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Scrubber or Mgo: A Carrier's Perspective Under Sulphur Cap 2020

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Abstract

In order to meet the requirements of Sulphur Cap 2020, this paper focuses on several coping strategies of existing liner companies. Currently, there are two main options, namely switching to MGO fuel or apply a scrubber system. In order to compare the two schemes, a mixed-integer linear mathematical model is established, based on the existing mathematical model and discretising techniques. This paper selects the voyage data of COSCO Asia-North Europe route as a case, inputting the data collected into the model constructed. The results show that based on the current oil price level and transportation pattern, the strategy of the vessel modification scrubber system is slightly better than the scheme of switching to Maritime Gas Oil fuel.

Keywords

Liner shipping ; scrubber ; MGO.

1. Introduction

Over the past 40 years, the pace of globalisation has driven significant growth in the shipping industry. The growth of the shipping industry will inevitably drive the growth of maritime trade and the global fleet, which will bring environmental pollution problems. Maritime transport activities not only pose a hazard to the environment (by causing extreme weather such as global warming) but also pose a threat to marine life, where sulfur plays an important role. Wang and Corbett [1] pointed out that the sulphur emissions per ton-mile of a ship's transport cargo are higher than other modes of transport because the ship's fuel contains a higher sulphur content.

In order to control such a difficult situation, IMO [2] introduced stricter sulfur regulations. “From 1 January 2020, the limit for sulphur in fuel oil used onboard ships operating outside designated emission control areas will be reduced to 0.50% m/m (mass by mass). ”In response to such regulations, major shipping companies have responded, such as switching to maritime gas oil(MGO), choosing new building LNG vessels, and installing scrubbers.

Current vessel scrubbers can be classified into dry and wet types. Due to their relatively low price and smaller footprint, wet scrubbers are superior to dry scrubbers. Panasiuk et al. [3] pointed out that there are three main types of wet scrubbers provided by the manufacturer, namely open-loop scrubbers, closed-loop scrubbers, and hybrid scrubbers. The open-loop scrubber system is simpler and more economical to operate than a closed-loop scrubber system. However, its use is limited in waters such as the Baltic Sea. For hybrid scrubber systems, the closed-loop scrubber system does not differ significantly in weight and footprint. Brynolf et al. [4] pointed out that the fuel consumption required for a closed-loop scrubber system is typically about 0.5%. Therefore, in the study herein, the choice of the scrubber was determined to be the choice of whether to install a closed-loop scrubber.

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The investment of vessel scrubber installations is between $3 million and $5 million. Comparing to direct conversion to MGO fuel, this will result in a pre-investment amount; However, the vessel with a scrubber can use the same fuel, heavy oil (HFO) as before. After the installation of the scrubber, the surplus operating cost of the scrubber incurred by the vessel during navigation is much smaller than that of the vessel using MGO fuel directly. In other words, installing scrubber by shipping companies might be a more cost-effective solution.

Dulebenets pointed out that the vessel scheduling model proposed in the existing liner literature generally combines the cost of the vessel route into an objective function. However, Dulebenets believes that the components of the vessel route cost have conflicting nature. For example, the vessel operating cost and the vessel fuel consumption cost generated by the liner company to meet the route demand have conflicting properties. Dulebenets proposed a multi-objective mixed-integer nonlinear mathematical model that divides the ship's route cost into two different parts. That is, the service cost of the route increases with the increase of the time required for the liner route: total vessel weekly operational cost, total container inventory cost, total vessel late arrival cost, and route service cost decrease with the increase of the time required for the liner route: total fuel consumption cost, port handling cost, total CO2 emission cost. Based on this model, Dulebenets derives the optimal solution for both conflicts. However, this paper believes that liner companies should consider the cost of their vessel routes to be integrated into an objective function. Therefore, the model of Dulebenets has been modified. This paper believes that the cost of delays for ships should be treated differently depending on the port of call. Based on the sulfur ceiling regulations issued by IMO, this paper divides the model into a model of ship-to-MGO and a model of a ship-modified scrubber system [5].

The focus of this paper is to find the best strategy to deal with Sulphur cap 2020, in order to avoid potential economic losses, shipping companies can minimise sulfur emissions and improve vessel operations efficiency. In the vessel scheduling problem, the model takes into account the speed of the vessel on the route, the time of arrival at the port, the time of leaving the port, the handling cost of the port of call, and the number of ships required to meet the agreed port service frequency as factors.

This paper is organised as follows: Section 2 describes the problem. Section 3 establishes the mathematical model of green vessel scheduling. Section 4 carries out Empirical analysis. Finally, Conclusions are given in Section 5.

2. Problem Description

2.1 Targeted Routes Choice

This study selected COSCO Shipping's Asian to the European cycle route, as shown in Figure 1. As of April 2019, this route includes 12 ports of call. The information about the port of this route is shown in Table 1.

Figure 1. Asia-North Europe (AEU1) route.

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Table 1. Route port information

Docking port sequence	Port name	Distance to the next port (nautical miles)
1	shanghai	186.7
2	Ningbo	495.4
3	xiamen	291.3
4	Yantian	1476.6
5	Singapore	8351.7
6	Felixstowe	97.5
7	Zeebrugge	946.2
8	Gdansk	757.3
9	Wilhelmshaven	3113.7
10	Piraeus	5475.7
11	Port Kelang	4948.5
12	Hong Kong	858.7
1	Shanghai	

2.2 Service Cost of The Ship

On Asian-North European liner routes, COSCO Shipping will meet the weekly shipping service. The serial number of the port that is scheduled to stop on the liner route is P={1,2,...,n}. COSCO Shipping can choose different handling rates at each port of call si = {h1，h2，…，hi}, (USD/TEUs). The vessel arrives at the port of call within the expected time window (TW). The active time window of the port of call may vary depending on the port, but Dulebenets [5] considers it generally not more than three days.

Once the ship arrives at the port of call, the ship will first be parked at the designated location, then it will be towed to the designated berth by the tugboat, and then the dock cranes of different handling rates will load and unload the containers stored on the ship. Once the vessel arrives at the port of call p after the end of the time window, COSCO Shipping will be subject to additional penalties (the cargo owner's goods are expected to arrive at the port of call at the right time, although the delay does not bring substantial losses to the liner company. However, inevitably, the intangible assets of the liner company (such as credit and customer satisfaction) will be subject to additional penalties). Since the importance of each port of call on the vessel liner route is different, the port of each port is ranked according to the container throughput of the port, and the ratio of weights is divided. Its weight is divided into: Kp={80,48,20,5.5,68,7.5,3,3,1,8,24,40}, (Lloyd’s List [6]). The total cost of vessel delays can be calculated using the following formula:

$$C^{LT}=C_{lt}\sum_{p} K_p T_p^{l} \tag{1}$$

C^{LT} is total cost of vessel delays (USD);

K_p is the weight value of the port p;

C_{lt} is the delay cost of the unit at the port of call (USD/hour);

T_p^{l} is the delay hours of the vessel at the port p.

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Different handling rates correspond to different handling productivity hp_{pi}, $\forall p \in P, i \in s_i$ (TEUs/h). During the duration of the time window, the handling time estimated by the vessel at the port of call p under the handling rate s_i is: $HT_{pi} = \frac{NC_p^{PORT}}{hp_{pi}}$, NC_p^{PORT} is the number of containers that the vessel is handling at the port of call p (TEUs). Then the handling cost of the vessel at the port of call p is $c_{pi}^{pc} = NC_p^{PORT} s_i$ (USD). The total cost of handling containers at the port of call can be calculated by the following formula:

$$C^{TP} = \sum_p \sum_i c_{pi}^{pc} x_{pi} \tag{2}$$

C^{TP} is the total cost of handling containers at the port (USD);

x_{pi} is the decision variable of the handling rate selected by the vessel at the port of call p (if the vessel selects the loading rate s_i for the duration of the time window, it is 1, otherwise 0).

T_p^w is the waiting time for the ship. Once the vessel arrives at the port of call, it will wait at the port of call. This is due to the congestion of the port.

2.3 Vessel Fuel Consumption Costs

This study assumes that a series of homogeneous ships with similar technical characteristics serve this liner route. As of April 2019, the vessel capacity of this route deployed by COSCO Shipping Company was 14,000 TEUs, serving the Asia-North Europe liner service. The fuel consumption of the vessel is positively correlated with the speed of the ship. As emphasized by Wang and Meng [8], the fuel consumption of a vessel is mainly affected by the speed of the ship. According to the existing literature, the fuel consumption of a ship can be estimated using the following relationship:

$$dfc\left(\bar{v}\right) = dfc\left(v^*\right)\left(\frac{\bar{v}}{v^*}\right)^{\alpha} = \beta\left(\bar{v}\right)^{\alpha} \tag{3}$$

$dfc\left(\bar{v}\right)$ is the average daily fuel consumption of the vessel (tons of fuel/day);

$\bar{v}$ is the average daily speed of the vessel (knots);

$dfc\left(v^*\right)$ is average daily fuel consumption when the vessel is sailing at the designed speed (tons of fuel per day);

v^* is vessel design speed (knots)

α and β are the coefficient of fuel consumption function of the vessel.

So FCp is the fuel consumption per nautical mile at voyage leg p, and the total fuel consumption cost on this liner route is calculated using the following formula:

$$FC_p = DFC\left(v_p\right)\left(\frac{T_p^s}{24}\right)\frac{1}{l_p} = \beta\left(v_p\right)^{\alpha}\frac{l_p}{24v_p}\frac{1}{l_p} = \frac{\beta\left(v_p\right)^{\alpha-1}}{24} \tag{4}$$

$$C^{TF} = C_{fc}\sum_p l_p FC_p \tag{5}$$

l_p is the length of the voyage leg connecting between the port p and p+1(nmi);

v_p is the speed of the vessel at voyage leg connecting between the port p and p+1 (knots)

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T_p^s is the time required for the vessel to sailing at voyage leg connecting between the port p and p+1 (h);

C^{TF} is the total cost of fuel required by the vessel throughout the voyage (USD);

C_{fc} is the unit fuel cost required for the vessel to sailing (USD/ton).

Then the sailing time of the vessel on the voyage leg connecting between the port p and p+1 is $T_p^s = \frac{l_p}{v_p}$. In order to make it linearized, this paper will reciprocate the sailing speed of the ship, so that the sailing time can be linearized, namely: $u_p = \frac{1}{v_p}$, $p \in P$. The constraint set (5) is the amount of fuel consumption, which is discretized by the reciprocal velocity value, that is, the set K which is discretized to a finite value K={1, 2, . . . , h}, and calculate the fuel consumption corresponding to the set K of finite values. If the speed at which the vessel is sailing on voyage leg connecting between the port p and p+1 is the reciprocal of its speed value, then let $y_{pk} = 1$ (otherwise be 0). The reciprocal discrete value of the speed of the vessel at the voyage leg connecting between the port p and p+1 is u_{pk}. FC_{pk} is the fuel consumption per nautical mile estimated based on the reciprocal discrete value of the speed of sailing.

2.4 Container inventory cost

The shipping company's route cost also includes the inventory cost of the container. Wang et al. [10] pointed out that the total inventory cost over the entire voyage can be estimated by:

$$C^{IC} = C_{ic} \sum_p T_p^s N_p^{SEA} \tag{6}$$

C^{IC} is the total inventory cost (USD);

C_{ic} is the inventory cost per unit container (US$/(TEUs*h));

N_p^{SEA} is the number of containers that the vessel transports at voyage leg connecting between the port p and p+1 (TEUs).

Once COSCO SHIPPING selects the speed of the upper segment of the liner route from Asia to Europe, the assumed speed of the segment remains unchanged. Since the fuel consumption of the auxiliary engine of the vessel generally does not fluctuate to a large extent during the entire liner route, the cost of the relevant fuel consumption of the auxiliary engine will be attributed to the ship's weekly operating cost (along with the ship's maintenance cost, insurance costs, vessel staff, etc.). This study did not consider the cost of container stocks generated by ships at the port of call. When the vessel is handling services at the port of call, the container inventory cost at this time is generally not borne by the shipping company, so this study did not consider it.

3. Mathematical Model

In this section of the paper, the proposed mixed-integer linear model is mathematically constructed, and its solution is described. One is that the vessel is converted to MGO fuel to meet the requirements, called VSP1; the other is the vessel modified scrubber system, using HFO fuel, called VSP2.

3.1 Terminology

Set

P={1,2,…,n} is a set of ports of call visited on the liner route;

$s_p=\{h_1,h_2,\ldots,h_i\}, \forall i \in N, \forall p \in P$ is a set of available handling rates to the vessel at the port of call p(USD);

$K_p=\{K_1,K_2,\ldots,K_p\}, \forall p \in P$ is the weight set of the port p;

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$l_t=\{l_1,l_2,\ldots,l_t\}, \forall p \in P$ is a set of lengths connecting the port p and p+1(nautical miles);
K={1,2,…,h} is the inverse value of the sailing speed is discretized into a finite set;
Decision variables
$x_{pi} \in \{0,1\}, i \in s_i$ is a binary variable. If the vessel selects the handling rate s_i for the duration of the time window of the port p, it is 1. Otherwise it is 0;
$y_{pk} \in \{0,1\}, k \in K$ is a binary variable. If the vessel is selected at the voyage leg connecting between the port p and p+1, the reciprocal of a certain speed value is 1, otherwise 0;
Auxiliary variables
$n \in N$ is the number of ports of call on the round route;
$Q \in N$ is the number of vessels meeting the frequency of service at each port on the liner route;
$u_p, \forall p \in P$ is the reciprocal value of the speed of the vessel at voyage leg between the port p and port p+1;
$T_p^a \in R^+$ is the arrival time of the vessel at the port p (h);
$T_p^d \in R^+$ is the departure time of the vessel at the port p (h);
$T_p^w \in R^+$ is the waiting time of the vessel at the port p (h);
$T_p^s \in R^+$ is the sailing time of the vessel at the voyage leg connecting between the port p and p+1 (h);
$T_p^l \in R^+$ is the delay time of the vessel at the port p (h);
$T_p \in R^+$ is the virtual time of the vessel at the port p (for the compensation value of the vessel delay time) (h);
$T^v \in R^+$ is the compensation time for the entire voyage to meet the required number of ships(h);
$FC_p \in R^+$ is the amount of fuel consumed per nautical mile at the voyage leg connecting between the port p and p+1 (ton/nmi);
$FC_p^o \in R^+$ is the amount of fuel per nautical mile consumed by the vessel operating the scrubber system at the voyage leg connecting between the port p and p+1 (ton/nmi);
Parameters
C_{fc} is the unit fuel cost required for the vessel to sail (USD/ton).
α、γ are the coefficients of the fuel consumption function;
C_{wo} is the weekly operating cost per unit of the vessel (USD/week);
C_w is the unit vessel modification scrubber system cost (depreciation is a weekly fee) (USD/week);
v_{min} is the lower limit of the sailing speed of the vessel (knots);
v_{max} is the upper limit of the sailing speed of the vessel (knots);
C_{lt} is the unit cost of detailing at the port of call (USD/h);
C_{ic} is the inventory cost per unit container (USD/(TEUs*h));
N_p^{SEA} is the number of containers that the vessel transports at voyage leg connecting between the port p and p+1 (TEUs);
N_p^{PORT} is the number of containers handled by the vessel at the port of call (TEUs);

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HT_{pi} is the handling time estimated by the vessel at the port of call at the handling rate s_i (h);

c_{pi}^{pc} is the handling cost of the vessel at the port of call p under the handling rate s_i (USD);

TW_p^s is the start time of the time window of the port p (h);

TW_p^e is the end time of the time window of the port p (h).

3.2 Mixed-Integer Linear Mathematical Model

Mathematical Model For Switching To MGO Fuel

VSP1:

$$\min F_1 = C_{wo}Q + C_{fc}^{MGO}\sum_p l_p FC_p + \sum_p \sum_i c_{pi}^{pc} x_{pi} + C_{1t}\sum_p k_p T_p^l + C_{ic}\sum_p T_p^s N_p^{SEA} \tag{7}$$

Satisfied:

$$\sum_{i \in s_i} x_{pi} = 1, \forall p \in P \tag{8}$$

$$\sum_{k \in K} y_{pk} = 1, \forall p \in P \tag{9}$$

$$u_p = \sum_{k \in K} y_{pk} u_{pk}, \forall p \in P \tag{10}$$

$$T_p^s = u_p l_p \tag{11}$$

$$FC_p = \sum_{k \in K} y_{pk} FC_{pk}, \forall p \in P \tag{12}$$

$$T_p^a \geq TW_p^s, \forall p \in P \tag{13}$$

$$T_{p+1}^w \geq TW_{p+1}^s - T_p^d - T_p^s, \forall p \in P, p < |P| \tag{14}$$

$$T_1^w \geq TW_1^s - T_p^d - T_p^s + 168Q, \forall p \in P, p = |P| \tag{15}$$

$$T_p^a + T_p^w + \sum_i \left(HT_{pi} x_{pi}\right) + T_p - T_p^l = TW_p^e, \forall p \in P \tag{16}$$

$$T_p^d = T_p^a + T_p^w + \sum_i HT_{pi} x_{pi}, \forall p \in P \tag{17}$$

$$T_{p+1}^a = T_p^d + T_p^s, \forall p \in P, p < |P| \tag{18}$$

$$T_1^a = T_p^d + T_p^s - 168Q, \forall p \in P, p = |P| \tag{19}$$

$$\sum_p \sum_i \left(HT_{pi} x_{pi}\right) + \sum_p T_p^w + \sum_p T_p^s + T^v = 168Q \tag{20}$$

$$\frac{1}{V_{\max}} \leq u_{pm} \leq \frac{1}{V_{\min}}, \forall p \in P, \forall m \in M \tag{21}$$

In the mathematical model of switching to MGO fuel (VSP1), the goal of the model is to obtain the minimum value of the objective function (7). The constraint set (8) ensures that each port of call can only have one handling rate to serve the ship. The constraint set (9) ensures that the vessel can only select a reciprocal value of the sailing speed over each leg of the voyage. The constraint set (10) calculates the fuel consumption value corresponding to the selected sailing speed of each leg of the

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vessel over the entire voyage. The constraint set (11) calculates the sailing time of the vessel on the voyage leg p. The constraint set (12) calculates the fuel consumption value of the vessel on each leg of the entire voyage. The constraint set (13) indicates that the vessel must arrive at the port after the time window of the port of call. The constraint set (14) and the constraint set (15) calculate the waiting time of the vessel at each port of call. The constraint set (16) calculates the delay time of the vessel at each port of call. The constraint set (17) calculates the departure time of the vessel from which the handling service is completed from each port of call. The constraint set (18) calculates the arrival time of the vessel arriving at the next port of call. The constraint set (19) calculates the arrival time of the vessel from the last port of call to the starting port. The constraint set (20) ensures that the minimum weekly service frequency for this liner route can be met. The constraint set (21) ensures that the speed of the vessel on each leg of the liner route during each voyage cannot exceed its established range.

Mathematical model of the modified scrubber system

VSP2:

$$\min F_2 = \left(C_{wo} + C_w\right)Q + C_{fc}^{HFO}\sum_p l_p\left(FC_p + FC_p^o\right) + \sum_p\sum_i c_{pi}^{pc}x_{pi} + C_{1t}\sum_p k_p T_p^1 + C_{ic}\sum_p T_p^s N_p^{SEA} \tag{22}$$

Satisfied:

Constraint set (8)-(21)

$$FC_p^o = 0.005 FC_p \tag{23}$$

In the mathematical model of the modified scrubber system (VSP2), the goal of the model is to obtain the minimum value of the objective function (22). The objective function (22) is more than the objective function of the VSP1 mathematical model (7). The investment cost (depreciation is the weekly cost) consumed by the ship-modified scrubber system and the fuel cost required for the vessel operating the scrubber system. The constraint set (23) calculates the amount of fuel per nautical mile consumed by the vessel operating the scrubber system at the voyage leg connecting between the port p and p+1.

4. Empirical Analysis

If you follow the “checklist” your paper will conform to the requirements of the publisher and facilitate a problem-free publication process. Section 4 is a numerical experiment of the above-mixed integer linear mathematical model. The model compares the costs of the two options in detail and provides a reference for the decision of the shipping company. In order to improve the accuracy and speed of the solution, the VSP1 and VSP2 mathematical models are coded into GAMS and solved by CPLEX.

4.1 Input Data

The data used in the numerical experiments are mainly from the existing liner shipping, vessel scheduling and scrubber literature. The selected parameter values are shown in Table 2. Evergreen Marine pointed out that the initial fixed cost of the scrubber system for the modification of the 11,000 TEU vessel is $5 million. The vessel scrubber system of this paper is calculated according to the depreciation of fixed assets. Its service life is ten years, then its annual depreciation cost is 500000 USD, that is, the weekly depreciation cost Cw is about 9615 USD.

Table 2. Input Data

parameter	Numerical value	source
Number of ports of call：n	12	COSCO [11]

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Number of port handling rates：si $\forall i \in I$	[700;625;550;475]	World Bank [12]; The Port Authority of New York and New Jersey [13]
Coefficients of fuel consumption: α、β	$\alpha = 3$、β=0. 012	Dulebenets [5]
The weekly operating cost of a single ship:C_{wo} (USD/week)	300000	Dulebenets et al. [14]
Weekly depreciation cost of a ship-modified scrubber system:C_w (USD/week)	9615	N/A
Ship unit delay cost:C_{lt} (USD/h)	200	N/A
Container unit inventory cost:C_{ic} (USD/(TEUs*h))	1	N/A
Unit MGO fuel cost:C_{fc} (USD/ton)	628.5	Ship and bunker [15]
Unit HFO fuel cost:C_{fc} (USD/ton)	369.5	Ship and bunker [15]
Number of containers transported by voyage: $N_p^{SEA}, \forall p \in P$ (TEUs)	U[10000； 14000]	N/A
Number of containers handled at the port of call: $NC_p^{PORT}, \forall p \in P$ (TEUs)	U[200； 2000]	Dulebenets [16,17]
Ship sailing speed lower limit:V_{min} (knots)	15	Wang and Meng [7,8,9]
Ship sailing speed upper limit:V_{max} (knots)	24	COSCO [11]

There are 12 ports of call on the Asia-North Europe route, and there are four handling rates for each port. According to the existing literature, s_i is set to [700; 625; 550; 475] (USD / TEU), corresponding to four available handling rates (World Bank [12]; The Port Authority of New York and New Jersey [13]). This study assumes that each port of call can provide four types of handling rates, each of which corresponds to a corresponding handling rate. In practice, the handling rate of each port of call may be the same, but the corresponding handling productivity may be different. Therefore, in this study, if the vessel selects the handling rate s_i at the port, its handling productivity is $hp_{pi} = hp_{pi}^{average} \pm U\left[0, 25\right], \forall p \in P, i \in s_i \left(TEUs / h\right)$. $hp_{pi}^{average}$ is the average handling productivity corresponding to the handling rate s_i of the port p (TEUs/h), be set to $hp_{pi}^{average} = \left[180, 150, 120, 90\right], \forall p \in P, i \in s_i$ (TEUs/h). The start time of the time window of each port of call is related to the start time of the time window of the previous port of call, the distance of the voyage leg between successive ports of call and the minimum speed of the ship's sailing speed, namely: $TW_{p+1}^s = TW_p^e + \frac{l_p}{V_{\min}}, \forall p \in P$. Dulebenets [5] assumes that the number of containers that can be handled per week at the port of call on the liner route is $N_p^{PORT} = U\left[200, 2000\right], \forall p \in P$ (TEUs), where U represents a random number that is uniformly distributed. World Shipping Council [18] believes that a given port of call will only be attributed to a “large port of call” when its container throughput ranks in the top 20 in the world. It provides the number of containers for handling U[500 ,

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2000] TEUs; the rest is attributed to a smaller port of call, which provides for handling containers of U [200, 1000] TEUs. Based on the existing experimental values, a total of 20 numerical experiments were developed. These two scenarios will be further analysed by these 20 numerical experiments.

4.2 Analysis of results

The results of the 20 numerical experiments are analyzed, as shown in Table 3:

(1) The optimal values F1 and F2 of VSP1 and VSP2;

(2) Meet the number of vessels required to provide services on the liner route Q;

(3) $AHP = \frac{\sum_p c_p^{pc} x_p}{\sum_p N_p^{PORT}}$ is average handling productivity selected at the port of call (TEUs/h);

(4) $AST = \frac{\sum_p T_p^s}{\sum_p I_p}$ is the average speed of the vessel over the entire voyage (knots).

Table 3. Numerical experiment results

	VSP1				VSP2			
Instance	F1 107USD	Q	AHP	AST	F2 107USD	Q	AHP	AST
1	3.221476	12	475.03	21.08	3.077444	12	475.03	22.08
2	3.005207	12	475.00	20.92	2.863016	12	475.00	22.00
3	3.093727	12	475.00	21.25	2.949357	12	475.00	21.75
4	3.043465	12	475.51	20.83	2.901130	12	475.51	22.17
5	3.059373	12	475.00	21.08	2.915224	12	475.00	22.42
6	3.075308	12	475.00	20.83	2.907918	12	475.00	22.08
7	2.993831	12	475.00	20.92	2.849907	12	475.00	22.00
8	3.108157	12	475.00	21.00	2.964611	12	475.00	22.17
9	3.091892	12	475.00	21.17	2.947389	12	475.00	22.75
10	3.151435	12	475.00	21.00	3.006621	12	475.00	22.83
11	3.090927	12	474.68	20.92	2.947537	12	474.68	22.08
12	3.088926	12	475.00	21.00	2.945741	12	475.00	22.08
13	3.096822	12	475.00	21.17	2.952121	12	475.00	21.92
14	3.222890	12	475.00	21.00	3.078298	12	475.00	22.25
15	3.085336	12	475.00	21.33	2.941174	12	475.00	22.42
16	3.014591	12	475.00	21.00	2.871577	12	475.00	21.92
17	3.152314	12	475.00	21.67	3.008525	12	475.00	22.58
18	3.068970	12	475.00	21.17	2.924568	12	475.00	21.92
19	3.131455	12	474.92	21.00	2.987477	12	474.92	22.17
20	3.049244	12	475.00	20.42	2.837985	12	475.00	21.92

The results of these 20 numerical experiments (Table 3) show that the VSP1 scheme is superior to the VSP2 scheme. Based on the current oil price and transportation pattern, the shipping company chooses to switch to MGO more expensive than the modified scrubber system. Figure 2 shows the

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optimal cost comparison of 20 sets of numerical experiments for the two schemes. According to the model calculation, COSCO should use the modified scrubber scheme. It is worth noting that the average speed of VSP1 is lower than the average speed of VSP2; both VSP1 and VSP2 have the lowest handling productivity, and the consideration of handling efficiency will be the focus of future academic research.

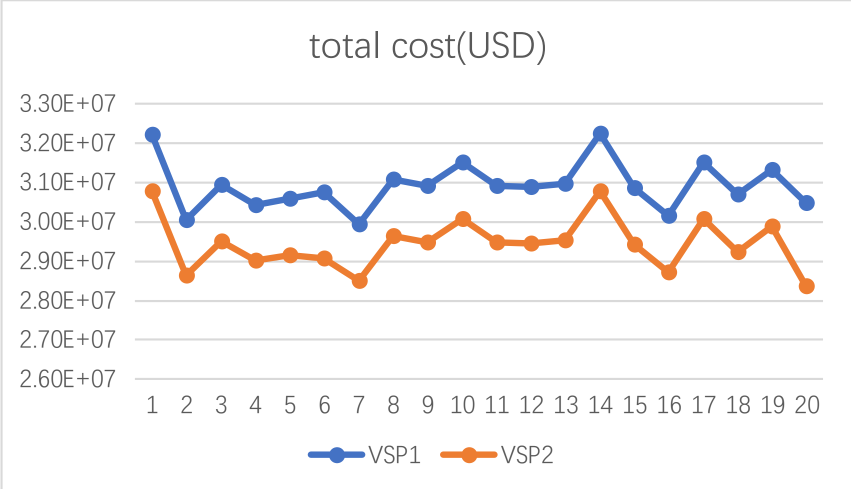

Figure 2. The total cost of VSP1 and VSP2

5. Conclusion

In order to meet the sulfur cap 2020 requirement, Many liner companies are keeping researching of the coping strategies. Therefore, it is of great value to study the scheme decision of switching to MGO fuel and refitting scrubber system. In this paper, the mixed-integer linear mathematical model is modified and improved based on previous scholars' model, and the COSCO example is used for empirical analysis. Based on the existing data of oil price, transportation pattern and COSCO route from Asia to Europe, in this case, COSCO should choose the scheme of modifying scrubber instead of to MGO, because of its low total cost. However, it was found that such a solution would reduce the handling productivity of ships at port. In future research, how to improve the handling productivity of ships in port is worthy of further study. At present, the attention to sulfur emission from ships is gradually increasing in the world, and the model in this paper can be used for reference in practice.

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