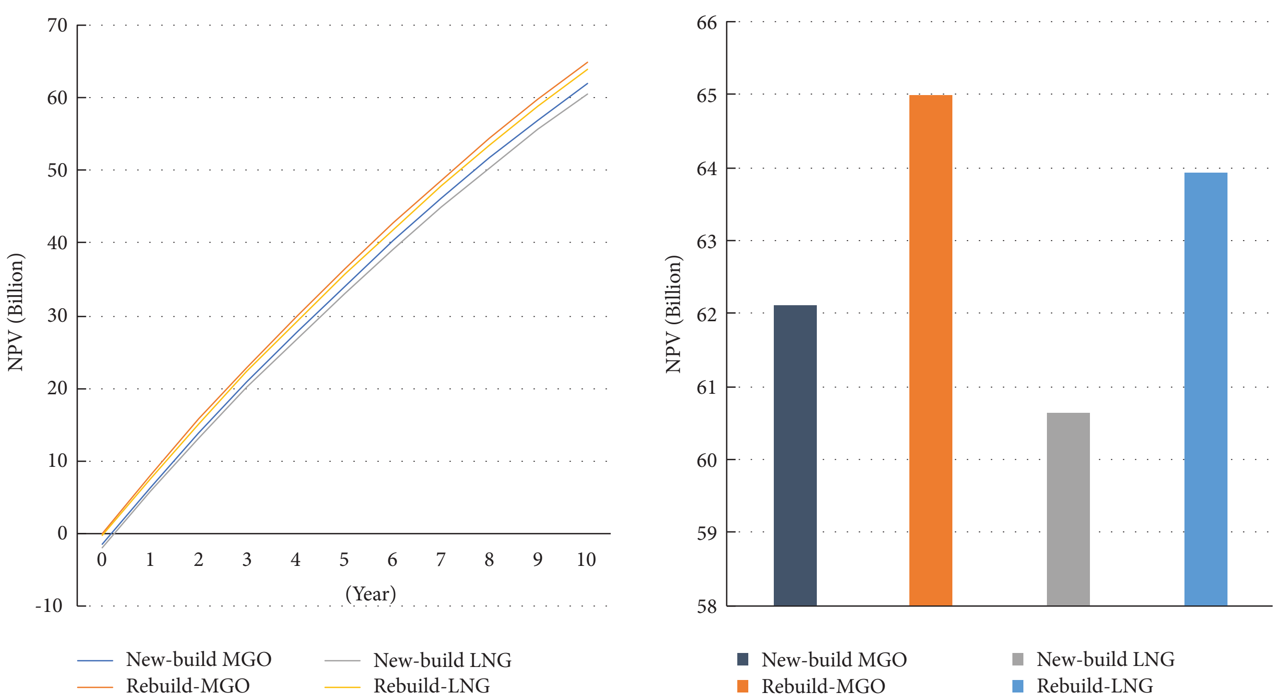

Figure 2: NPVs under the benchmark scenario.

extent will have an impact on the net present value of the fleet and the emission of pollutants. The NPV and BCR are analyzed for three scenarios of 10%, 20%, and 30% increase in sailing distance.

Figure 5 shows the NPV and BCR for the four abatement options at different round-trip distance ratios, which include three different ratios of sailing distances. The NPV of the abatement options decreases progressively with increasing sailing distance. As the distance travelled increases, the cost of fuel increases with distance travelled, resulting in lower NPV and BCR values. Based on the results of the scenarios with different distance increases, the NPV of the reduction option for ships using the retrofit option has a significant advantage. While using the MGO-fuelled vessel abatement option, it had a net present value and a good rate of return on cost and was able to adapt to ocean voyages and maintain good profitability as the voyage distance increased. While using LNG-fuelled vessels to increase route capacity, attention needs to be paid to route design and reduced sailing distances.

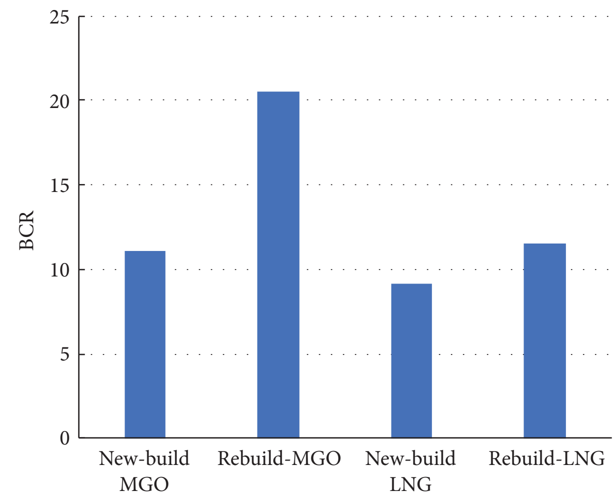

Figure 3: NPVs under the benchmark scenario.

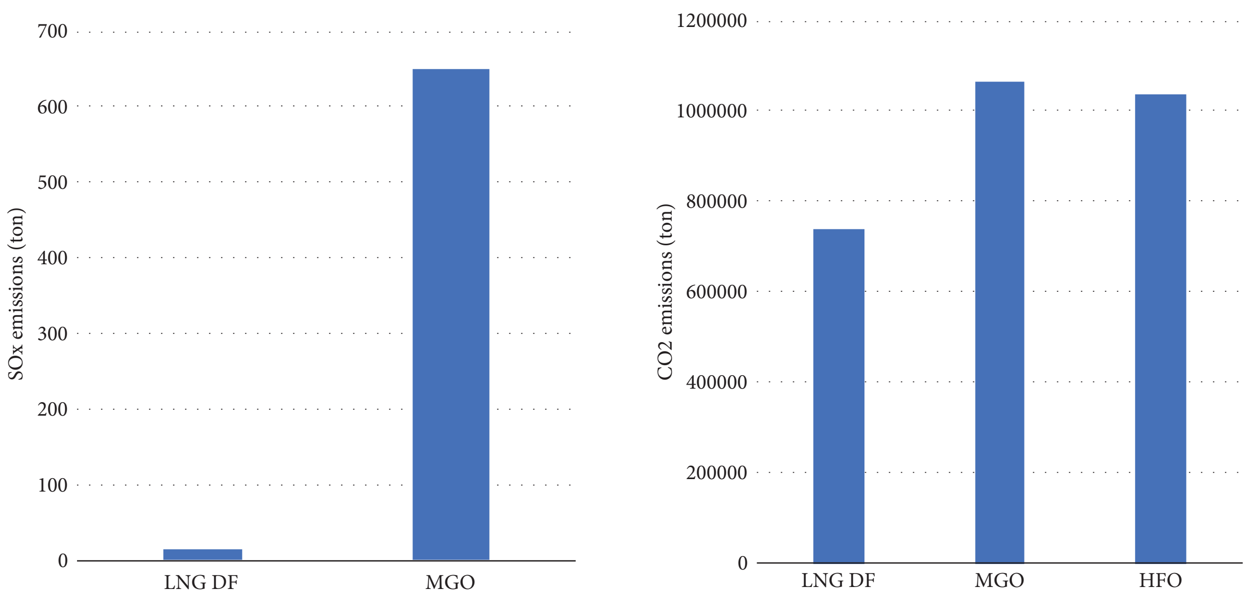

Figure 4: Comparison of SOx and CO_2 emissions between the LNG and MGO options.

As shown in Figure 6, the annual pollutant emissions of the LNG, MGO, and HFO fuel options over the life cycle are illustrated as the distance travelled increases. We calculated their pollutant emissions based on the fuel emission factors in Table 2, multiplied by the fuel consumption of each abatement option over the study period. For LNG, total SOx emissions increased from 16.8 to 20.4 tonnes when the sailing distance increased from 10% to 30%, and the growth rate increased from 10.3% to 33.8%. However, for MGO fuels, the growth rate of SOx emissions increases from 16.5% to 54.3%. It is clear that while the distance travelled with LNG fuels increases from 10% to 30%, the total CO_2 emissions increase from 850,399 tonnes to 1,101,069 tonnes, an increase rate from 14.1% to 29.5%. However, the total CO_2 emissions from MGO increased from 1,243,609 to 1,646,695 tonnes, an increase from 15.5% to 32.4%. The rate of increase in pollutant emissions from MGO has proven to be higher as the distance travelled increases. When undertaking long distance routes, the use of LNG fuel is recommended to be more effective in reducing pollutant emissions.

4.3. Scenarios for Fuel Price Differences. In the post-COVID-19 era, the implementation of dual carbon policies (carbon neutrality and carbon peaking) and the use of LNG as a major low-carbon energy source to reduce greenhouse gas emissions have led to an increase in the demand for cleaner fuels (LNG). The supply of LNG has accelerated the price differential between LNG and MGO [55]. The sensitivity analysis of NPV to different scenarios and possible changes in the price differential is important for the ship operator.

LNG and MGO prices for different periods from March 2019 to March 2022 are shown in Table 4. The price of LNG is approximately US$1,795.45 per tonne recently, while the

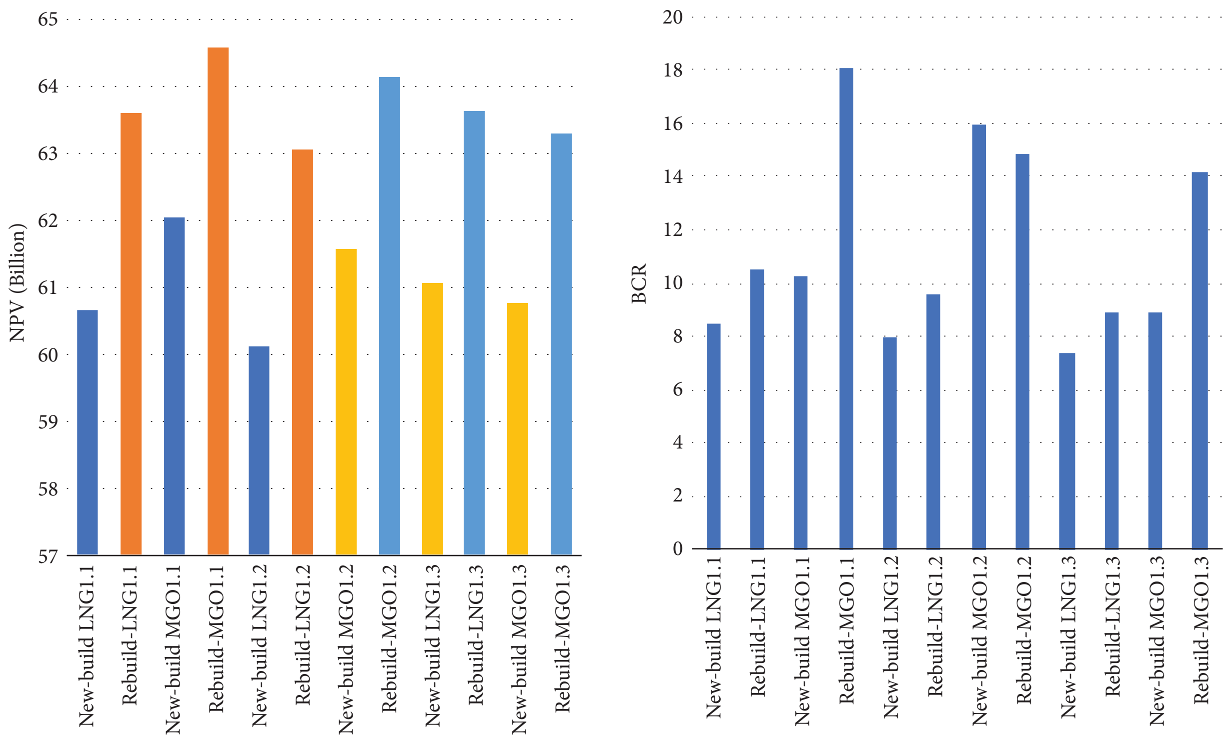

FIGURE 5: Change of NPVs at different route distances.

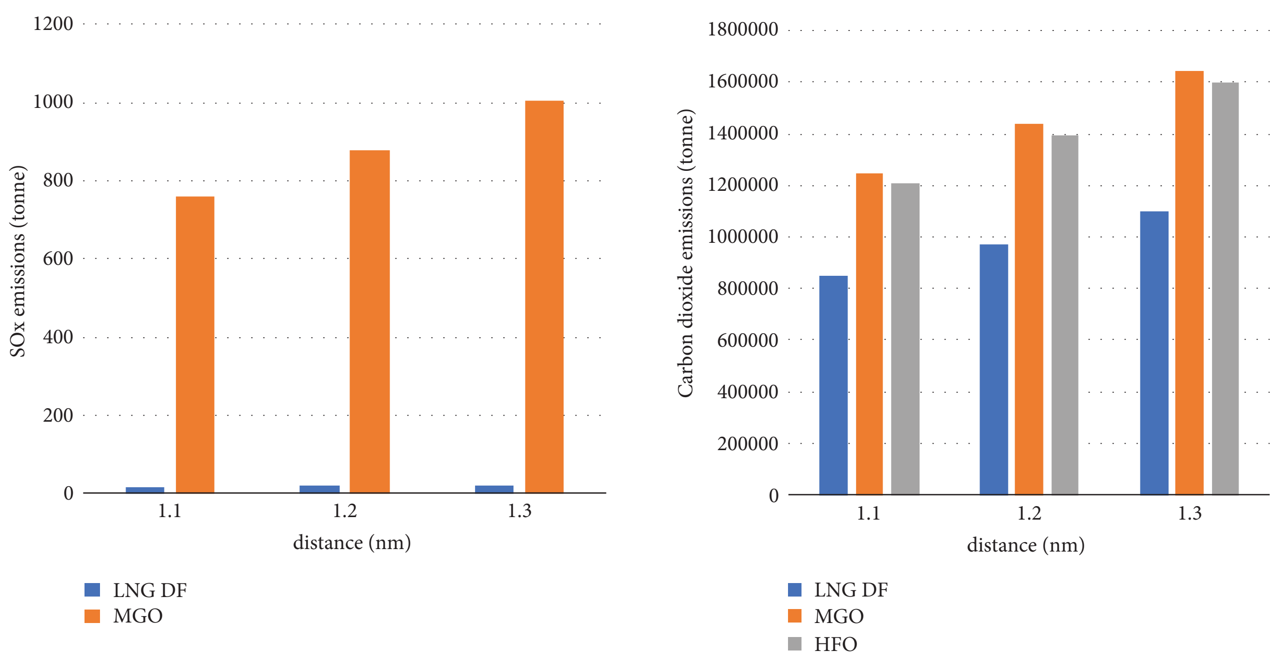

FIGURE 6: SOx and carbon emissions for different route distances.

TABLE 4: Fuel prices at different periods.

Time	LNG (USD/ton)	MGO (USD/ton)
March 2019	256.424	710
March 2020	155.445	414.19
March 2021	307.8775	577.31
March 2022	1795.45	1105.94
Average	546.9	618.75

(Data source: Shipping Intelligence Network (clarksons.net)).

price of MGO is approximately US$1,105.94 per tonne, namely, LNG approximately 62.3% more expensive than MGO.

Based on the NPV and BCR values for the abatement options shown in Figure 7, there is a continuous decrease with increasing fuel prices. In the early part of the pandemic, MGO fuel prices were 1.77 times higher than LNG fuel

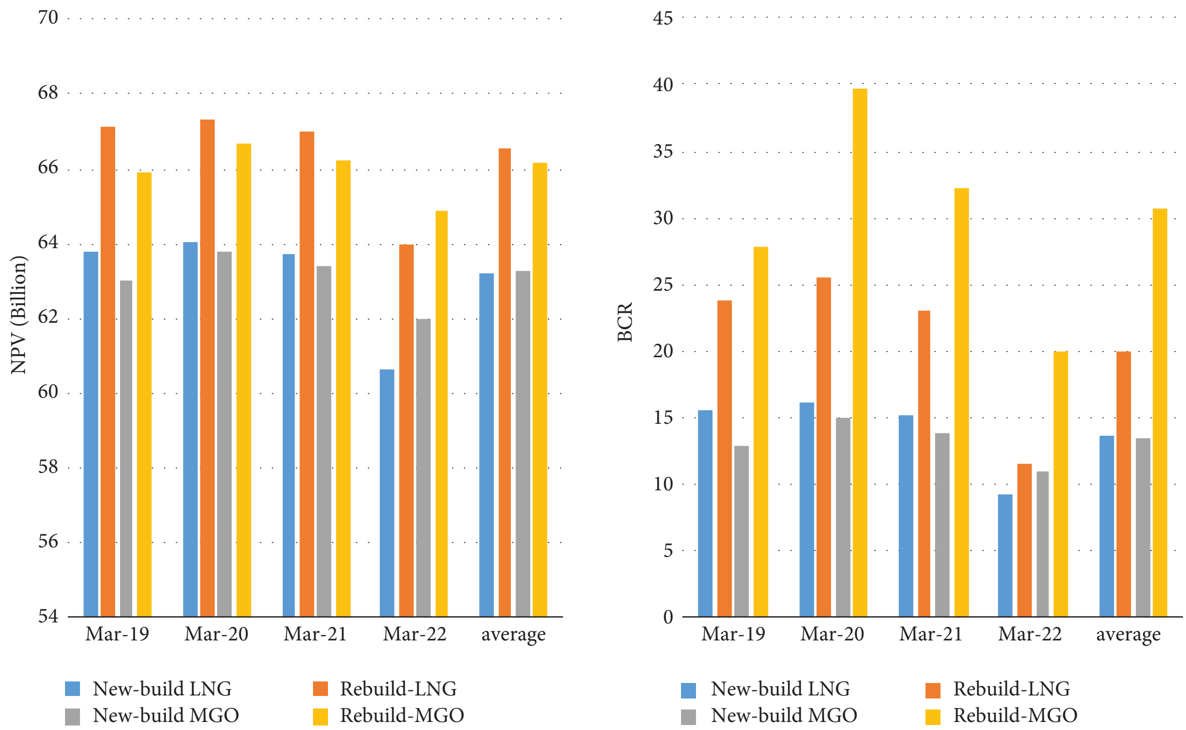

Figure 7: NPV and BCR for different fuel prices.

Table 5: Container freight rates.

Time	Europe-Far East container freight rate	Far East-Europe container freight rate
Mar 2019	637.14286	1382.05
Mar 2020	1191.36364	1452.5
Mar 2021	1609.69565	7529.17391
Mar 2022	1098.73913	13081.69565
Average	1180.660007	5562.8611

(Data source: Shipping Intelligence Network (clarksons.net)).

prices, and the NPV of newbuilds and conversions using the LNG option performed better than the MGO option, while the BCR of newbuilds was smaller than the conversion option due to the larger initial investment costs. With the development of the pandemic, the difference between LNG and MGO prices gradually decreases. The LNG price is 62.3% higher than MGO prices. The ships using the MGO abatement option have better NPV performance. Under current benchmark conditions, the difference between LNG and MGO prices is less than 2%, namely, new LNG vessels more attractive. The NPV of fuel switching gradually decreases as the price difference increases. When the price difference is less than 21.4%, the option of using converted LNG vessels can obtain better emission reduction.

4.4. Scenarios for Different Freight Rates. Compliance options are sensitive to fuel prices and can also be influenced by freight rates. Freight rates on Central European routes are currently running at high levels, and it is difficult to predict future freight rates for shipping companies. To investigate how freight rates affect the choice of abatement options, we use freight rates on the case route for different periods from March 2019 to March 2022 to investigate the impact of the COVID-19 pandemic on the investment decisions for abatement options, with freight rates as shown in Table 5.

Figure 8 illustrates the impact of freight rates on the NPV and BCR of the four abatement options during different periods of the pandemic. We can see that at the beginning of the pandemic, due to the low freight rates, the NPV of using a new LNG vessel is less than 0 at the end of the study period, which cannot recover the investment and does not have investment value. The payback period of a new MGO-fuelled vessel is 5 years, which has good investment value. The net present value of using the converted vessel under different conditions has obvious advantages. While the Far East-Europe container tariff is 1,446.34 ($/TEU) and the Europe-Far East container tariff is 307 ($/TEU), the new LNG vessel just recoups its investment at the end of the study period. While the Far East-Europe container is 1,196.02 ($/TEU) and the Europe-Far East container tariff is 254 ($/TEU), the new MGO vessel could recover the investment within the study period. While Far East-Europe container freight rates are above 1,446.34 ($/TEU) and Europe-Far East container

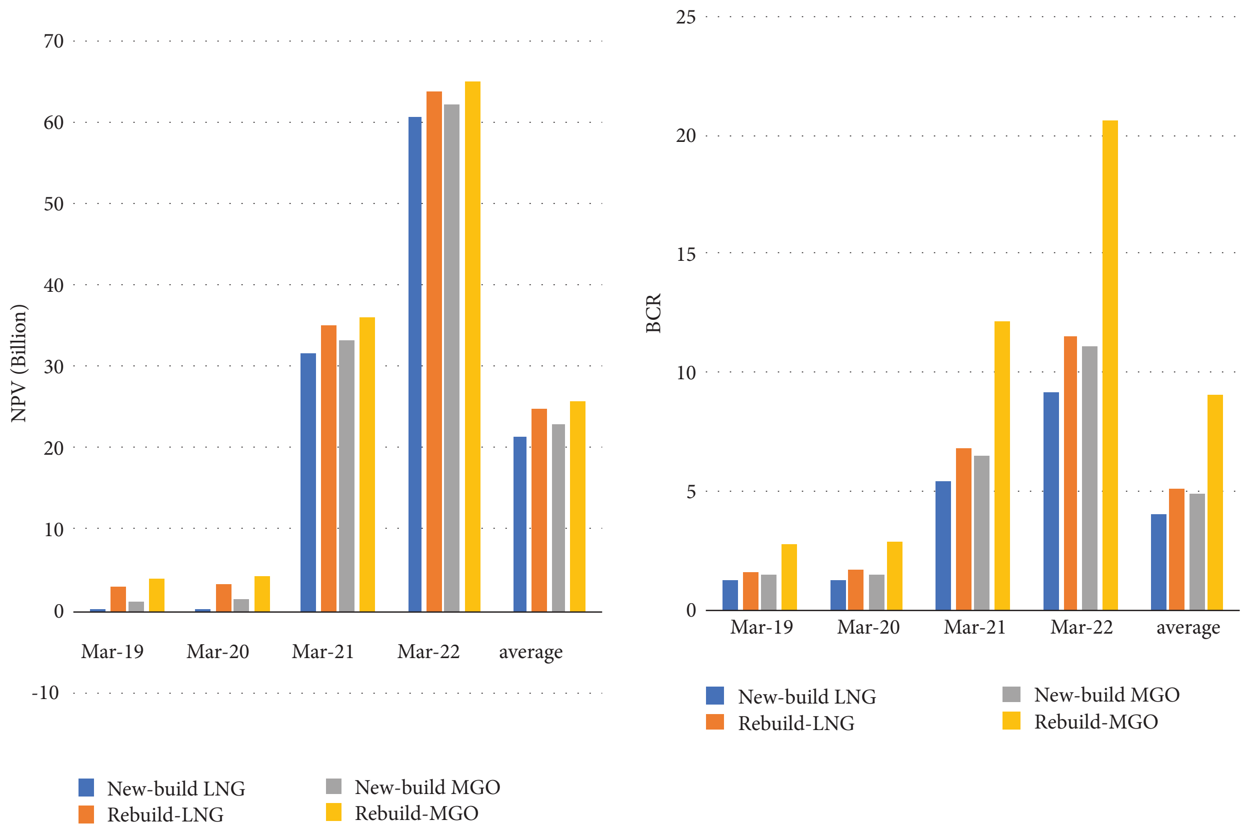

Figure 8: NPV and BCR under different vessel freight rates.

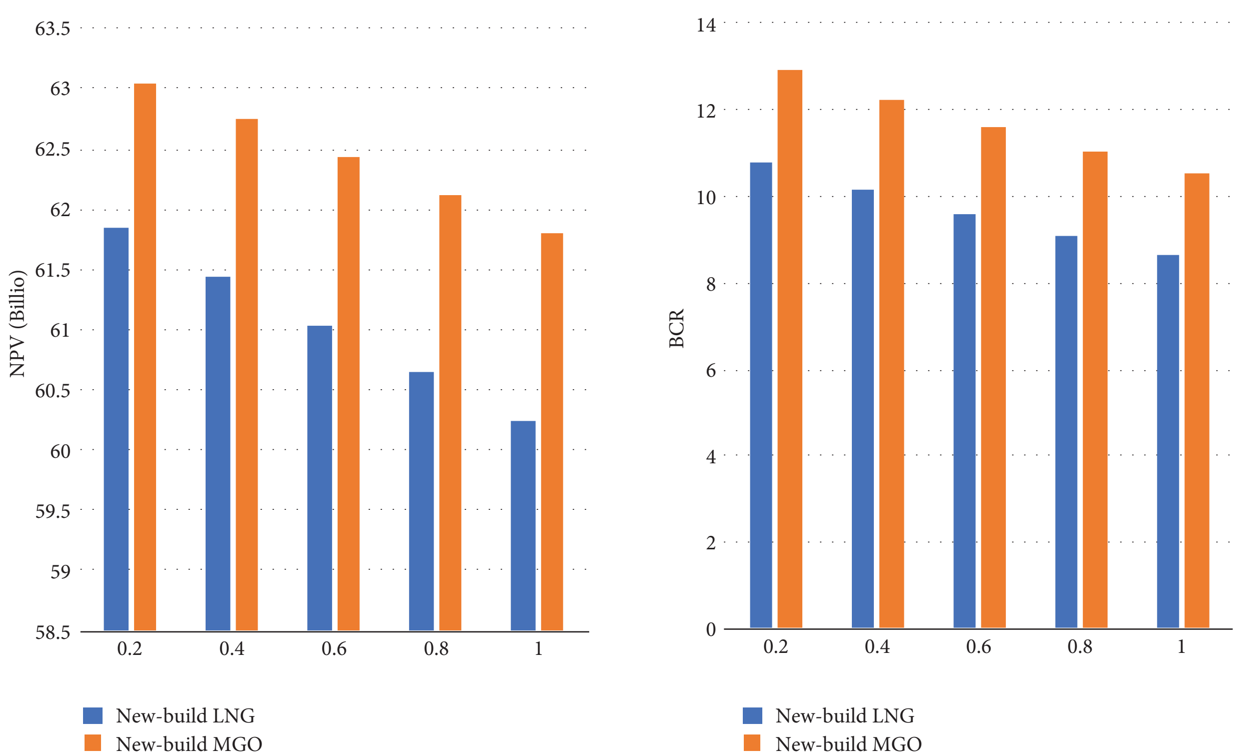

Figure 9: Comparison of the NPV of different initial investment amounts for new ships.

freight rates are above 307 ($/TEU), the LNG option can be chosen to achieve better emission reductions. The results show that ships using the MGO option are more resilient to the impact of a pandemic on container freight rates.

4.5. Scenarios for Different Loan Ratios. The loan ratio is a decision made by the decision-maker based on the shipping market's valuation of future cash flows. While the future cash flow is not optimistic, the loan ratio can be reduced to lower the capital cost of the project. While the future cash flow is more optimistic, the loan ratio can be increased to allow for emission reduction retrofits on more existing ships to fit future more stringent emission reduction policies and route capacity needs. To analyze the sensitivity of compliance options to different loan ratios, we use a 20%–80% interval in our study. Therefore, we compare discount rates of 20%, 40%, 60%, and 80% as shown in Figure 9.

As the loan ratio only affects the capital cost of the abatement option, it does not change the relative position of the two abatement options. Therefore, the MGO option is always better than the LNG option for the same loan ratio. With a higher loan ratio, the net present value of the abatement option is lower. While the ship operator chooses the new building option to increase route capacity and renew fleet capacity, they can appropriately reduce the loan ratio as a proportion of the total investment and increase the NPV of the abatement option.

5. Concluding Remarks

In this article, a quantitative approach is proposed for ship operators to make cost-effective choices. The above case study provides the following conclusions:

(1) Under current baseline conditions, although the NPV of LNG is lower than MGO, it is recommended to choose to retrofit the ship with the MGO fuel option for maximum economic benefits, considering the economic effect of pollutant reduction.

(2) With the advent of the postpandemic era and the introduction and implementation of the dual carbon (carbon neutral and carbon reduction) policy, the price of LNG fuel is gradually higher than that of MGO fuel, resulting in the NPV of the ship abatement scheme using LNG fuel being lower than that of the ship abatement scheme using MGO fuel. With the price of LNG fuel lower than the price of MGO fuel, ship operators can use the LNG ship option to increase the capacity of their routes and obtain better economic returns.

(3) The NPV of the new building option gradually decreases as the proportion of initial investment increases. Ship operators can consider reducing the initial investment amount appropriately to improve the profitability of the program and return on investment.

There are several limitations to this study. Firstly, we assume that the speed is uniform during the voyage, ignoring the acceleration and deceleration processes of the ship. Secondly, it is assumed that the operating time and operating cost of a ship that fits the scheme are over the life of the ship, ignoring the possible degradation of the ship's operating parameters. Thirdly, this article only focuses on the changes of single factors (e.g., sailing distance, fuel price, freight rate) in the compliance scenarios of ship reduction and profitability during the capacity enhancement process, and does not consider the impact of simultaneous changes of multiple factors on the ship's decision.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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