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Article

Cost-Benefit Evaluation on Promising Strategies in Compliance with Low Sulfur Policy of IMO

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Abstract: According to the amendment of the "International Convention for the Marine Prevention of Pollution from Ships" (MARPOL), Annex VI stating that the sulfur content in marine fuel oil cannot exceed 0.5 wt. % came into effect in 2020. This study uses cost-benefit analysis method to evaluate the feasibility and implementation benefits of those strategies. A container ship serving on the ship route is selected as a representative. It is found that the very low-sulfur fuel oil (VLSFO) strategy has a higher total incremental cost than the scrubber strategy in the first 4.14 years, but then, the trend is reversed. After this container ship is equipped with a scrubber, the pollutant emission reduction is 5% higher than the condition of VLSFO only in the first year. The SOx and PM emission reduction rates of VLSFO strategy are higher than that of the scrubber strategy by 9% and 25%, respectively, within five years. In addition, during 3.3 years after the scrubber is installed, the cost-benefit ratio is higher than that of the VLSFO strategy. Hence, the scrubber for the ocean route container ships is merely a short-term compliance strategy within 3.3 years. In contrast, the low sulfur fuel oil strategy that less pollutant is emitted is a compliance strategy for periods longer than 3.3 years.

Keywords: MARPOL; low sulfur fuel oil; scrubber; cost benefit; emission reduction

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1. Introduction

Over 90% of commercial merchandize in the world depends on ocean shipping [1], but the marine main engines generally have high power output, which is fueled by heavy fuel oil with poor quality and high sulfur content. In comparison to land and air transportation, ships emit considerable greenhouse gases. Therefore, ocean shipping is regarded as one of the least environmentally friendly means of goods transportation [2]. Moreover, ship-emission control policies and techniques have lagged behind land and air transportation for a long time, so the ship emission problem is getting worse. The effects of shipping activities on environmental sustainability and climate change have received increasing attention in the last decades [3,4]. The environmental sustainability is considered a more significant dimension than the social and economic dimensions among those three identified dimensions [5,6]. Di vaio and Varriale [7] suggest that managerial accounting instrument such as Balanced Scorecard and Tableau de Bord and training the workforce are effective measures for enforcing green port development. The significant effects of managerial key performance indicators (KPIs) for environment sustainability have been proposed and confirmed in order to reduce the negative environmental influences from shipping operations [8]. Lam and Notteboom [9] evaluated the effectiveness of the use of port management tools by the port authorities in the leading ports in Asia and Europe for achieving green port development and found the port authorities in Antwerp and Rotterdam have higher decisive influences.

There are varying amounts of solid or gaseous pollutant emissions from different ship engines, such as SOx, CO, NOx, PM (particulate matter), and VOCs (volatile organic compounds). According to the report of the International Maritime Organization (IMO), the CO_2 emissions from sea transport accounted for 2.8% of global CO_2 emissions during 2007 to 2012. Without any active improvement strategy, CO_2 emissions from sea transport in 2050 will be higher than that in 2012 by 50~250%. In terms of non-greenhouse gas emission, the ocean shipping industry is one of main sources of SOx emissions. The NOx and SOx emissions from ocean shipping accounted for about 13% and 12% of global total NOx and SOx emissions, respectively [10].

The PM emitted from ships is one of the key sources for environmental pollution. The emission of $PM_{2.5}$ per unit time of a medium sized container ship running with 70% rated engine power is equivalent to the $PM_{2.5}$ emission from 210,000 heavy trucks [11]. The $PM_{2.5}$ emitted from the ocean shipping industry accounts for 3–8% of global mortality caused by $PM_{2.5}$ [12]. The fates of these NOx, SOx, and PM pollutants are influenced by global climate, which may thereafter form secondary pollutants such as fine particulate matter and ozone. Such pollutants move towards lands extensively via the wind, causing severe hazard to human health and ecosystems, and inducing non-negligible climate change, acid rain, and soil acidification [13]. The severe ocean acidification in the northern hemisphere in summer is regarded as the result of the pollutants emitted by ships [14]. The extreme climate is also related to pollutants emitted by ships, such as sulfate aerosol [15]. The global merchant ships consume about 330 million tons of fuel oil annually, 80~85% of which is fuel oil with high sulfur content. With long-term usage of cheap high sulfur fuel oil (HSFO), the exhaust gas from ships contains much SOx, leading to severe environmental pollution, and attracting the close attention of the world community. Hence, it is necessary to effectively reduce the harmful pollutants emitted from ships.

The IMO adopted the "International Convention for the Prevention of Pollution from Ships" (briefly termed MARPOL convention) [16] in 1973 to prevent different contaminants from ships. The MARPOL convention has six annexes for eliminating various pollutions emitted from ships. Annex VI of MARPOL convention specifies air pollutants from ships. In recent years, the quantity and tonnage of ships using diesel engines as their main propelling power have greatly increased, resulting in worsening global air pollution. Therefore, the amendment of MARPOL Annex VI was adopted at the 58th meeting of the Marine Environment Protection Committee under IMO, which regulated that since 1 January 2020, the sulfur content in marine fuel oil shall decrease from 3.5 wt. % to 0.5 wt. %. This low sulfur fuel oil is defined as very low sulfur fuel oil (VLSFO) while high sulfur fuel oil (HSFO) refers to fuel oil with sulfur content higher than 1.0 wt. % [17]. According to the MARPOL convention, a ship running in a SOx Emission Control Area (SECA) with vulnerable environmental conditions shall use relatively clean fuel or fuel oil with sulfur content lower than 0.1%. The code has been in effect since 2015.

This study evaluates the containers' possible compliance strategies to meet low sulfur policy raised by IMO implemented in 1 January 2020. There are two available strategies according to the operating principle: (1) using very low sulfur fuel oil (VLSFO) and (2) installing SOx scrubbers together with using high sulfur fuel oil (HSFO) continuously. The first strategy is easy to use, but the VLSFO has a higher price, so the operating cost is increased. In addition, the lubrication of the main engine parts is deteriorated with low sulfur fuel oil [18]. If the second strategy is used, the containers can continue to use HSFO. However, the scrubber's installation cost is as high as 3–5 million USD in the initial stage.

The above two strategies have different strengths and weaknesses so that the global shipping companies find it difficult to choose the compliance strategy. Therefore, an effective, objective and fair strategy evaluation method is proposed herein as a reference frame for ship owners to choose strategy. Prior studies in the literature emphasized the evaluation method of specific strategies. For example, Kim and Seo [19] used the fuzzy Analytic Hierarchy Process (AHP) method to discuss the cost of investment in VLSFO. Some studies evaluated the influence of a SOx scrubber installed on a merchant ship on the reduction of pollutant emissions and environmental protection [20–22]. Tichavska and Tovar [23] proposed a calculation method of external costs from shipping emissions. Some other articles discussed the technical difficulties of different strategies or evaluated the equipment and operation costs [21,24–27]. However, few documents comprehensively discussed the incremental cost of investment resulting from the low-sulfur policy of IMO and the induced pollutant emission reduction. There is even no literature to evaluate the cost benefit of such various compliance strategies. Therefore, in compliance with the sulfur content reduction policy of the IMO, this study would systematically perform comprehensive evaluations of the amounts of incremental cost, pollutant reduction and cost-benefit of various feasible strategies for determining optimum strategy. The evaluation method and findings of this study can serve as references for ship owners and relevant scholars for policy making or further study.

As the container ship is the foremost type among different merchant ships in view of that the top 10 global shipping companies are running container ships [26]. The pollutants emitted from container ships have significant influence on global air quality. Therefore, this study only takes a container ship (represented by Vessel U) running on the ship route operated by one of top 10 container shipping companies of the world [28] as the research subject. The strengths and weaknesses of various feasible strategies in compliance with the low sulfur fuel oil policy of IMO, the difficulties in implementation and challenges are evaluated comprehensively. The cost-benefit ratios of such feasible strategies are calculated and compared to provide reference for carriers in making decisions in this study.

2. Cost Benefit Analysis for Compliance Strategies

The feasible strategies to be discussed in this study include using VLSFO and installing SOx scrubber, which are represented by Strategy VLSFO and Strategy Scrubber as shown in Table 1.

Table 1. Abbreviations for strategies evaluated in this study.

Strategy	Description
VLSFO	HSFO is replaced by VLSFO ($S \leq 0.5$ wt. %)
Scrubber	Install scrubber and continue to use HSFO ($S \leq 3.5$ wt. %)

The adoption of Strategy VLSFO does not affect refitting of ship equipment, so it requires lower initial investment. However, the lower sulfur content in the fuel oil results in insufficient lubricity of reciprocating parts of the main engine, and the cylinder jacket becomes worn soon [19,29]. Moreover, the increase in the operating cost induced by uncertain international VLSFO price [30] poses a major threat. In terms of Strategy Scrubber, there must be an initial investment in equipment alteration and scrubber installation, so the initial capital cost is higher [30]. In addition, the scrubber permanently occupies cargo space, resulting in operating loss. Moreover, some ports have definitely forbidden open-loop scrubbers. All these factors comprise the weaknesses and threats of Strategy Scrubber. However, the ship can continue to use HSFO of lower price than VLSFO after it is equipped with the scrubber. This is its foremost strength.

This study takes an 8500 twenty-foot equivalent unit (TEU) container vessel (briefly denoted as Vessel U) built in 2012 by Y shipping company, one of the Top 10 container carriers of the world [28] as the research subject. The container ship navigates 42 days per voyage, 8 voyages a year. The nominal power of the main engine at an engine speed 90.8 rpm is 84,024 PS (61,800 kW). The particulars of the ship are shown in Table 2 [31].

The voyage of the ship navigating among international ports is approximately divided into three phases, which are departure from the berth in the port of sailing to open waters, navigation in open waters, and the voyage from open waters to the port of destination. Phase 2 is full-speed running time; in this period, the marine main engine basically remains at full engine speed. The ship uses either HSFO or VLSFO during this phase. As this study aims at the cost-benefit analysis for two compliance strategies (i.e., Strategy VLSFO and Strategy Scrubber), the full-speed running time of the ship is used as the evaluation basis. The actual full-speed running time (6280 h/year) of the container vessel (Vessel U) in 2018 was used as the annual full-speed running time of Vessel U.

Table 2. Particulars of container Vessel U.

Built Year	2012
Total capacity	8500 TEU
MCR (Maximum Continuous Rating)	93,360 PS (at 94 rpm)
NCR (Normal Continuous Rating)	84,024 PS (61,800 kW at 90.8 rpm)
Fuel oil consumption rate	171.8 ± 5% (g/kWh)
Ship route	North America Loop
Days per voyage	42 days
Number of voyages per year	8
Full-speed running time	6280 (h/year)

Source: compiled by the authors from Ref. [31].

This study assumes that the Vessel U navigates east from Hong Kong via Yantian port (in China), Busan (in Korea) to Vancouver (in Canada) and Seattle (in America), and then returns to Hong Kong. The schematic diagram of the ports on the ship route is shown in Figure 1. The round voyage is about 12,229 NMs (Nautical miles), 1 NM = 1.852 km. For example, the distance from Kwangyang to Hong Kong is 1140 NMs and that from Hong Kong to Yantian is 59 NMs.

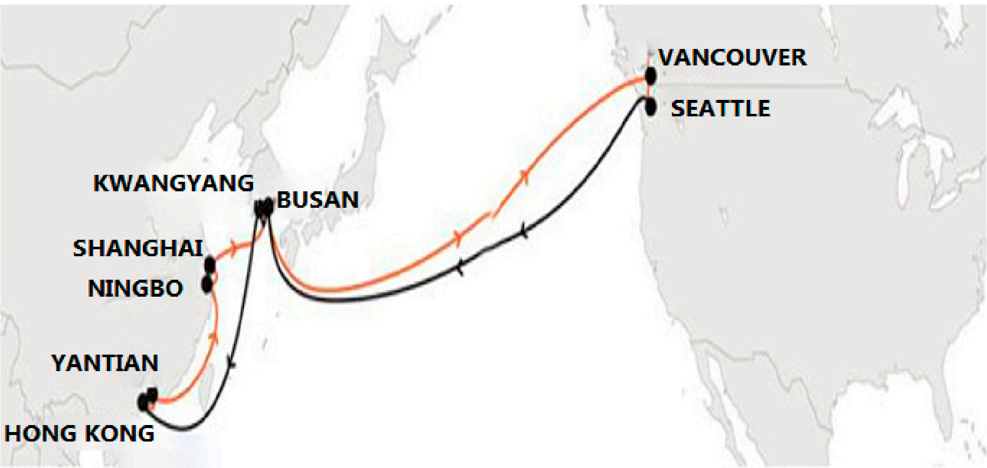

Figure 1. Schematic diagram of the ship route in this study.

3. Calculation Methods for Cost and Emissions

3.1. Estimation of Incremental Cost

This study would evaluate the annual total incremental cost, pollutant emission reduction and cost-benefit ratios after implementing different strategies in compliance with low-sulfur fuel oil policy of IMO. The calculation approaches for different items of incremental cost of different strategies are first described.

This study will use incremental cost to estimate the cost increase by implementing different compliance strategies. The items of incremental cost of installing a scrubber include the scrubber installation cost, 30~45 days' shipping loss and the payment for the crews during the scrubber installation period, and the fuel consumption cost for ship navigation. The two strategies have different cost items approximately divided into capital expenditure (denoted as CAPEX) and operating expense (as OPEX). The cost items of CAPEX and OPEX for implementing Strategy VLSFO and Strategy Scrubber are listed in Table 3.

Table 3. Cost items of implementing Strategy very low-sulfur fuel oil (VLSFO) and Strategy Scrubber.

Cost Item	**Strategy**	
	VLSFO	**Scrubber**
CAPEX	Nil	1. Scrubber equipment cost; 2. Scrubber installation cost; 3. Shipping loss during scrubber installation; 4. Crew salary cost during scrubber installation.
OPEX	1. Cost difference between VLSFO and HSFO; 2. Cost of fuel oil additive; 3. VLSFO surcharge cost.	1. Scrubber maintenance cost; 2. Cargo space loss cost for installing scrubber.

The calculation approaches for the total incremental cost of Strategy VLSFO and Strategy Scrubber are described below.

3.1.1. Calculation of Total Incremental Cost of Strategy VLSFO

The total incremental cost of Strategy VLSFO includes CAPEX and OPEX, expressed as Equation (1):

$$(\text{Total incremental cost})_{\text{VLSFO}} = \text{CAPEX}_{\text{VLSFO}} + \text{OPEX}_{\text{VLSFO}} \tag{1}$$

where the subscript VLSFO represents Strategy VLSFO. It is unnecessary to increase equipment when the HSFO is replaced by VLSFO, so its $\text{CAPEX}_{\text{VLSFO}}$ is 0. The calculation of $\text{OPEX}_{\text{VLSFO}}$ is expressed as Equation (2), including the price difference between VLSFO and HSFO (i.e., incremental cost of fuel oil), fuel oil additive cost and VLSFO surcharge cost.

$$\text{OPEX}_{\text{VLSFO}} = (\text{cost difference value between VLSFO and HSFO} + \text{fuel oil additive cost} - \text{VLSFO surcharge cost}) \tag{2}$$

The VLSFO price fluctuates with the international crude oil price and marine fuel oil price. The carriers generally forecast the future oil prices according to reliable information. This study uses the oil prices of HSFO and VLSFO during 2020 to 2023 forecasted by Drewry [32], as shown in Figure 2 as the yearly prices (USD/ton) of HSFO and VLSFO in the 5 years after the compliance strategy is implemented. Drewry [32] inferred that in the next five years, the price of HSFO will rise slowly year by year, but the price of VLSFO will fall rapidly. Hence, the price difference between the two fuel oils will be reduced gradually.

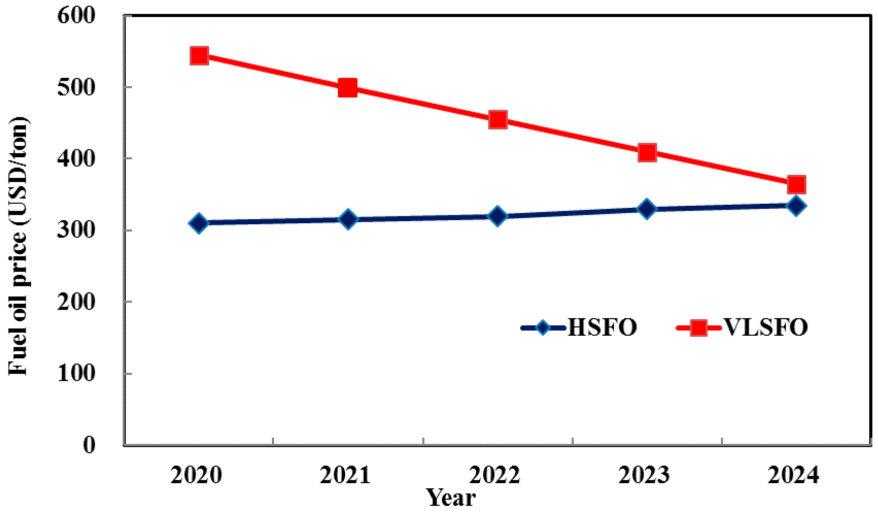

Figure 2. Variation of estimated price of fuel oils in the next 5 years. Source: plotted by authors based on data of [32].

In Equation (2), the cost difference value between VLSFO and HSFO of Vessel U using VLSFO for a round trip voyage on the ship route in a year is calculated by using Equation (3):

$$\begin{gathered}\text{Cost difference value between VLSFO and HSFO (USD/year)} = \text{Fuel oil consumption rate (g/kWh)} \times \\ [\text{VLSFO price} - \text{HSFO price}]\ (\text{USD/ton}) \times \text{full-speed running time (h/year)} \times \text{main engine output} \\ \text{horsepower (kW)} \times 10^{-6}\end{gathered} \tag{3}$$

In Equation (2), the fuel consumption rate (171.8 g/kWh) of the container vessel is based on the particulars of the vessel in Table 2 [31]. In addition, the sulfur content in VLSFO is greatly reduced to curtail the SOx emission in the exhaust gas, but the sulfur compound acts as a lubricant in the fuel oil. As a result, when the sulfur content in the fuel oil is reduced from 3.5 wt. % to 0.5 wt. %, the VLSFO will have insufficient lubrication for the moving parts of the main engine, leading to faster cylinder liner wear of the main engine and leakage loss. The lubricating additive is one of the efficient ways to solve this problem. For example, the lubrication of adding 3% biodiesel into VLSFO for the moving parts is the same as HSFO [33,34]. There are many commercial lubricant additives such as Total Acs and Croda Lubricants [35,36] available but their prices vary largely. Hence, the prices of commercial lubricant additives are hard to be the calculation base for additive cost. In contrast, biodiesel has been widely accepted to be an environmentally friendly, low-carbon and renewable alternative fuel and excellent lubricity additive without sulfur content [37]. Therefore, this study uses the price of biodiesel as the cost of the VLSFO additive. According to Lin and Hwang [38], the price of biodiesel is set as 1245.9 USD/ton, but the price will fall year by year with the maturation and advancement of biodiesel manufacturing technology. The annual price fall rate of biodiesel is set as 5% in this study.

The Low Sulfur Fuel Surcharge (LSS) in Equation (2) is a surcharge of marine transportation cost. As the VLSFO will increase the shipment and delivery cost, the container shipping company collects a surcharge besides ocean freight from the shipper or consignor so that the burden of VLSFO oil price is undertaken together by the shipper and shipping company. Hence, VLSFO surcharge cost is reduced from $\text{OPEX}_{\text{VLSFO}}$ in Equation (2). Generally, the surcharge is 30~70 USD/TEU according to the port of export and container size. The 8500 TEU in this study is a medium sized container ship. The median of the surcharge is 50 USD/TEU, about 10% of VLSFO price. Therefore, the LSS per unit container of each voyage is set as 10% of the annual floating VLSFO price in this study. Vessel U has eight voyages a year, so

$$\begin{gathered}\text{Annual LSS (USD/year)} = \text{number of available cargo spaces} \times \text{LSS per unit cargo space (USD/TEU)} \\ \times\, 2 \times \text{number of voyages/year}\end{gathered} \tag{4}$$

where 2 means each voyage has two ship route segments.

3.1.2. Calculation of Total Incremental Cost of Strategy Scrubber

One of the key factors in the attraction of Strategy Scrubber to carriers is the price difference between HSFO and VLSFO, which will influence whether the scrubber installation cost can be recovered in the lifetime of the ship. The calculation equation for the total incremental cost of this strategy is expressed as follows:

$$(\text{Total incremental cost})_{\text{Scrubber}} = \text{CAPEX}_{\text{Scrubber}} + \text{OPEX}_{\text{Scrubber}} \tag{5}$$

where the subscript Scrubber represents Strategy Scrubber. According to Table 3, the CAPEX of Strategy Scrubber contains scrubber equipment cost, scrubber installation cost, operating loss from scrubber installation and the crew salary cost during the suspension of shipping service for scrubber installation, with the individual items on the right-hand side (RHS) of Equation (5) expressed as

$$\text{CAPEX}_{\text{Scrubber}} = (\text{scrubber equipment cost} + \text{scrubber installation cost} + \text{operating loss from scrubber installation} + \text{crew salary cost during scrubber installation}) \tag{6}$$

After the scrubber is installed, the container continues to use HSFO, so the incremental cost of HSFO is 0. Hence,

$$\text{OPEX}_{\text{Scrubber}} = \text{Scrubber maintenance cost} + \text{cargo space loss for installing scrubber} \tag{7}$$

The scrubber equipment costs and installation costs of newbuilt and retrofit ships are shown in Table 4 according to the report of the Danish Environmental Protection Agency [39]. Referring to the data in this table, the calculation methods for the equipment cost and installation cost of scrubber in Equation (6) are described item by item below:

Table 4. Scrubber equipment cost and installation cost.

SOx Scrubber	Amount	Unit
SOx Scrubber cost (newbuilt)	292	USD/kW
SOx Scrubber cost (retrofit)	327	USD/kW
Installation costs − ships < 6000 kW	3	% of newbuilt
Installation costs − ships ≥ 6000 to <15,000 kW	2	% of newbuilt
Installation costs − ships ≥ 15,000 kW	1	% of newbuilt

Source: compiled by the authors from Ref. [39].

(1) Scrubber equipment cost: The container vessel (Vessel U) has been in service since 2012, so it is applicable to the equipment cost data of retrofit vessel in Table 4, i.e., 327 USD/kW multiplied by the diesel main engine horsepower (61,800 kW) of Vessel U to obtain the equipment cost of the scrubber. Sum-of-the-years'-digits method [40] was used to calculate the annual amount of depreciation and the net amount of the installed scrubber in turn.

(2) Scrubber installation cost: as the nominal output of the main diesel engine of target Vessel U is 61,800 kW which is greater than 15,000 kW, according to Table 4, the scrubber installation cost = Scrubber equipment cost (292 USD/kW) × 1% of main engine nominal output (61,800 kW). This means that the scrubber installation cost is 1% of newbuilt scrubber (i.e., 292 USD/kW) multiplied by the power of main diesel engine.

(3) Operating loss from scrubber installation: The scrubber installation needs about 45 days (i.e., 1.5 months), and the ship stops working during this period. The ship rent is counted daily and varies with ship size. According to the data of Harper Petersen Index (HARPEX), a famous international freight website, the ship rent of an 8500 TEU container is 26,000 USD a day [41].

(4) Crew salary during scrubber installation: When the ship is being equipped with the scrubber in the dockyard, the crew still serves onboard. However, they stop ocean shipping service, so the crew payroll expense must be classified within the total incremental cost. According to the author Wu's 7 years' of experience in working as chief mate of a large container ship, the crew salary of a shipping company varies with rank, ship route and seniority. This item was estimated using the minimum configuration of 16 members of general merchant ships. The crew salaries of various ranks are based on International Transport Workers' Federation (ITF) [42]. Therefore, in Equation (6),

$$\text{Crew salary cost (USD/month)} = (2 \text{ persons (captain and chief engineer)} \times 10{,}000 \text{ USD/person} + 2 \text{ persons (chief mate and second engineer)} \times 6000 \text{ USD/person} + 4 \text{ persons (third mate and engineer)} \times 5000 \text{ USD/month} + 8 \text{ persons (rank B crew)} \times 3000 \text{ USD/person}) \times 1.5 \text{ months} \quad (8)$$

(5) Scrubber operation cost can be calculated by Equation (9)

$$\text{Scrubber operation cost (USD/year)} = [\text{Fuel oil consumption rate (g/kWh)} \times \text{HSFO price (USD/ton)} \times \text{full-speed running time (h/year)} \times \text{main engine output horsepower (kW)} \times 10^{-6}] \times 0.02 \quad (9)$$

where the scrubber is a large equipment, so additional 2% power is required for its operation [43], the scrubber operation HSFO cost shall be then multiplied by 0.02.

For calculating $OPEX_{Scrubber}$ in Equation (7), the methods are described below:

(1) Scrubber maintenance cost: The annual cost of this item is set as 3% of the scrubber price [44].

(2) Cargo space loss for installing scrubber: Alphaliner [45] indicates that the scrubber occupies about 200 TEU cargo space of a 20,150 TEU ultra-large container ship, meaning the scrubber occupies 1% of the total amount of cargo space. Hence, the cargo space occupied by the scrubber is 85 TEU of an 8500 TEU container ship in this study. The container freight rate varies largely with the market supply and demand, and reflects the international situation and oil price. The average container freight rate of Ship Route of North America from 2010 to 2017 is shown in Figure 3 according to the report of the United Nations Conference on Trade and Development (UNCTAD) in 2018 [46]. It is observed that the freight rate decreased greatly during 2010 to 2011, perhaps because the carriers built large vessels in succession, leading to redundant cargo space. This study took the annual container freight rate of the Ship Route in Figure 3 in the last five years as the freight rate from the first to the fifth year after installation, in order to calculate the freight lost because the cargo space was occupied by a scrubber in Equation (10).

$$\text{Annual cargo space loss for installing scrubber (USD/year)} = \text{total amount of cargo space} \times 1\% \times \text{container freight rate (USD/TEU)} \times 2 \times \text{number of voyages/year} \quad (10)$$

where 2 is due to outward and return segments of each voyage.

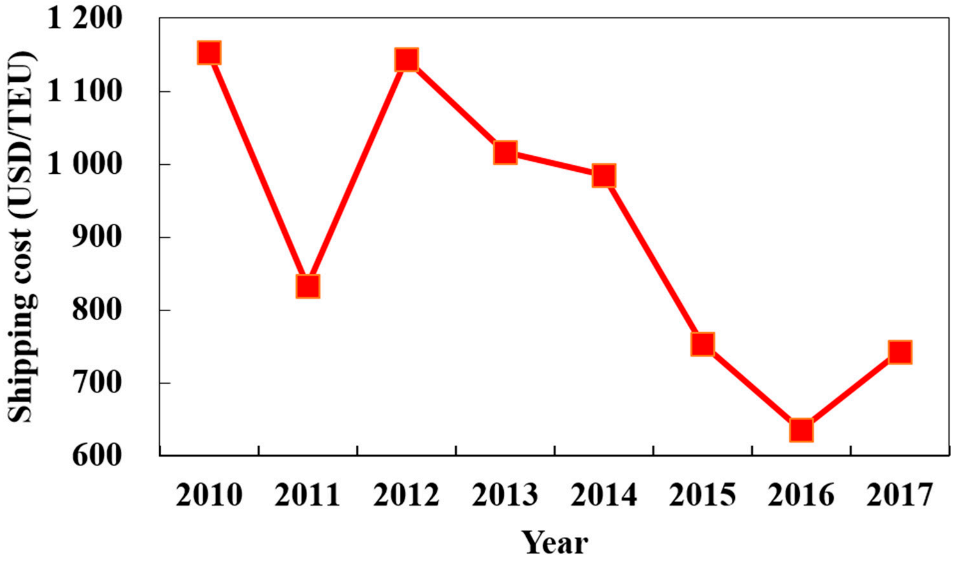

Figure 3. Shipping cost of 20′ container freight in 2010–2017. Source: plotted by authors based on data of [45].

3.2. Calculation of Pollutant Emission

The calculation methods of emission reduction of different pollutants (SOx, NOx, and PM) resulting from using different strategies were described. It is assumed that different pollutants have the same importance or weight for health and environment. The emissions or emission reductions of different pollutants are added directly to obtain the total emission or total emission reduction of different pollutants. As HSFO is used before improvement, the annual emission of a pollutant (e.g., SOx) is estimated by the following equation.

$$\text{Annual emission of a pollutant (tons/year)} = \text{HSFO emission coefficient (g/kWh)} \times \text{marine main engine power (kW)} \times \text{full-speed running time (h/year)} \times 10^{-6} \quad (11)$$

where emission coefficient represents the pollutant emitted (g) from a main diesel engine power (kW) multiplied by running hours (h), the value varies with the application of HSFO or VLSFO [47,48]. If the HFSO is replaced by VLSFO, the emission coefficient of SOx decreases from 13 g/kWh to 2 g/kWh. The emission coefficients of different pollutants of HSFO and VLSFO are shown in Table 5. To calculate the pollutant emission from VLSFO, the HSFO emission coefficient (g/kWh) in Equation (11) is changed to VLSFO emission coefficient (g/kWh).

Table 5. Emission coefficients (g/kWh) of different pollutants emitted from burning HSFO or VLSFO. Source: plotted by authors based on data of [47,48].

Fuel Type	SOx	NOx	PM	COx
HSFO (S < 3.5 wt. %)	13	12	1.5	630
VLSFO (S < 0.5 wt. %)	2	8	0.25	630

In Equation (11), the full-speed running time of this Vessel U is 6280 h/year, and the marine main engine horsepower is 61,800 kW.

After the Vessel U is equipped with the scrubber, the pollutant emission from the ship is reduced. The annual emission reduction of a pollutant (tons/year) can be calculated according to the following equation:

$$\text{Emission reduction of a pollutant (tons/year)} = \text{HSFO emission coefficient (g/kWh)} \times \text{reduction rate of scrubber for a pollutant (\%)} \times [1 - \text{annual performance deterioration rate of scrubber (\%/year)}] \times \text{marine main engine horsepower (kW)} \times \text{full-speed running time (h/year)} \times 10^{-6} \quad (12)$$

where the annual performance deterioration rate of the scrubber means the performance of a scrubber will deteriorate gradually with service time. The period of cost recovery or lifetime of a scrubber for remaining adequate scrubbing performance is about 10 years [49]. Therefore, the annual performance deterioration rate of the scrubber is assumed as 10% in this study. In addition, according to the test result of Panasiuk and Turkina [50], the reduction rate of a scrubber for the PM emitted from the diesel main engine is 60~85%, and the SOx reduction rate is 90~98%. The PM and SOx reduction rates after the ship is equipped with a scrubber are taken as averaged values of 73% and 94%, respectively.

The ship pollutant emission is reduced after the VLSFO is used, so the annual emission reduction of a pollutant (tons/year) can be calculated according to the following equation:

$$\text{Emission reduction of a pollutant (tons/year)} = \text{annual emission of a pollutant (tons/year)} - [\text{VLSFO emission coefficient (g/kWh)} \times \text{marine main engine horsepower (kW)} \times \text{full-speed running time (h/year)} \times 10^{-6}] \quad (13)$$

where the annual emission of a pollutant (tons/year) is calculated by Equation (11).

To calculate the total pollutant emission reduction and total pollutant emission reduction rate in five years upon the implementation of a strategy, the equations are expressed as follows:

$$\text{Total pollutant emission reduction in five years} = \text{total emission of a pollutant within five years using HSFO} - \text{total emission of a pollutant within five years upon the implementation of an improvement strategy} \quad (14)$$

$$\text{Total pollutant emission reduction rate in five years (\%)} = \text{total pollutant emission reduction in five years/total pollutant emission in five years using HSFO} \times 100\% \quad (15)$$

3.3. Cost-Benefit Analysis Method

The cost-benefit analysis compares the costs and benefits of implementing a strategy. This method aims to find out the maximum benefit at the minimum cost. The cost-benefit ratios of a merchant ship using Strategy VLSFO and Strategy Scrubber are compared to determine which strategy shall be implemented first. The benefit defined in this study is the total pollutant emission reduction (tons/year) after the strategy is implemented. The Cost-Benefit Ratio (CBR) of a strategy is calculated as follows.

$$\text{CBR (Cost-Benefit Ratio)} = \text{total pollutant emission reduction (tons)/total required incremental cost (kUSD)} \quad (16)$$

The unit kUSD is thousand (k) United States Dollar (USD). This study calculates the ratio of total pollutant emission reduction and total incremental cost to evaluate the promising strategy. If a strategy has a high CBR, it meaning it has higher cost benefit and large total pollutant emission reduction under the same total incremental cost, it can then be a preferential strategy.

4. Results and Discussion

4.1. Comparison of Incremental Costs of Strategies

The total incremental cost of adopting Strategy VLSFO is calculated according to Equation (1). The LSS cost is the extra charge collected by the carrier from the shipper for the replacement of VLSFO, calculated by Equation (4). The results of incremental costs from the first year to the fifth year are shown in Table 6.

According to Table 6, the total incremental cost of Strategy VLSFO in five years is 39,888 kUSD. The annual fuel oil cost of HSFO without any strategy can be calculated by Equation (9). The fuel oil costs from the first year to the fifth year are added together to obtain the total fuel oil cost in five years, which is 107,348 kUSD.

Table 6. Incremental costs of Strategy VLSFO.

Year of Implementing Strategy	VLSFO Price (USD/Ton)	HSFO Price (USD/ton)	Cost Difference between VLSFO and HSFO (kUSD/Year)	Fuel Additive Cost (kUSD/Year)	LSS Cost (kUSD/Year)	Total Incremental Cost (kUSD/Year)
1st year	545	310	15,595	2480	3672	14,403
2nd year	500	315	12,277	2356	3400	11,233
3rd year	455	320	8959	2232	3060	8131
4th year	410	330	5309	2108	2788	4629
5th year	365	335	1990	1984	2482	1492
Total of five years	-	-	-	-	-	39,888

Figure 2 shows the estimated international oil price variation; the VLSFO price falls year by year, but the HSFO price rises. In consequence, the price discrepancy between the HSFO and VLSFO decreases rapidly. Therefore, the total incremental cost decreases from 14,403 kUSD in the first year to 1492 kUSD in the fifth year, which is only 10% of the first year.

The total incremental cost of adopting Strategy Scrubber to meet low sulfur regulation of IMO is calculated based on Equation (5). The service life of scrubber is estimated to be 10 years. This study uses sum-of-the-years'-digits [40] to amortize the annual scrubber equipment cost.

The cargo space loss for installing scrubber is calculated by Equation (10). This study assumes that the scrubber occupies 1% of the total amount of cargo space (85 cargo spaces) of this container ship (Vessel U). The average freight rate (USD/TEU) per cargo space uses the data in Figure 3. In addition, a voyage of Vessel U lasts about 42 days with 8 voyages a year. The total incremental cost in 1~5 years after the scrubber is installed is shown in Table 7. The unit kUSD (thousand United States Dollar) is used.

Table 7. Total incremental cost after Strategy Scrubber is implemented unit: kUSD.

	CAPEX			OPEX		Total Incremental Cost in Five Years
	Scrubber Equipment Cost	Shipping Loss Cost during Scrubber Installation	Other	Scrubber Maintenance Cost	Cargo Space Loss from Scrubber	
1st year	5608	390	38	612	1382	8030
2nd year	4486	312	30	612	1340	6780
3rd year	3365	234	23	612	1024	5267
4th year	2243	156	15	612	865	3891
5th year	1121	78	8	612	1010	2829

According to Table 7, the scrubber equipment cost is the major one among various incremental costs for Strategy Scrubber, and it decreases slowly year by year. The annual scrubber costs from the 1st to the 5th year were calculated based on the sum-of-the years'-digits method [40]. The other cost listed in the capex cost in Table 7 included the operating cost from scrubber installation and crew salary cost during scrubber installation based on Equation (6). The scrubber cargo space loss cost varies with the market supply and demand of cargo space. The other incremental costs mostly decrease or remain steady. Therefore, the total incremental cost after Strategy Scrubber is implemented decreases slightly since the first year. The total incremental cost in five years is 28,924 kUSD.

The total incremental cost resulting from using Strategy VLSFO decreases rapidly from 14,404 kUSD in the first year after installation to 1493 kUSD in the fifth year as shown in Figure 4. The price difference between HSFO and VLSFO is estimated to decrease from 235 USD/ton in the first year after the strategy is implemented to 30 USD/ton in the fifth year. Moreover, the fuel oil additive price will fall year by year as the manufacturing technology of fuel additive matures, so the total incremental cost of Strategy VLSFO will decrease gradually. In fact, the total incremental cost of Strategy VLSFO depends mainly on the price of VLSFO. When the Strategy VLSFO is taken, the major risk to the carrier is the uncertainty of the VLSFO price. However, the VLSFO surcharge fluctuates with the VLSFO price, so the risks induced by the fluctuation of oil price will be shared by the carrier and shipper [51].

The total incremental cost of Strategy Scrubber decreases relatively slowly from 8030 kUSD in the first year to 2829 kUSD in the fifth year after installation as shown in Figure 4. Because the initial investment in scrubber installation is large, but the estimated oil price increasing amplitude of HSFO in the next 5 years is very small, the annual total incremental cost decreases with the decrease of CAPEX. In addition, the loss of cargo space cost from the scrubber installation varies with average freight rate, so the decreasing amplitude of total incremental cost changes yearly. It is noteworthy that in comparison to Strategy VLSFO, the main risk of Strategy Scrubber to the carrier is the large initial investment amount. The scrubber equipment is a major cost item of initial investment [19].

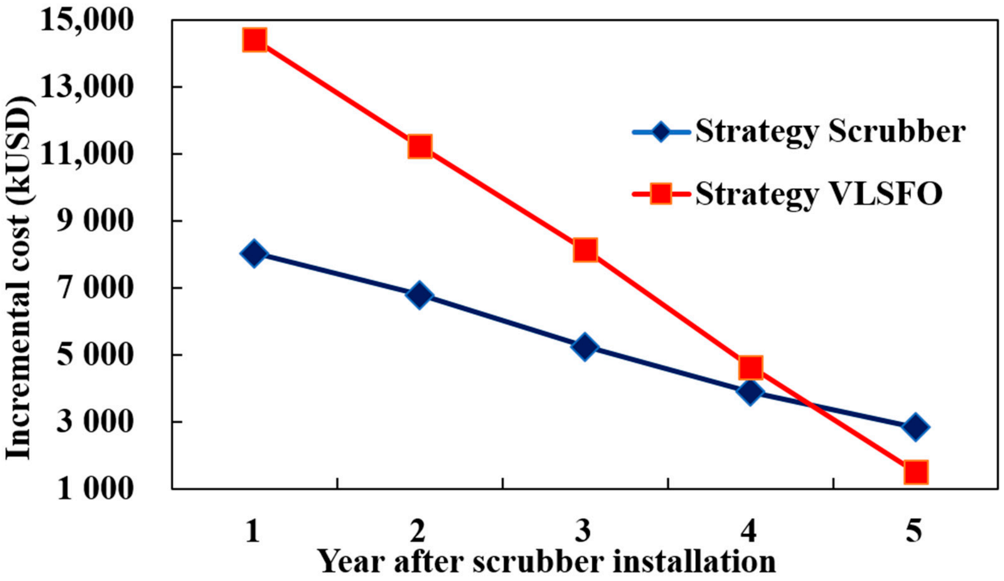

Figure 4. Total incremental costs in 1~5 years after Strategy VLSFO and Strategy Scrubber are implemented.

The total incremental cost of Strategy Scrubber in five years is 28,924 kUSD, which cost is increased by 27% compared with that without taking any strategy. In addition, according to Figure 4, the total incremental cost of Strategy VLSFO in the first year is a little higher than Strategy Scrubber, which is 6373 kUSD. The difference of annual incremental cost between those two strategies then decreases year by year, and in 4.14 years after the strategy implementation, the incremental cost of Strategy Scrubber crosses the total incremental cost of Strategy VLSFO, which is 4279 kUSD. The total incremental cost of Strategy Scrubber is then higher than Strategy VLSFO. The total incremental cost of Strategy VLSFO in the fifth year decreases greatly, perhaps because the price of VLSFO falls greatly to significantly reduce the price difference between HSFO and VLSFO.

The total incremental cost in five years of implementing Strategy VLSFO is 39,888 kUSD, which is higher than 28,924 kUSD of Strategy Scrubber by 38%. The price difference between HSFO and VLSFO is the key factor determining the total incremental cost in five years of the two strategies. According to the author's 7 years' service experience working on container ships, a 25-year-old 1000 TEU container ship consumes 15–20 tons of fuel oil a day. The scrubber installation cost may not be recovered before the ship is discarded. Hence, it is not suggested that the carrier chooses Strategy Scrubber. On the contrary, a 25-year-old container ship with cargo space of 6000 TEU may consume 150 tons of fuel oil a day. The period of scrubber cost recovery is obviously shortened. A younger container vessel with larger cargo space has longer operating life and shortened time of cost recovery after a scrubber is installed. In contrast, when the ship is old or small or has less cargo space, using VLSFO rather than installing a scrubber is preferential, which finding agrees with Lindstad et al. [29]. In addition, after practical operation on the installed scrubber for a few months, a few owners and marine engineers of container vessels complain of high maintenance costs and long period of payback of the scrubber [52].

4.2. Comparison of Pollutant Emission Reduction of Strategies

The pollutant emission reduction of different strategies is also required for cost-benefit evaluation. The reduction amount of ship pollutant emission is calculated by Equation (12) for Strategy VLSFO. The marine main engine horsepower is 61,800 kW, and the full-speed running time is 6280 h/year for Vessel U in this study. The results of annual emission reduction of Strategy VLSFO are shown in Table 8.

Table 8. Annual pollutant emission reduction of Strategy VLSFO.

Pollutant	HSFO Emission Coefficient (g/kWh) [37,38]	VLSFO Emission Coefficient (g/kWh) [37,38]	HSFO Emission (Tons)	VLSFO Emission (Tons)	Pollutant Emission Reduction (Tons)	Total Pollutant Emission Reduction (Tons)
PM	1.5	0.25	582	97	484	5141
NOx	12	8	4657	4269	388	
SOx	13	2	5045	776	4269	
COx	630	630	244,505	244,505	0	

The COx in Table 8 includes CO and CO_2. There is no obvious difference between the COx emissions from HSFO and VLSFO, but significant differences in PM, NOx, and SOx. When the HSFO is replaced by VLSFO, the PM and NOx emission reductions are 484 tons and 388 tons, respectively, and the SOx emission reduction is even as high as 4269 tons. The reduction rates of PM, NOx, and SOx by replacing the fuel oil from HSFO to VLSFO are 88%, 8.3%, and 84.6%, respectively. Therefore, the Strategy VLSFO has quite a significant effect on reducing SOx emission, which result agrees well with Krakowski [53].

The emission reduction of various pollutants of Strategy Scrubber is calculated according to Equation (13). The results of emission reduction of various pollutants in the first year after scrubber installation are shown in Table 9. After the scrubber installation, the reduction rates of PM, SOx, and NOx are 73%, 94%, and 0%, respectively. This implies that the scrubber has little scrubbing effect on NOx.

Table 9. Emission reduction in the first year after scrubber installation.

	HSFO Emission Coefficient (g/kWh)	Emission Reduction Rate (%)	Pollutant Emission Reduction (Tons)	Total Emission Reduction (Tons)
PM	1.5	73	425	5168
NOx	12	0	0	
SOx	13	94	4743	
COx	630	0	0	

As shown in Table 9, the scrubber has a significant effect on reducing the pollutant emission of PM, SOx, and greenhouse gases [54]. The reduced emissions reach 425 tons and 4743 tons, respectively. However, the scrubber performance deteriorates by 10% annually. The Strategy VLSFO has relatively stable pollutant emission reduction, but the emission-scrubbing effect of Strategy Scrubber declines year by year. Therefore, the emission reductions of various pollutants from Vessel U decrease gradually. The annual total pollutant emission reduction after Vessel U adopts Strategy Scrubber is shown in Table 10. In comparison with Tables 8 and 10, the total pollutant emission reduction of the ship using Strategy Scrubber is larger than that using Strategy VLSFO by 5% only in the first year after the strategy implementation. The emission-scrubbing effect declines as the scrubber deteriorates with the service time. The total pollutant emission reduction of Strategy Scrubber is apparently lower than Strategy VLSFO after the second year, and their difference increases year by year. Therefore, Strategy VLSFO could be a relatively environmentally friendly and perpetual option in compliance with the low-sulfur fuel oil regulation of IMO [55].

Table 10. Total pollutant emission reduction (PM + SOx, in tons) in five years after Strategy Scrubber is implemented.

Year of Implementing Strategy				
1st	2nd	3rd	4th	5th
5168	4651	4134	3617	3101

The total pollutant emission reduction and emission reduction rate of SOx and PM after the aforesaid VLSFO and Scrubber strategies are implemented during five years are calculated by Equations (15) and (16). The results are shown in Table 11.

Table 11. Total pollutant emission reduction (tons) and total pollutant emission reduction rate (%) in five years of implementing Strategy VLSFO and Strategy Scrubber.

	SOx Emission			**PM Emission**		
	HSFO	**Strategy VLSFO**	**Strategy Scrubber**	**HSFO**	**Strategy VLSFO**	**Strategy Scrubber**
Total emission in 5 years (tons)	25,227	3881	6256	2911	485	1212
Total pollutant emission reduction in 5 years (tons)	-	21,346	18,971	-	2426	1699
Total pollutant emission reduction rate in 5 years (%)	-	85	75	-	83	58

According to Table 11, after the Strategy VLSFO is used, the SOx and PM emissions will be reduced respectively by 85% and 83% in 5 years. In contrast, the SOx and PM emissions can be reduced respectively by 75% and 58% if Strategy Scrubber is used. This means that the Strategy VLSFO can reduce the SOx and PM emissions from Vessel U more effectively than the latter one. Because the pollutant reduction effect of the scrubber declines, the pollutant emission will be higher than using VLSFO gradually. Moreover, the SOx and PM emission coefficients of burning VLSFO are apparently lower than those of HSFO [56], as shown in Table 8, leading to significantly lower SOx and PM emissions from the ship powered by VLSFO.

The total incremental costs in five years of implementing Strategy VLSFO and Strategy Scrubber are higher than that without any strategy by 37% and 27%, respectively, as shown in Tables 6 and 7. Therefore, Strategy VLSFO requires higher total incremental cost than Strategy Scrubber by 10% in five years, but the former causes more significant reduction effect on pollutant emission [57], particularly for emissions of SOx and particulate matters.

4.3. Comparison of Cost Benefits of Strategies

The cost-benefit ratio (CBR) is defined as the benefit of pollutant emission reduction per unit incremental cost paid by the carrier for adopting a compliance strategy in this study. A strategy with a higher CBR is preferential to be implemented [58]. In the first year of implementing the compliance strategy, Strategy Scrubber has a higher CBR value than Strategy VLSFO. However, the difference between their CBR values decreases gradually because the CBR value of Strategy VLSFO increases rapidly as the price difference between HSFO and VLSFO decreases greatly. Figure 5 shows that in 3.3 years after the strategy implementation, the CBR value of Strategy VLSFO has approached that of Strategy Scrubber. The trend is then reversed; the Strategy VLSFO has a higher CBR value than Strategy Scrubber and the difference between the CBR values of those two strategies increases year by year. In the fifth year, the difference between the CBR values of the two strategies has been 2.39, as shown in Figure 5.

The Strategy Scrubber has higher cost-benefit ratio in the first 3.3 years after the scrubber installation. This implies that it has higher pollutant emission reduction at the same total incremental cost. Hence, this strategy is advantageous in implementation in the first 3.3 years. Afterwards, the Strategy VLSFO has higher cost-benefit ratios than the former one because the VLSFO price falls year by year. The total incremental cost decreases rapidly, resulting in rapid increase of the cost-benefit ratio. In addition, the pollutant scrubbing performance of the scrubber declines year by year, causing the CBR value to increase slowly. In consequence, the CBR value of Scrubber strategy becomes lower than Strategy VLSFO after 3.3 years. The difference of CBR values becomes more and more apparent. Therefore, this study infers that Strategy VLSFO is an intermediate to long-term strategy in compliance with low-sulfur fuel oil regulation of IMO, and Strategy Scrubber is a preferable short-term strategy.

Ocean water, after being pumped by an open-loop scrubber to wash away gaseous and particulate emissions and other toxic matters, flows into the ocean again. Hence, the operation of open-loop scrubber is considered to cause ocean acidification and pollution [59]. The finding agrees with that of Teuchies et al. [60]. Moreover, the cleaning performance of a scrubber decreases gradually with operating time. The costs-benefit ratio (CBR) of a scrubber decreases with its operating period accordingly. In addition, an older vessel installed with a scrubber has shorter operating life to recover the equipment cost. Hence, older vessels or a vessel with less cargo space is suggested to use VLSFO directly in order to comply with the low-sulfur regulation of IMO.

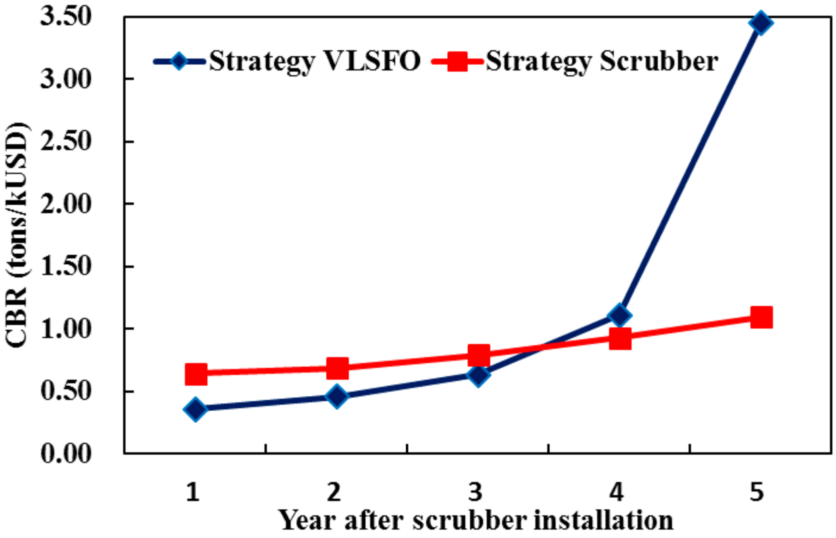

Figure 5. Cost-benefit ratios of Strategy VLSFO and Strategy Scrubber.

5. Conclusions

The cost-benefit approach was applied to evaluate the carriers' compliance strategies for the low-sulfur fuel oil regulation of MARPOL in 2020. Major results are summarized as follows:

(1) In compliance with Annex VI of MARPOL international convention, feasible strategies include using VLSFO and installing a scrubber together with HSFO for oceangoing container ships.

(2) The risks of Strategy VLSFO and Strategy Scrubber are the uncertainty of price difference between HSFO and VLSFO and the too high initial investment cost of scrubber, respectively. If the international oil price difference between HSFO and VLSFO decreases, the period of scrubber cost recovery will be prolonged.

(3) The Strategy VLSFO requires higher total incremental cost than Strategy Scrubber in the first 4.14 years after the strategy implementation. The trend then is reversed and the difference of total incremental cost between those two strategies increases year by year.

(4) The total incremental cost in five years of implementing Strategy VLSFO is higher than that of Strategy Scrubber by 38%. In addition, compared with the condition without taking any pollutant emission control measures, the total incremental cost in five years of Strategy VLSFO and Strategy Scrubber are increased by 37% and 27%, respectively. For the merchant ships at large ages or with less cargo space, this study suggests using VLSFO instead of installing a scrubber.

(5) The pollutant emission reduction of Strategy Scrubber is higher than that of Strategy VLSFO by 5% only in the first year. The performance of scrubber then declines gradually to decrease its pollutant emission reduction effect. The Strategy VLSFO then has higher pollutant emission reduction than Strategy Scrubber and their difference of emission reduction between strategies increases with years.
(6) The total pollutant emission reduction of Strategy VLSFO in five years is apparently higher than that of Strategy Scrubber. The SOx and PM emissions are reduced by 85% and 83%, respectively in 5 years for adopting Strategy VLSFO.
(7) The Strategy Scrubber has higher cost-benefit ratio than Strategy VLSFO at the first 3.3 years after the strategy implementation. The trend of the cost-benefit ratios is then reversed and the difference of the cost-benefit ratios between those two strategies increases year by year.
(8) Using VLSFO is a suitable intermediate to long-term while installing a scrubber is a short-term compliance strategy for the regulation of low-sulfur fuel oil of IMO for the carriers.
(9) The results of cost-benefit ratio in this study might be influenced by shipping route, vessel type, and vessel age, which are not considered here. In addition, sensitivity analysis is suggested to be carried out for relevant research in the future in order to increase extent of objectivity of the study. The sensitivity analysis would be used to measure how the impact of uncertainties of input variables such as scrubber age or VLSFO price can lead to the uncertainties of output variables like operating cost or capital expenditure.

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Abbreviations

AHP	Analytic Hierarchy Process
CAPEX	Capital Expenditure
CBR	Cost-Benefit Ratio
HSFO	High Sulfur Fuel Oil
IMO	International Maritime Organization
kUSD	thousand United States Dollar
MARPOL	International Convention for the Prevention of Pollution from Ships
OPEX	Operating Expense
PM	Particulate Matter
SECA	SOx Emission Control Area
TEU	Twenty-Foot Equivalent Unit
UNCATD	United Nations Conference on Trade and Development
VLSFO	Very Low Sulfur Fuel Oil
VOCs	Volatile Organic Compounds

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