The Pennsylvania State University

The Graduate School

The College of Engineering

OPTIMIZATION OF CONTAINER LINER SPEED AND DEPLOYMENT BASED ON NEW ENVIRONMENT AND BUNKERING REGULATION

A Thesis in

Industrial Engineering and Operation Research

by

Kai Zhou

Submitted in Partial Fulfillment
of the Requirements
for the Degree of

Master of Science

May 2012

The thesis of Kai Zhou was reviewed and approved* by the following:

Paul Griffin
Professor of Industrial and Manufacturing Engineering
Head of the Department of Industrial Engineering
Thesis Advisor

M. Jeya Chandra
Professor of Industrial and Manufacturing Engineering

Tao Yao
Assistant Professor of Industrial and Management Engineering

*Signatures are on file in the Graduate School

ABSTRACT

Bunker price for container ships will increase dramatically in the future as ship operators will have to change their bunker fuel grade to higher quality ones that contain lower sulphur contents. This is due to the new regulation of the revision of MARPOL Annex VI. In this thesis we optimize ship speed and deployment problems for a specified container liner (Cosco AWE2) serving the transpacific route which will be typically influenced by the new regulation from the year 2012. Our study builds convex nonlinear optimization models for four different periods after 2012 according to the different steps for the enforcement of MARPOL Annex VI respectively. The optimal results show significant savings from the current deployment strategy of Cosco AWE2 based on the new regulations. The thesis also conducts sensitivity and comparison analysis for different bunker prices and different ship capacities. Three subsequent impacts on the entire supply chain due to our optimal strategy are further discussed. The increased transit time is a negative impact, while, improved capacity utilization and reduced CO_2 emission costs are positive ones. We quantify and incorporate these factors into our mathematical model, analyze the results and provide suggestions for container liner operators. Generally, the thesis indicates the future trends for container liner operation based on the new regulations and the mathematical model can easily be applied when data and parameters for other specific container liner is obtained. Our study could be a beneficial reference for shipping companies from the standpoint of operation research.

TABLE OF CONTENTS

List of figures

List of tables

Acknowledgements

I wish to acknowledge the support of the Penn State Department of Industrial and Manufacturing Engineering. I especially thank Dr. Paul Griffin for his role as my thesis advisor as well as teacher throughout my time in Penn State. I also would like to thank my family for all of their support in my study.

Chapter 1

INTRODUCTION

Background of shipping industry

Shipping industry and status of container liner

Maritime shipping is delivering around 90% of international trade. Trading by maritime transportation is continuing to expand, benefiting consumers all over the world due to competitive freight costs and high-capacity. The improving efficiency of international shipping and economic globalization help the shipping industry to continue to vigorously grow. Currently there are over 50,000 merchant ships trading internationally; for most kinds of consumer goods and raw materials.

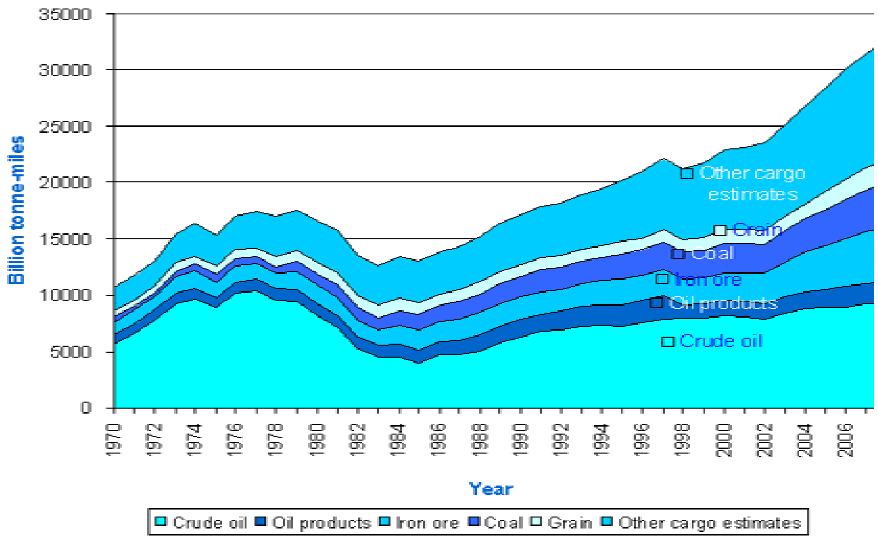

Figure 1-1 World seaborne trade 1969-2006

Source: www.marisec.org

There are five different types of ships in the world merchant fleet. They are container ships, bulk carries, tankers, ferries and cruise ships and specialist ships.

Container ships deliver most of the world's manufactured products, through scheduled liner services. Bulk carries carry raw materials such as metal ore and grain. Tankers deliver petroleum products, chemicals and crude oil. Bulk carries and tankers are generally operated via time charter or voyage charter.

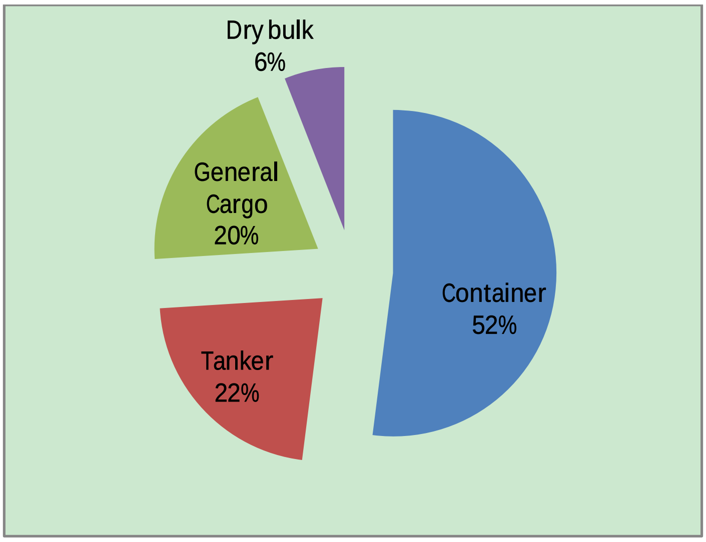

Figure 1-2 Value of world seaborne trade (US$)

Data Source: www.worldshipping.org

This thesis focuses on operation research problems of international container ships service, which falls into the category of liner shipping. Liner shipping is the service of transporting goods by means of high-capacity, ocean-going ships that transit regular routes on fixed schedules. There are approximately 400 liner services in operation today, most providing departures of fixed frequency from all the ports that each service calls. Container ships, which are cargo ships that carry all of their cargo in truck-size containers measured by TEU (a twenty-foot equivalent unit), are the most commonly utilized vessel in liner shipping.

Table 1-1 Future container fleet capacity according to order all over the world

Ship Size	End of 2011		End of 2012		End of 2014		2011-14
By TEU	Amount	TEU	Amount	TEU	Amount	TEU	CAGR
>1,0000	118	1,484,740	174	2,209,870	262	3,421,670	40.10%
7,500-9,999	289	2,488,540	316	2,726,234	390	3,390,172	10.60%
5,100-7,499	462	2,835,935	486	2,990,593	518	3,202,743	5.00%
4,000-5,099	710	3,210,200	752	3,397,956	813	3,680,875	4.60%
3,000-3,999	329	1,122,261	347	1,186,431	380	1,307,112	4.40%
2,000-2,999	722	1,836,659	730	1,857,409	757	1,926,477	1.40%
1,500-1,999	596	1,011,239	608	1,032,689	634	1,077,437	2.10%
1,000-1,499	717	845,642	753	882,746	762	892,395	1.90%
500-999	804	593,060	817	603,849	817	603,849	0.50%
100-499	244	79,817	244	79,817	244	79,817	-2.20%
Total	4991	15508093	5227	16967594	5577	19582547	8.20%

Data Source: Shipping industry research report by National Trust 2011/10/31 [1]

The data of table 1-1 shows that the capacity of container fleet is increasing in the near future. In addition, new construction trends are towards larger capacity, exceeding 10000 TEU.

Bunkering and its effects on shipping operations

Fuel oil is of great importance to the shipping industry. The bunkering industry provides the shipping industry with the fuel oil that the vessels consume. The quality of the fuel oil provided will ensure the safe operation of vessel.

There are three types of marine fuel mainly used by marine vessels that we discuss below:

Marine Gas Oil (MGO)

Marine gas oil is the result of blending light cycle gas oil with distillate oil to produce one of the highest marine fuel grades. MGO is more expensive because it is a lighter fraction and better quality fuel than diesel fuel. This fuel has a maximum sulphur content of 0.1%. It is sometimes used in the auxiliary engines.

Marine Diesel Oil (MDO)

Marine diesel oil is a type of fuel oil and is a blend of gasoil and little heavy fuel oil (residual oil). It is cheaper than MGO and more expensive than IFO. MDO usually has world average sulphur content of 0.65%. Both MGO and MDO have lower sulphur content than heavy fuel oil. MDO and MGO are also collectively known as light fuel oil.

Intermediate Fuel Oil (IFO)

Ships generally run on heavy fuel oil (HFO or known as IFO).Nearly 95% of the fuel used in maritime shipping is heavy fuel oil like IFO380 (mostly used) and IF0 180. Both IFO 380 and IFO 180 are mix of residual oil and distillate oil. IFO180 is expensive than IFO 380 because it has a lower viscosity and metals content. The world average sulphur content of intermediate fuel oil is 2.67%.

When bunker fuel price is around US$ 500 per metric ton, bunker fuel cost constitutes about three quarters of the total operations cost of a large containership [2] when the vessel is operated at a full speed.

In the bunkering market, the bunker prices constantly fluctuate as shown below:

Figure 1-3Bunker prices (IFO 380) at major ports (2002-2012)

Source : www.bunkerworld.com

Figure 1-4 Bunker prices for different grades of fuel oil (2002-2012)

Source : www.bunkerworld.com

With the exception of the period of the world financial crisis in 2008, the bunker prices were consistently increasing by years over the past ten years. The price for IFO 380 now is more than US$ 650 per metric ton.

From the viewpoint of operation research, and according to Lloyd's Register's report [3] , a 1% reduction in vessel speed can result in approximately a 2% to 2.5% saving in fuel consumption, it is economically significant to research on problems of reoptimizing vessel speed and deployment if the bunkering prices are continually soaring in future.

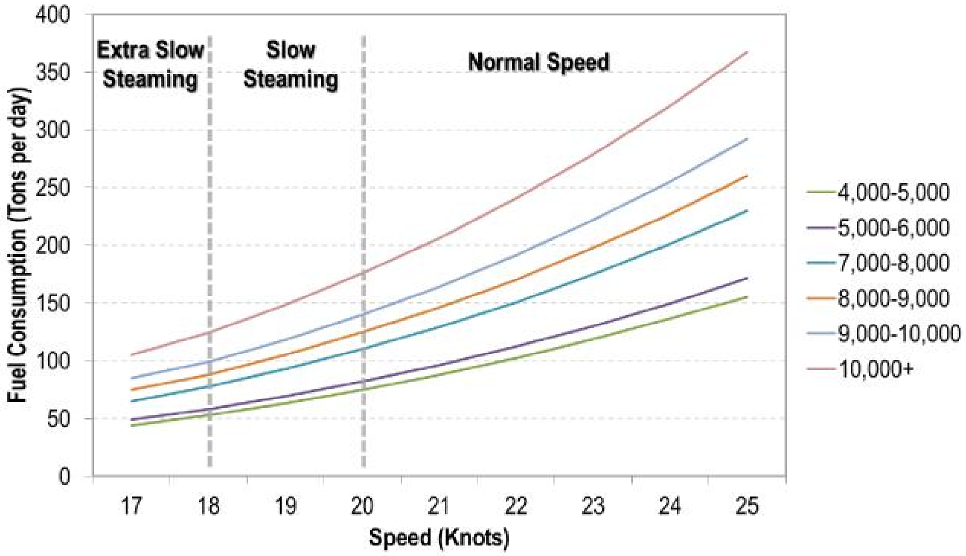

Figure 1-5 Bunker fuel Consumption rate for different size of containership at different ship speeds

Source :

http://people.hofstra.edu/geotrans/eng/ch8en/conc8en/fuel_consumption_containerships.html

Revision of MARPOL Annex VI

Regulations of reduction in sulphur oxide (SOx) emissions from ships

In addition of the continuing high fuel oil price, another factor will inevitably rise the shipping bunkering cost in future.

In October 2008, the Marine Environment Protection Committee (MEPC) of the International Maritime Organization (IMO) adopted amendments to the MARPOL Annex VI regulations to reduce harmful emissions from ships even further, when it met for its 58th session at IMO's London headquarters.

The main changes to MARPOL Annex VI are a progressive reduction in sulphur oxide (SOx) emissions from ships.

Two sets of emission and fuel quality requirements are defined by Annex VI: (1) global requirements, and (2) more stringent requirements applicable to ships in Emission Control Areas (ECA). An Emission Control Area can be designated for SOx emissions from ships, subject to a proposal from a party to Annex VI. [4]

Annex VI regulations include caps on sulfur content of fuel oil as a measure to control SOx emissions. The sulfur limits and dates of enforcement are listed in Table 1-2 and illustrated in Figure 1-6.

Table 1-2 Revised MARPOL Annex VI Sulphur limit for fuel oil

Data	*Sulphur Limit in fuel (% m/m)*	
	SOx ECA	*Global*
2000	1.50%	4.50%
2010.07	1.00%	
2012		3.50%
2015	0.10%	
2020		0.50%

Data Source : www.imo.org

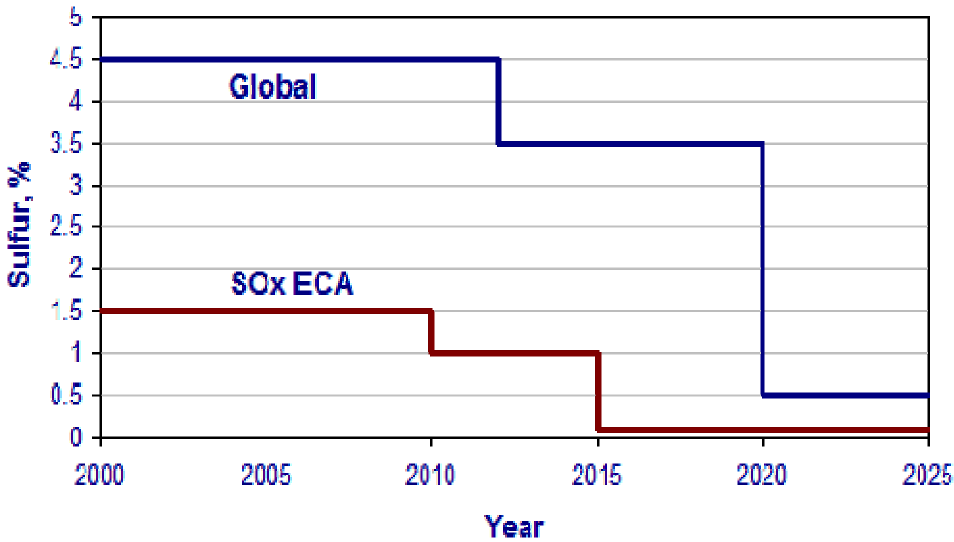

Figure 1-6 Revised MARPOL Annex VI Sulphur limit for fuel oil

Source: www.imo.org

As shown above, there will be a dramatic reduction of the sulphur content of marine fuel to be consumed by ships from year 2012 to 2020. This regulation requires the ship operator to purchase fuel oil of higher quality compared to the fuel oil consumed previously. This also indicates that the shipping companies and operators will bear a significantly increasing cost in bunkering in future.

Evolution of bunkering cost of container liner in transpacific route

This thesis specifically chooses to study on the operations problems of container liners in transpacific routes, which is the typical container liner service affected by the new regulation of revised MARPOL Annex VI.

Prior to January 2012, the existing ECAs (Emission control areas) in the world include Baltic Sea and North Sea in Europe which are not within the transpacific route. However, the International Maritime Organization (IMO) recently amended the International Convention for the Prevention of Pollution from Ships (MARPOL) designating specific portions of U.S. and Canadian as an Emission Control Area (ECA). The proposal for ECA designation was introduced by the U.S. and Canada, reflecting common interests, shared geography and interrelated economies. Allowing for the lead time associated with the IMO process, the North American ECA will become enforceable in August 2012. [42]

The area of the North American ECA includes waters adjacent to the Pacific coast, the Atlantic/Gulf coast and the eight main Hawaiian Islands. It extends up to 200 nautical miles from coasts of the United States, Canada and the French territories, except that it does not extend into marine areas subject to the sovereignty or jurisdiction of other States. [42]

Figure 1-7 Area of the North American ECA [42]

Therefore, according to the dates of enforcement of sulphur limits by MARPOL Annex VI, there will be four main stages for evolution of bunkering requirements and costs in the future for container liners serving the transpacific route (for example a route from the port of Shang Hai via the Panama Canal to the port of New York)

Stage one : from January 2012 to August 2012

Starting in January 2012, the sulphur content limits of fuel oil fall from 45000 ppm (4.50%) to 35000 ppm, and will effective on the entire shipping route from Asia visa Pacific Ocean to North American East Coast.

Stage two : from August 2012 to January 2015

From August 2012, the North American ECA will become enforceable, thus within the 200 nautical miles off the coasts of the United States, the sulphur content limits of fuel oil will fall from 35000 ppm to 10000 ppm. Limits in other areas in the transpacific route remain at 35000 ppm. This will be effective until January 2015.

Stage three : from January 2015 to January 2020

From January 2015, the sulphur content limits of fuel oil in the North American ECA will fall from 10000 ppm to 1000 ppm. Limits in other areas in the transpacific route will remain at35000 ppm. This is effective until January 2020.

Stage four: after January 2020

After January 2020, the sulphur content limits of fuel oil will fall from 35000 ppm to 5000 ppm, and will be effective on the entire shipping route from Asia via the Pacific Ocean to the North American East Coast. The one exception is, for the North American ECA where the sulphur content limits remain at 1000 ppm.

The four stages of sulphur content limits evolution of fuel oil for the shipping industry indicates a dramatic increase in bunkering costs for shipping operations in future. Even if the bunkering price will remain at the same level in over the next twenty years, the ship operators will have to change the fuel oil into the higher quality oil to be consumed in compliance with the revised MARPOL Annex VI regulations. A change such as altering from IFO 380 to MDO will incur more than hundreds of US dollars as extra cost for fuel oil per metric ton, as shown in Figure 1-4.

What's more, due to the increasing of the number and capacity of new buildings of ships(shown in Table 1-1) and the corresponding increase in demand for Marine fuel oil, the bunkering price for the same grade of fuel oil will also increase in near future (the detailed forecasting will be shown in Chapter 3) .

Based on the current situation and the upcoming regulation, we develop and approach to optimize container liner speed and deployment based on the new bunkering requirement and price. We will illustrate the approach with data from an actual container liner serving the transpacific routes.

The remaining layout of this thesis is as follows. The next Chapter contains a review of related literature. Chapter three presents the research methods and develops a mathematical model. Chapter four studies real cases and analyzes results. Chapter five provides rigorous considerations and discussion. The final chapter presents conclusions and potential future research opportunities.

Chapter 2

REVIEW OF LITERATURE

Bunker fuel consumption rate

One of the most important starting-point of our thesis is the relationship between ship speed and bunker fuel consumption rate of main engine of the ship.

Early in 1956, G. C. Manning stated that for a motor ship, the bunker fuel consumption of the main engines is directly related to the third power of the vessel's speed [26]. In 1982, Ronen [6] applied the "third power" relationship and studied on the optimal operational speed for a single vessel. He stated that:

$$F_i = F_o \cdot (V_i / V_o)^3$$

where F_o is the fuel consumption rate at ship full speed V_o and that F_i is the fuel consumption rate at ship speed V_i.

After these, many researchers have used the cubic function to present the relationship between ship speed and bunker fuel consumption rate, such as Psaraftis, H.N in 2009[23] and James J. Corbett in 2009 [27]. Some additional studies have applied a liner function of the operational speed of a ship [7] or a quadratic function [8] to approximate the bunker fuel consumption rate.

And in 2011, Zhishuang Yao, Szu Hui Ng, and Loo Hay Lee [2] found that

$$Fc = K_1 \cdot V^3 + K_2$$

is a good empirical model to express this relationship, where Fc denotes the bunker fuel consumption rate (tons/day), V denotes the ship speed (knots) and K_1, K_2 are coefficients. This model is an intrinsically linear model with K_2 as an intercept and K_1 as the gradient of V. They found that K_1 and K_2 are different for different sizes of containerships and the general trend for K_1 and K_2 is increasing with sizes of containership, which indicates that the bunker fuel consumption increases much faster with speed for the larger ships.

Study for ship speed and deployment from the view of operation research

Research for single vessel

A recent review study on operation research in maritime transportation by Christiansen in 2007[28] indicated that relatively little research has been published regarding optimizing the speed of vessels.

Following the oil crisis in the 1970s Ronen in1982 [6] presented three models for determining the optimal speed of vessels with a single engine operating under different commercial circumstances. However, each of these models analyzed a single vessel at a time and did not take into account service frequency (service frequency will be further discussed in next Chapter).

In 2004, Angelos [29] analyzed and expounded on the bunkering industry and its effect on shipping operations. He performed cost calculations for different ship sizes and different voyages. He also analyzed EU ship emissions and summarized operational problems. However his research only focused on mathematical analysis on a single ship. And he did not work on any optimization problems.

Wong, Hsieh and Chi-chen in 2007 [31] developed a mathematical model for optimizing containership size and speed. They analyzed the trade-off between the cost and revenue resulting from size and speed of container ship. They showed that their nonlinear programming model was a strictly concave function and therefore had a globally unique optimal. They also conducted on sensitivity analysis for bunker price and sailing distance. However, they only analyzed the case for a single container ship, omitting the entire container liner, and the sensitivity analysis for bunker price was based on the bunker price range from US$120/mt to US$180/mt. However, the market bunker price now is approximately US$700/mt.

Norstad, Fagerholt and Laporte in 2011 [30] studied the tramp ship routing and scheduling problem with speed optimization. They presented a multi-start local search heuristic to solve this non-linear programming problem. They assumed that the fuel consumption rate can be approximated by a quadratic function of speed which is actually not accurate in real cases. They worked on tramp shipping which is not similar to container ship and only single ship operation problem is considered instead of entire fleet. They did not consider the service quality or frequency problem in their study.

Research for container liner

Boffey, T. B., Edmond, E. D., Hinxman, A. I., and Pursglove, C. J. in 1979[32] built an interactive computer based program and worked to solve the problem of scheduling containerships on the route from North West Europe to the U.S. North East Coast and Canada. They were the first to determine the ports-points that must be called and the order. They then determined the route that the ship will follow by utilizing a heuristic optimization model. The objective of the model was to determine the speed of the ships and different combination of ports to be called. Profitability, total buffer time of the route and transit time were taken into consideration as decision variables in the model. Their model analyzed a real container liner route, but the impact of bunker cost on ship speed was not considered. The model is useful in new route design and ports selection for the setup of a new shipping company or fleet.

Powell and Perakis in 1997 [32] formulated an integer programming model for container liner deployment. In their model, the objective function was to minimize the cost of operating and layup for the ships in container liners operated on various routes. They considered the facets of route, service, charter, and compatibility as the constraints, and determined the optimal deployment of the fleet. The model is applied to a real liner shipping problem and the consequent savings by the new model are reported. Again, their work does not consider the impact of bunker cost for container liners. And in recent years, this cost is approximately half to three quarters of the total cost for container liner and so significantly influences the deployment strategy of container liner.

Notteboom and Vernimmen in 2009 [5] developed a model that calculated the cost for container liners at different ship speeds and ship sizes on real routes. Their research focused more on the impact from bunker costs of different bunker fuel types for the container ship speeds. However, there model was descriptive. They did not develop any optimization programming in their research. Nevertheless, their study discussed sulphur emission control and its impact on bunker costs. They stated that when entering an emission control area, the vessel would have to switch to another grade of fuel oil. However they did not analyze how this switch will influence the bunker cost of a vessel. They performed a real case study for container liner on a North-East Asia route. However, no real analysis was done on a transpacific route and no practical analysis was performed on the impact of the new MARPOL Annex VI regulations. Further, although they considered the optimal speed under different bunker prices for a North-East Asia route, they applied the same ship speed for the entire route. Our thesis will obtain optimal ship speeds for segments, in both ECAs and non-ECAs over one route, which will provide detailed and a practical reference for real container liner operations management.

In 2011, Zhishuang Yao, Szu Hui Ng and Loo Hay Lee [2] considered a bunker fuel management strategy for shipping liner service. They devised a mathematical model. In their model, they jointly considered the bunkering ports selection, bunkering quantity determination and ship speeds, and consequently provided an optimal bunker fuel management strategy. They chose the Asia Europe Express (AEX) service route, and analyzed the impact of fast rising bunker prices on the management strategy in their model. They did not incorporate service frequency which is the most important characteristic of container liner. They also did not consider the impact of the new regulation-IMO MARPOL Annex VI.

Study for impact by IMO revision of MARPOL Annex VI on marine transportation -EU studies

None of the previous literatures listed before considered the impact by IMO revision of MARPOL Annex VI which was adopted in October 2008. To this point there are only eight studies, and all of them consider the impact on Europe referring to the new MARPOL requirements. (Baltic Sea and North Sea in Europe are the current IMO emission control area and entered into force in 2005 and 2006)

The common aspect of these studies is the economic effect on Europe by the 1000 ppm sulphur content limitation within the emission control areas, and the impact on current transportation patterns within and around the emission control areas in Europe by year 2015. All these studies stated that the bunker price for ship transportation within emission control area will increase and all these studies assumed that the marine gas oil (MGO) will be utilized instead of types of heavy fuel oils which are now widely utilized by ships regarding the implementation of 1000 ppm sulphur content limitation.

In these studies, three have been conducted by the European Commission [41]. One is called "COMPASS" study, consigned by DG Environment in 2010. This study investigated the impact of the new environmental policies on transport costs, transport volumes and emissions. It also studied the potential effects on trade flow between Europe and other countries due to the new environmental policies [15]. Over 200 origin-destination pairs were selected for investigation of the risk for modal shift from short sea shipping to inland transportation modes. The second study conducted by the European Commission is called "AEA" study, was consigned by the AEA in 2009. This study examined the impact of emission reduction regulations (for the year 2015 and year 2020) in maritime activities by analyzing the benefits of the new IMO marine fuel and engine standards and calculating the costs of emission reduction due to the new standards. [39] The last study conducted by the European Commission is named the "SKEMA" study and was also commissioned in 2010. It specially assessed the effects on the Mediterranean and Atlantic European Seas by the application of new sulphur limits. It also examined the potential modal shift that may occurred from short sea transportation in the specified areas to inland transportation due to the new sulphur limitation that will be introducted in 2015 and 2020. [40]

The European Community Ship owner Association (ECSA) conducted a study in 2010. The study also focused on the impact of the new requirement of IMO MARPOL Annex VI on costs and prices of short sea traffic in the Emission Control Areas. The study also focused on the new regulations impact on transportation model splits in the Emission Control Areas as well as the external costs with an emphasis on short sea shipping in Europe. [38]

The remaining four studies are all regionally oriented and conducted or commissioned by EU Member States located within or around emission control areas respectively. The first one is a "Finnish Study" and was consigned by the Centre for Maritime Studies at the University of Turku in 2009 [34]. This study examined the effect of revised MARPOL Annex VI on the fuel cost of maritime traffic in Finland and continental Europe due to the 1000 ppm sulphur content requirements within emission control area related to Finland. It also studied the effects on the import and export status of Finland due to the increased marine fuel oil costs. The second study for the consequences of the IMO’s new marine fuel sulphur regulation was conducted by Swedish Maritime Administration in 2009. [35] This study examined the availability of low-sulphur fuel after the year 2015. It also referred to the Finish study, and investigated the risk of transportation pattern shift for shipping to and from Sweden due to the increased marine fuel cost. The third study is from the United Kingdom, and conducted by ENTEC in 2010 [36]. It was a review report which compared and draw together the research results of six other reports (all are from the eight studies mentioned in this section of our thesis) for the potential effects of the revised MARPOL Annex VI regulations. The last study is made by Germany and conducted by the Institute of Shipping Economics and Logistics in 2010 [37]. It researched the impact of new IMO regulation on the short sea transportation for RoRo shipping and Container Shipping in the North Sea and Baltic Sea. The resulting impacts on the ports were also considered.

All of these studies focused on the impact of IMO revision of MARPOL Annex VI on marine transportation. These studies are comprehensive including estimation of the fuel price in the future, the changing of the logistics pattern, and even the economic impact. These studies further provided detailed statistical data and, illustrated the new regulation and research methods. However, all these studies covered a wide field and rare research specified on the impact on the industry of an international container liner service. Further, none of the studies provided any decision support strategies to help improve operations. Finally, these studies are all limited to Europe.

Besides of these studies, very little research has been conducted for the operational problems for commercial transportation on transpacific route and on the U.S. coast where bunkering cost will be significantly impacted by the new MARPOL regulation from the year

2012. Our thesis will study this issue from the perspective of container shipping companies from the viewpoint of operation research.

Chapter 3

METHODS AND METHEMATICAL MODELS

Problem description and methodology

This thesis considers the optimization problems of container fleet speed and deployment for a container liner service upon new bunkering price. The objective is to reduce the ship operator's daily cost and maximize the profit from the shipping companies' point of view. Before detailed mathematical models are developed, characteristics and assumptions for a container liner service will be specified.

Service frequency

One of the most important characteristics of a container liner is that the carriers provide fixed frequency of service, which is different from bulk shipping industry and tank shipping industry. Container ships are usually operated on closed routes (also known as cycles or strings or loops) and follow a published schedule of sailings. A route is a specified sequence of calling ports that each container ship assigned to that route repeats on each voyage. After a ship operator assesses the market to be served and the distribution of the service demand, he will design the sailing schedule. According to the sailing schedule published, each port on the schedule will be called at for a fixed frequency. For most of the container liners in the world, they will try to have at least a weekly service.

Given a desired service frequency and a desired number of ships deployed on the liner service, the total cycling voyage time should not exceed a certain threshold [5]:

$$T_r \leq \frac{n \cdot 7}{F} \qquad (1)$$

In the above formulation, T_r is the total cycle time in days; n is the number of ships deployed on the liner service and F is the frequency of the he liner service in number of vessel calls per week in each port of call.

We will assume that F is a constant equal to one.

In practice, most container liners in the world are now applying a service frequency at one call for a port per week which is efficiently and practically suitable to shipper's demand. The roundtrip of an international container liner takes from a few weeks up to a few months to complete. They require a fleet composed by multiple vessels to operate on the route with weekly phasing between the ports so that they can provide a weekly service for the ports of calling. Thus, a route that takes 8 weeks and provides weekly service will need eight vessels to run. This threshold is the most important constraint in our model.

In formulation (1), the total round trip

$$T_r = \sum_{i=1}^{p} T_i + \frac{D}{V \cdot 24} \qquad (2)$$

T_i is the total port time in port i in days; p is the number of ports of call on route; D is the distance of the cycle(route) in nautical miles (one nm is defined as 1.852 km); V is the vessel speed in nautical mile per hour (knot). In our model, p D and T_i are assumed to be constant for a certain container line, and the route (sequence of calling ports) is already specified.

Combining (1) and (2) we have the constraint for service frequency:

$$\frac{D}{V \cdot 24} \leq \frac{n \cdot 7}{F} - \sum_{i=1}^{p} T_i \qquad (3)$$

In this constraint, the variables are V and n. When the speed of fleet in the liner service is decreased, more vessels need to be added into the service in order to maintain the required service frequency.

For the purpose of our model, we make other two important assumptions for the container liner:

1. Vessels that operate on the same route and serve for the some container liner have similar physical parameters and can be considered identical for practical purposes (usually sister ships serve on the same route in real container lines).
2. Demand (TEU) per week from every port on the route does not change. Thus if the container line maintains the same service frequency, the daily revenue of the company is the same. In our model, then, in order to maximize the daily profit, we just have to make an equivalent objective function as minimize the total daily cost of the container line.

Cost structure of a single container liner

The cost of the vessels for a container liner service includes vessel operation cost, vessel capital cost, bunker cost and port charges (including canal toll).

Due to the service frequency for container liner is fixed in our model, the frequency of calling at a certain port is constant and the total port charges (including canal toll) for a cycle divided by the total cycle (roundtrip) time of voyage is a constant. As this part of cost does not change when the bunkering price increases or the container liner slows down its fleet's speed, our model does not take the port charges (including canal toll) into account.

Vessel operation cost

For a container ship, the operation cost includes crew, insurance, repair and maintenance, stores and lubes, fuel for auxiliary power (mostly MGO), and administration. The operation cost per vessel is incurred regardless of whether or not the ship is sailing on the sea or berthing at ports. Thus the total daily operation cost for the entire fleet is subject to changes in the amount of deployed ships in the container liner.

Vessel capital cost

In addition of the operations cost, the capital cost of a ship should be taken into account in our model. The capital cost of a ship can be seen as the substitution and interest costs. When the substitution and interest costs are paid annually, then this annuity can be allocated over the days of operation. The result will be the daily vessel capital cost. Accordingly the annuity can be calculated as follows:

$$R \cdot \frac{r \cdot (r+1)^m}{(r+1)^m - 1} \tag{4}$$

where R is the construction price of the ship, r is the annual interest rate and m is the number of years until the loan has been repaid. Generally, the vessels are in operation for 350 days in one year [9], so the daily capital cost per vessel is :

$$\frac{R}{360} \cdot \left[\frac{r \cdot (r+1)^m}{(r+1)^m - 1} \right] \tag{5}$$

Both the vessel operations cost and the vessel capital cost are incurred even when the ship is not sailing. The total daily capital cost for the entire fleet is also subject to changes in the amount of deployed ships in the container liner.

A daily chartering rate could reflect both the daily operation cost and daily capital cost for a ship.

Bunker cost

The bunker cost is related to the energy consumed for the ship's sailing on the sea. (The fuel cost for ships at port is auxiliary power cost which is categorized into vessel operation cost. The auxiliary engines always consume MGO on matter the ship is sailing at sea or berthing at the port.) The bunker cost is subject to the bunker price and bunker fuel consumption rate for a ship. The bunker fuel consumption rate is particularly subject to a ship's parameter and sailing speed.

After the bunker fuel consumption rate is obtained, the daily bunker cost for a container liner is related to the number of the ships deployed in the fleet, sailing days at sea and total cycle time of one voyage.

Relationship between bunker fuel consumption rate and ship speed

In order to calculate the bunker fuel consumption per day for a ship, we have to first determine the relationship between bunker fuel consumption rate and ship speed. As Zhishuang

Yao, Szu Hui Ng, and Loo Hay Lee [2]'s study and based on the data they acquired from a shipping liner, they suggest the following empirical model [2]:

$$Fc = K_1 \cdot V^3 + K_2 \tag{6}$$

to express this relationship, where Fc denotes the bunker fuel consumption rate (tons/day), V denotes the ship speed (knots) and K_1, K_2 are coefficients. From their data and study, they obtain the information shown in Figure 3-1.

Coefficients for different sizes of containerships.

Size (TEU)	k_1	k_2	Number of data points[a]	Speed interval of the data (knots)
0–1000	0.004476	6.17	73	(10.5, 16.5)
1001–2000	0.004595	16.42	65	(12.5, 19.5)
2001–3000	0.004501	29.28	51	(13.5, 21)
3001–4000	0.006754	37.23	82	(14.5, 21.5)
4001–5000	0.006732	55.84	193	(15, 24)
5001–6000	0.007297	71.4	170	(14, 24)
6000+[b]	0.006705	87.71	53	(18, 25)

[a] Number of data points: each data point consists of one (ship speed, bunker fuel consumption rate) pair.

[b] 6000+: the largest ship in our data is 8110 TEU.

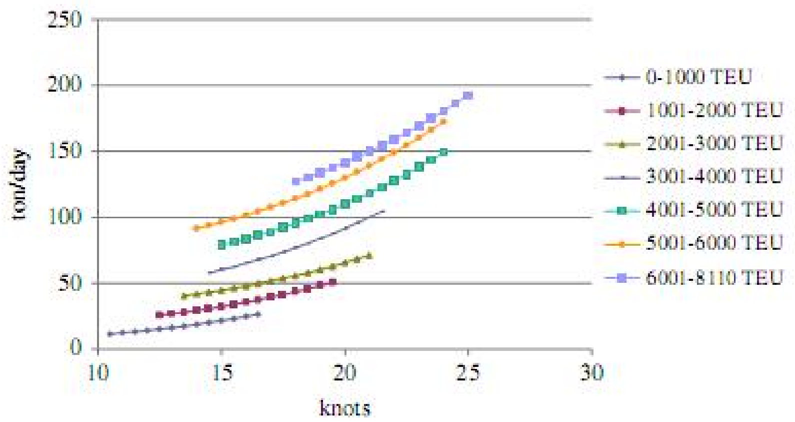

Figure 3-1 Relationship between bunker consumption rate with ship speed

Source: Zhishuang Yao, Szu Hui Ng, Loo Hay Lee's empirical model [2]

Their relationship model has two main differences when compared to other existing studies. First, their model has the coefficient K_2, which can make the approximation more accurate. Second, they found that the coefficients of the model are different for different sized container ships, while most existing studies ignore this difference. [2] We will use the formulation (6) to describe relationship between bunker consumption rates with ship speeds in our optimization model described next.

Mathematical model

Notations

C_o	Operation cost per vessel [US$/day]
R	Construction price of ship [US$]
r	Annual interest rate for calculating capital cost per vessel
m	Number of years until the ship's loan has been repaid
n	Number of ships deployed in the liner service
T_r	Total round trip (cycle) time [days]
p	Number of ports of call on the service route
T_i	Total port time in port i [days]
D	Distance of the round trip excluding emission control area [nautical miles]
D_e	Distance of the round trip in emission control area [nautical miles]
F	Service frequency of the container liner
B_p	Bunkering price outside emission control area [US$/metric tonne]

B_{pe}	Bunkering price inside emission control area [US$/metric tonne]
$V_{\min}$	Minimum ship speed [knots: nautical miles per hour]
$V_{\max}$	Maximum ship speed [knots]
V	Operational speed out of emission control area
V_e	Operational speed in emission control area
K_1, K_2	Bunker consumption coefficient

Model for the route without emission control area

If the container line service route does not contain emission control area, the sulphur limitation as well as the bunkering requirement should be the same along the entire route. The model for a single container liner service is presented as follows:

Minimize

$$\left\{ C_o + \frac{R}{360} \cdot \left[\frac{r \cdot (r+1)^m}{(r+1)^m - 1} \right] + \frac{B_p \cdot (K_1 \cdot V^3 + K_2) \cdot \dfrac{D}{0.92 \cdot V \cdot 24}}{\dfrac{D}{0.92 \cdot V \cdot 24} + \sum_{i=1}^{p} T_i} \right\} \cdot n \tag{7}$$

Subject to

$$\frac{D}{0.92 \cdot V \cdot 24} \leq \frac{n \cdot 7}{F} - \sum_{i=1}^{p} T_i \qquad \text{for all } i \tag{8}$$

$$V_{\min} \leq V \leq V_{\max} \tag{9}$$

$$n \in \text{int}. \tag{10}$$

This is a nonlinear programming problem. The independent variable is the bunkering price B_p and the decision variables are the speed of the fleet V and the number of vessels n that are deployed in the fleet. Operation cost C_o (measured per vessel per day) and capital cost $\frac{R}{360}\cdot\left[\frac{r\cdot(r+1)^m}{(r+1)^m-1}\right]$ (measured per vessel per day) are constant and do not change when the ship speed changes.

The objective function is to minimize the total daily cost of the vessels in the fleet. Since the revenue per day for the container line does not change, the daily profit will be maximized. In the formulation (7), $\dfrac{B_p\cdot(K_1\cdot V^3+K_2)\cdot\dfrac{D}{0.92\cdot V\cdot 24}}{\dfrac{D}{0.92\cdot V\cdot 24}+\sum_{i=1}^{p}T_i}$ represents the daily bunker cost per vessel. $0.92\cdot V$ means there is a 8% speed loss in (slip) sailing comparing the effective sailing speed with the settled speed of the engine.

Constraint (8) ensures that the container liner maintain a service frequency F and constraint (9) ensures the operational speed of the vessel is in the range of the vessel engine's speed capacity.

This model is suitable for the bunkering price evolution stage one discussed in Chapter one. It is also suitable for future regulations when all areas in the world are subject to a limitation at 1000 ppm for sulphur content of fuel oil after year 2020.

Model for the route passing through emission control area

If the container line service route passes through emission control area, which is discussed in Chapter one, there will be two sulphur limitations and the bunkering requirements which should not be the same along the entire route. As a result, two bunkering prices will be applied in one roundtrip.

The model for a single container liner service is:

Minimize

$$\left\{ \begin{array}{l} C_o + \frac{R}{360} \cdot \left[\frac{r \cdot (r+1)^m}{(r+1)^m - 1} \right] + \\ \dfrac{B_p \cdot (K_1 \cdot V^3 + K_2) \cdot \frac{D}{0.92 \cdot V \cdot 24} + B_{pe} \cdot (K_1 \cdot V_e^{\ 3} + K_2) \cdot \frac{D_e}{0.92 \cdot V_e \cdot 24}}{\frac{D}{0.92 \cdot V \cdot 24} + \frac{D_e}{0.92 \cdot V_e \cdot 24} + \sum_{i=1}^{p} T_i} \end{array} \right\} \cdot n \tag{11}$$

Subject to
$$\frac{D}{0.92 \cdot V \cdot 24} + \frac{D_e}{0.92 \cdot V_e \cdot 24} \leq \frac{n \cdot 7}{F} - \sum_{i=1}^{p} T_i \tag{12}$$

$$V_{\min} \leq V \leq V_{\max} \tag{13}$$

$$V_{\min} \leq V_e \leq V_{\max} \tag{14}$$

$$n \in \text{int}. \tag{15}$$

$\frac{D}{0.92 \cdot V \cdot 24}$ is the total sailing days outside the emission control area for one roundtrip and $\frac{D_e}{0.92 \cdot V_e \cdot 24}$ is the total sailing days in the emission control area for one roundtrip.

This model is suitable for the bunkering price evolution stages two through four discussed as in Chapter one.

Chapter 4

CASE STUDY AND RESULTS

Case study

Container liner service of Cosco AWE2

In the thesis, we use the FAR EAST/ U.S.East Coast Express Service（AWE2）of Cosco CONTAINER LINERS CO.,LTD as a case study.

Cosco container liner is one of the top five container lines in the world [1], and it provides five liner services from Asia to U.S. The liner-AWE2 is the most typical container liner that will experience the new environment regulation and bunkering price evolution as during the stages discussed in Chapter 1.

Currently, the AWE2 service has an Asia-U.S.East Coast-Asia route with a total roundtrip time of 63 days.

Figure 4-1 shows a service map of AWE2 service:

Figure 4-1 Service map of the COSCO AWE2 service

Source: www.coscon.com

In AWE2 service, there are currently 9 vessels. They are actually sister ships with similar fleet parameters. The capacity of these ships ranges from 4196 TEU to 5089 TEU. The average capacity is 4666 TEU.

Table 4-1 Vessels deployed on the COSCO AWE2 service

Vessel name	Capacity(TEU)
Yuan He	4215
Cosco New York	5089
Cosco Nagoya	4506
Tian Yun He	5089
River Wisdom	4196
Tian Bao He	5089
Cosco Boston	5089
Shan He	4221
Cosco Osaka	4506
Average	4666.666667

Source : www.coscon.com

The vessel with the closest average capacity is Cosco Nagoya with a capacity of 4506 TEU. We select the parameter of Cosco Nagoya as the vessel in this liner for the model development.

In table 4-2, an example of an AWE2 service schedule is presented

Table 4-2 AWE2 schedule of Cosco Nagaya

Port	**ETA**	**ETD**	**Port Time(days)**	**Travel Time(days)**	**Distance(nm)**	**Speed(knots)**
Qingdao	2012/1/17 2:20	2012/1/17 17:45	0.642361111	1.010416667	445	18.35051546
Shanghai	2012/1/18 18:00	2012/1/19 17:00	0.958333333	0.458333333	163	14.81818182
Ningbo	2012/1/20 4:00	2012/1/20 18:00	0.583333333	2.583333333	1045	16.85483871
Yokohama	2012/1/23 8:00	2012/1/23 15:00	0.291666667	12.70833333	6137	20.12131148
Lazaro Cardenas	2012/2/5 8:00	2012/2/5 14:00	0.25	3.5	1602	19.07142857
Panama Canal	2012/2/9 2:00	2012/2/9 18:00	0.666666667	0.041666667	24	24
Colon Container Terminal	2012/2/9 19:00	2012/2/10 8:00	0.541666667	3.416666667	1576	19.2195122
Savannah	2012/2/13 18:00	2012/2/14 16:00	0.916666667	1.291666667	542	17.48387097
Norfolk	2012/2/15 23:00	2012/2/16 18:00	0.791666667	1	309	12.875
New York	2012/2/17 18:00	2012/2/18 18:00	1	1	404	16.83333333
Boston	2012/2/19 18:00	2012/2/20 18:00	1	6.333333333	2191	14.41447368
Panama Canal	2012/2/27 2:00	2012/2/27 18:00	0.666666667	21.5	8631	16.72674419
Qingdao	2012/3/20 6:00	2012/3/20 19:00				
Voyage:017E/017W	*vessel:COSCO NAGAYA*	**Roundtrip time(days)**	**Total Port Time(days)**	**Total Travel Time(dyas)**	**Total Distance(nm)**	**Average(knots)**
		63.15277778	8.309027778	54.84375	23624	17.94795821

Data source: www.coscon.com Distance calculated by: www.dataloy.com

Currently, total scheduled roundtrip time T_r for this AWE2 service of Cosco Container lines is 63.15 days of which over 8.31of port time. The average effective sailing speed for AWE2 service fleet is 19.78. (Commonly the maximum speed and minimum speed for container ship are 25 knots and 11 knots respectively)

The maximum allowable roundtrip time for the liner service at nine vessels deployed and a frequency of one call per week (F =1) is 63 according to formula (1). This implies the AWE2 schedule at the current speed and current number of vessels is very tight.

Parameters for Cosco Nagoya

In order to apply our model developed in Chapter 3, we have to obtain the parameters of Cosco Nagoya. This includes the vessel operation and vessel capital costs

Vessel operation cost

The daily operation cost for Cosco Nagoya is presented in table 4-3 :

Table 4-3 cost structure for Cosco Nagoya (TEU: 4506, year built: 2008)

Cosco Nagaya	US$/day
Manning cost	2850.56
Insurance	1283.8
Repair and mainteinance	3409.93
Stores and Lubes	2039.67
Administration	1219.61
Total	10803.57

Data source: Cosco America Inc.

Vessel capital cost

Cosco Nagoya is built by Samsung Shipbuilding & Heavy Industries Co Ltd in 2008. The beneficial owner for Cosco Nagoya is Doun Kisen Co Ltd. [10] The construction cost of this ship was US$ 65200,000. The lifespan of the vessel is 20 years and the interest rate is set on 0.06125[9]. Thus, according to our model parameter defined in Chapter 3,

R = 65200000

r =0.06125

m =20

Applying formula (5), the daily capital cost for Cosco Nagoya is US$ 15950.7

Another measure of ship daily costs (daily operation cost plus daily capital cost) could have been the daily charter rate. However the charter rate fluctuates and is subject to many factors in the market. This is why a charter rate does not work very well as a general measure of ship cost. Interestingly however, the daily cost calculated from data above is $26754.27($10803.57+$15950.7), which is very closed to the chartering rate at $ 26000 to $28000 for Cosco Nagoya according to Cosco America Inc.

Bunker consumption coefficients K_1, K_2 of Cosco Nagoya

Based on operational data of Cosco Nagoya (Appendix A), and applying the statistic tool Minitab for regression, we obtain the bunker consumption coefficients for Cosco Nagoya:

K_1 = 0.0071339

K_2 = 15.6983

For comparison with "third power" relationship between fuel consumption and ship speed, where $Fc = \left(\frac{V}{V_0}\right)^3 \cdot F_0$ (Fc is the fuel consumption at the current ship speed V, F_0 is the fuel consumption at full speed V_0), we list the total deviation for the two formulations the relationship between fuel consumption and ship speed.

The deviation of the "third power" relationship calculated by excel is 55.8763 while the deviation of the regression of formulation (4) is 7.7624. Therefore, formulation (4) obtains a higher accuracy in presenting the relationship between fuel consumption and ship speed compared to most of the previous studies.

Forecasting for the bunker prices

The bunker prices from the year 2012 to 2020 are the independent variable in our optimization problem. Before applying our model to the Cosco cases, we estimate the bunker prices for different geographic areas on the AWE2 Asia-U.S.East Coast-Asia service route.

As discussed in Chapter one, there are four main stages for evolution of bunkering requirement according to the dates of enforcement of sulphur limits by MARPOL Annex VI.

Table 4-4 shows the stages for evolution of bunkering requirement:

Table 4-4 Stages for evolution of container ship bunkering requirement

Dates of enforcement by Marpol Annex VI	Globle area		200 nautical miles from coasts of the United States	
	Sulphur content limit (ppm)	Bunker grade required	Sulphur content limit (ppm)	Bunker grade required
Before January 2012	45000	IFO380	45000	IFO380
After January 2012	35000	IFO180*	35000	IFO180
After August 2012	35000	IFO180	10000	MDO
After January 2015	35000	IFO180	1000	MGO
After January 2020	5000	ULS180	1000	MGO

IFO180*: Actually in bunkering industry, there is IFO380 that contains a sulphur content of 35000ppm ("380" is used for measuring the viscosity of the fuel grade). However, the price of IFO380 that contains a sulphur content of 35000ppm is close to the price of IFO180 that contains a sulphur content of 35000ppm. Both IFO380 and IFO180 that contains the sulphur content of 35000ppm are expensive than IFO380 that contains a sulphur content of 45000ppm. Thus we use IFO180 in the table to represents the fuel grade that contains lower sulphur content compared to IFO380 which generally has a sulphur content more than 35000ppm.

Based on the estimation from James Kehoe and Johan Woxenius (2010) [11] and adjusting their estimated bunker prices by Platts price [12], we obtain Table 4-5 which forecasts the bunker prices in future:

Table 4-5 Forecasting for the bunker prices until year 2020

Fuel Sulphur Content	4.50%	3.50%	1.50%	1%	0.50%	0.10%
Fuel Grade/(US$/mt)	(IFO380)	(IFO180)	(LS180)	(MDO)	(ULS180)	(MGO)
2010	507.46	522.53	552.66	731.96	757.64	774.96
2012	680.55	718.12	793.23	972.54	1002.21	1021.14
2015	851.36	918.76	964.04	1143.35	1173.02	1226.48
2020	1054.38	1121.78	1167.06	1346.37	1376.04	1395.56

The bunker prices in year 2012 in table 4-5 are based on the real market price in January and February. The bunker prices in year 2015 and 2020 are estimated based on Kehoe and Johan Woxenius (2010)'s analysis, methodology and data, where historical data, and the demand as well as the availability of oil products in future are studied.

The forecasting of the detailed figures will not equal to the bunker price in future precisely. However it indicates the increasing trends and the price differentials between different grades of marine fuel oil. These scenarios of estimated prices will be applied in our model for the case study. Whenever real prices in future are obtained, they could be easily treated as the independent variable for optimizing operational parameters for container liner fleet applying the model similarly as illustrated in our thesis.

Results

Based on our case study above, for the container ship of the size of 4506TEU and COSCO AWE2 service route, we obtain the general inputs for our mathematical models now:

R = 65200000

r =0.06125

m =20

F =1

K_1 = 0.0071339

K_2 = 15.6983

V_{min} =11

V_{max} =25

$$\sum_{i=1}^{p} T_i = 8.31$$

Optimal deployment strategy for route of single emission standard

Period from January 2012 to August 2012

From January 2012 to August 2012 according to table 4-4, the entire route of AWE2 container liner service will require bunker grade of IFO180 which contains a sulphur content of 35000ppm. Thus we obtain the independent variables for our mathematical model:

B_p = 718.12 (US$38 extra per MT more than IFO380 used before year 2012)

D = 23624 (no emission control area on the entire route)

C_o =10803.57 (for year 2012)

Applying our model for the service route without emission control area, we utilize the Microsoft Excel Solver and obtain the optimal decision variables:

V =15.58

n =11

and we get a tight constraint (formula (8)) with total roundtrip time of 77 days.

Based on our assumptions discussed previously, the results indicates that under the new IMO MARPOL Annex VI regulation and during the period from January 2012 to August 2012, container liner service of COSCO AWE2 should deploy 11 vessels of a single vessel size of 4506 TEU and set its fleet sailing speed at 15.58 knots in order to get a maximal daily profit. Table 4-6 presents the optimal deployment strategy comparing to current deployment strategy of COSCO AWE2.

Table 4-6 Comparison for deployment strategies of AWE2 with bunker price at 718 US$/mt

Strategy	Optimal	Current
Vessel deployed	11	9
Fleet speed* (Knots)	15.58	19.59
Daily cost(US$) excluding port charge	594847.4	629206.9
Daily port charge (US$)	90857.14	90857.14
Total(US$)	685704.54	720064.04
Differencial(US$)		34359.5
Cost per TEU per roundtrip(US$)	1371.40908	1440.12808

The fleet speed in table 4-6 represents the engine setting speed. The effective speed is 92% of the theoretical speed. The operation TEU is 3500 for a Cosco Nagaya(78% of total capacity), as data collected from Cosco America Inc.

Table 4-6 shows that the optimal strategy saves approximately 5% cost from current strategy of COSCO AWE2 liner service at a bunker price at US$718, even with two more ships added to the fleet to maintain the required weekly service frequency.

Figure 4-2 shows the daily cost (excluding port charge) of AWE2 change curve against different fleet speed and number of ships deployed, when the bunkering price is US$718/mt and maintaining a weekly service frequency.

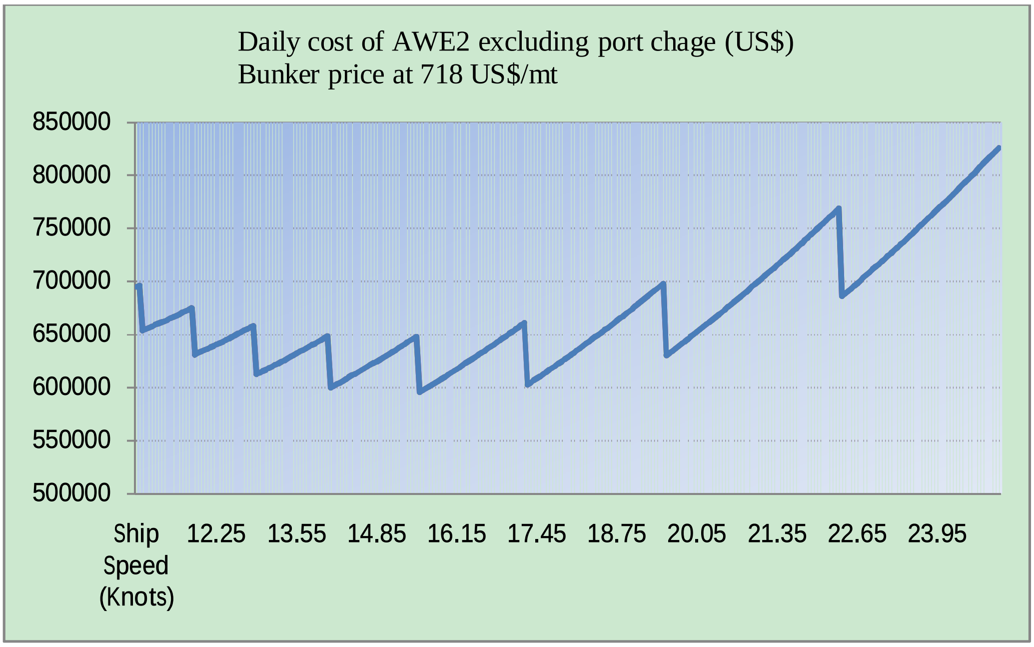

Figure 4-2 Daily cost of AWE2 versus ship speed, bunker price at US$718/mt

The chart shows that there are several local optimum results that could be achieved when constraint (8) is tight. This means further decreasing of ship speed from the local optimum solution required more ships to be added into the service in order to maintain a weekly service frequency. Additional ships to be added means more capital cost and operation cost to be added to total cost per day.

Period after 2020

There is the trend which implies that all the ocean area after year 2020 is going to be emission control area with the sulphur content limit for marine fuel oil is maximum 1000 ppm globally. At least according to IMO MARPOL Annex VI, from January 2012, the global area is required for a sulphur content limit of maximum 5000 ppm, and 1000 ppm for emission control area. The bunker grades for these two requirements have similar prices. Table 4-5 shows, the price for ULS180 and MGO are US$1376/mt and US$1395/mt respectively. Our mathematic model for unique emission requirements is also suitable for this scenario.

We first update the input for this scenario:

B_p = US$1395/mt

And according to the study by HSH Nordbank, Ernst & Young and Econum[14], operational costs of container ships is increasing by a moderate rate of 6.6% per year as compared to the long-term average. Thus we obtain the operation cost in 2020 as:

$C_o = 10803.57 \cdot (1+0.066)^8 = 18014.61$ (US$ per vessel per day)

Other inputs do not change. Applying our model for the service route without emission control area (for unique bunker requirement), we utilize the Microsoft Excel Solver and obtain the optimal decision variables:

V =14.14

n =12

and we get a tight constraint (formula (8)) with total roundtrip time of 84 days.

Based on our assumptions discussed previously, the optimal ship speed in this scenario is 14.14 knots and optimal number of ships deployed is 12. The total cost per day excluding port charge of the container liner is US$ 948317.4.

Table 4-7 presents the optimal deployment strategy comparing to current deployment strategy of COSCO AWE2:

Table 4-7 Comparison for deployment strategies of AWE2 with bunker price at 1395 US$/mt

Strategy	Optimal	Current
Vessel deployed	12	9
Fleet speed* (Knots)	14.14	19.59
Daily cost(US$) excluding port charge	948317.4	1061188
Daily port charge (US$)	90857.14	90857.14
Total(US$)	1039174.54	1152045.14
Differencial(US$)		112870.6
Cost per TEU per roundtrip(US$)	2078.34908	2304.09028

Table 4-7 shows that the optimal strategy saves approximately 10% of the cost of the current strategy of COSCO AWE2 liner service at a bunker price at US$1395, even with three more ships added into the fleet to maintain a weekly service frequency.

Figure 4-3 shows the daily cost (excluding port charge) of AWE2 change curve against different fleet speed and number of ships deployed, when the bunkering price is US$1400/mt and maintaining a weekly service frequency in the future scenario after year 2020.

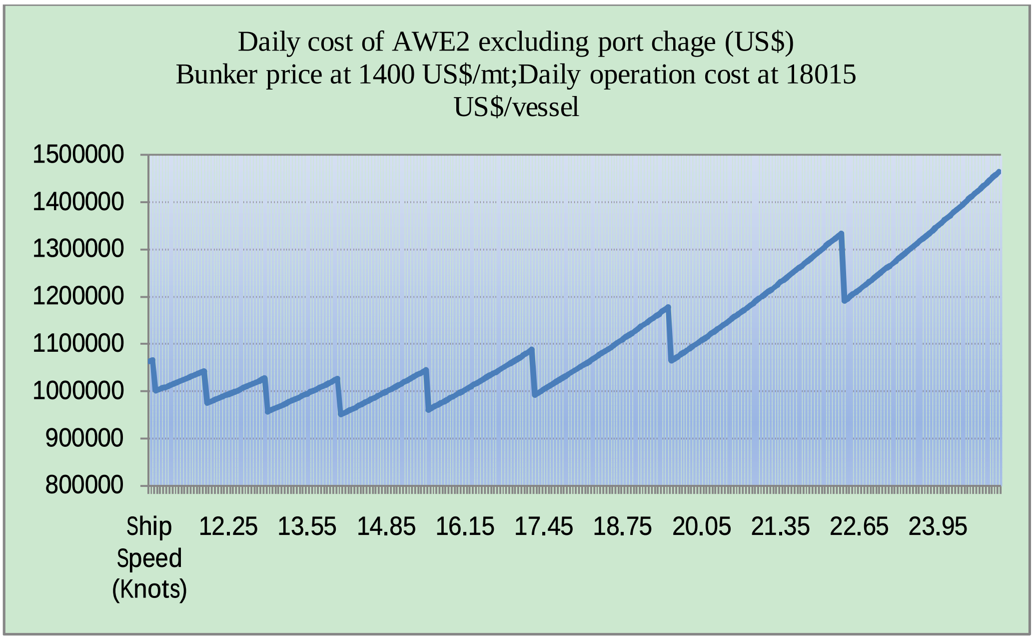

Figure **4-3** Daily cost of AWE2 versus ship speed, bunker price at 1400 US$/mt

Comparison and sensitivity analysis of optimal strategy upon different bunker prices

In order to analyze the sensitivity of daily cost versus the ship speed change curve upon different bunker prices, we draw the a comparison chart for daily cost versus ship speed upon bunker price of S$400U /mt, US$600/mt, US$800/mt, US$1000/mt, US$1200/mt and US$1400/mt.

Assuming the same daily operation cost and service frequency upon the different bunker prices, Figure 4-4 illustrates the daily cost (excluding port charge)-ship speed change curves for a 4506 TEU container ship for AWE2 service route.

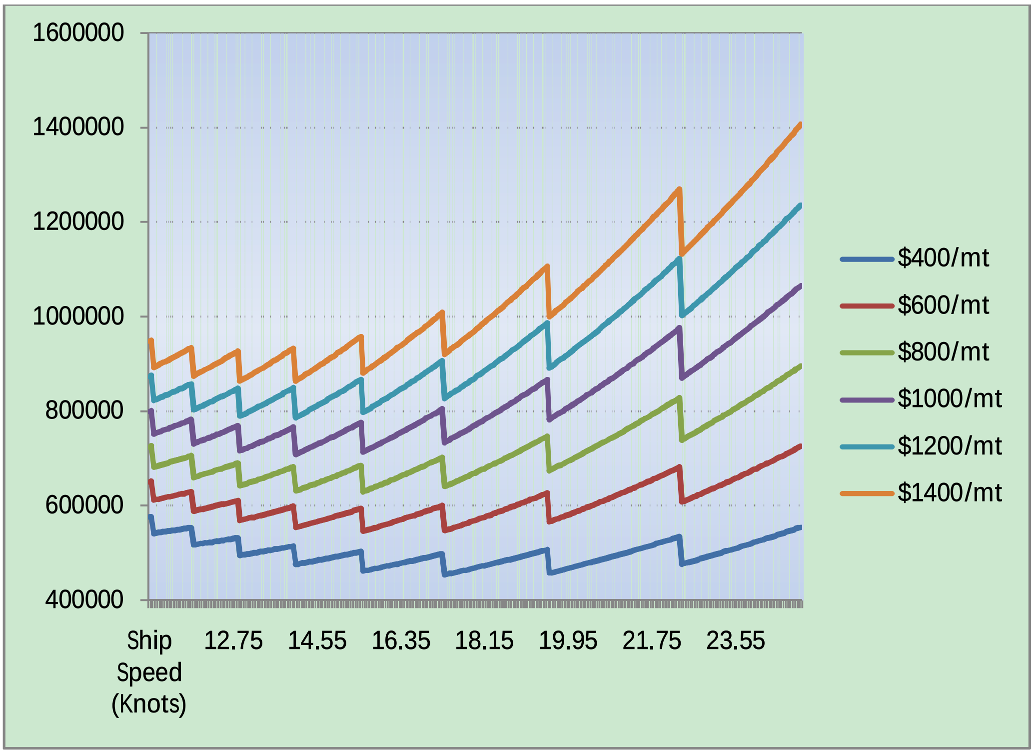

Figure 4-4 Daily cost (US$)-ship speed change curves upon different bunker price

Figure 4-4 illustrates that when bunker price increases, the global optimal ship speed for the minimal daily cost of container liner is going to decrease.

Actually, the daily operation cost also increase while the bunker price increases. However, the optimal ship speed is still going to decrease even though more vessels will be added to maintain the service frequency. Comparing Figure 4-3 with Figure 4-2, the optimal ship speed in year 2012 is 15.58 knots at bunker price US$718/mt while daily operation cost is US$10803.57 per vessel, and the optimal ship speed after year 2012 is 14.14 knots at bunker price US$1400/mt while daily operation cost is US$ 18014.61 per vessel. The bunker cost will increase dramatically not only because the bunker price is fast rising, but also because the ship operator has to upgrade fuel oil due to the new IMO MARPOL Annex VI regulations.

Comparison and sensitivity analysis of optimal strategy upon different sizes of container ship

Our previous analyses were all based on the container ship size of 4506 TEU. According to table 1-1, the capacity of container fleets is increasing in recent future and the newbuildings are on the trend to be larger.

Applying our mathematical model for unique emission requirement route (unique bunler price) and the container liner service route AWE2, we compare the optimal container ship speed and minimal daily cost for different sizes of container ships in this part.

Table 4-7 shows the parameters for three different types of container ships.

Table 4-8 The parameters for three different sizes of container

Vessel Size(TEU)	4000-5000	5000-6000	6000-8000
Daily Cost*(US$)	36849	53810	73912
K1*	0.007134	0.007279	0.006705
K2	15.698	71.4	87.71

Daily Cost*(US$): Daily cost per vessel includes daily operation cost, daily capital cost and daily port charge. K1*: K1 and K2 are the bunker consumption rate coefficients defined preciously. The parameters for vessel size of 4000-5000 are the same as obtained for Cosco Nagoya. The daily cost for a vessel size of 4000-5000 and a vessel size of 6000-8000 are referring to Eef Delhaye (2010) [15]. The bunker consumption rate coefficients for vessel size of 4000-5000 and vessel size of 6000-8000 are based on Zhishuang Yao(2011) [2].

Applying our mathematical model, Figure 4-5 shows the optimal container ship speed and minimal daily cost (US$) (including port charge) for different sizes of container ships at a bunker price US$718 applying the AWE2 service line route.

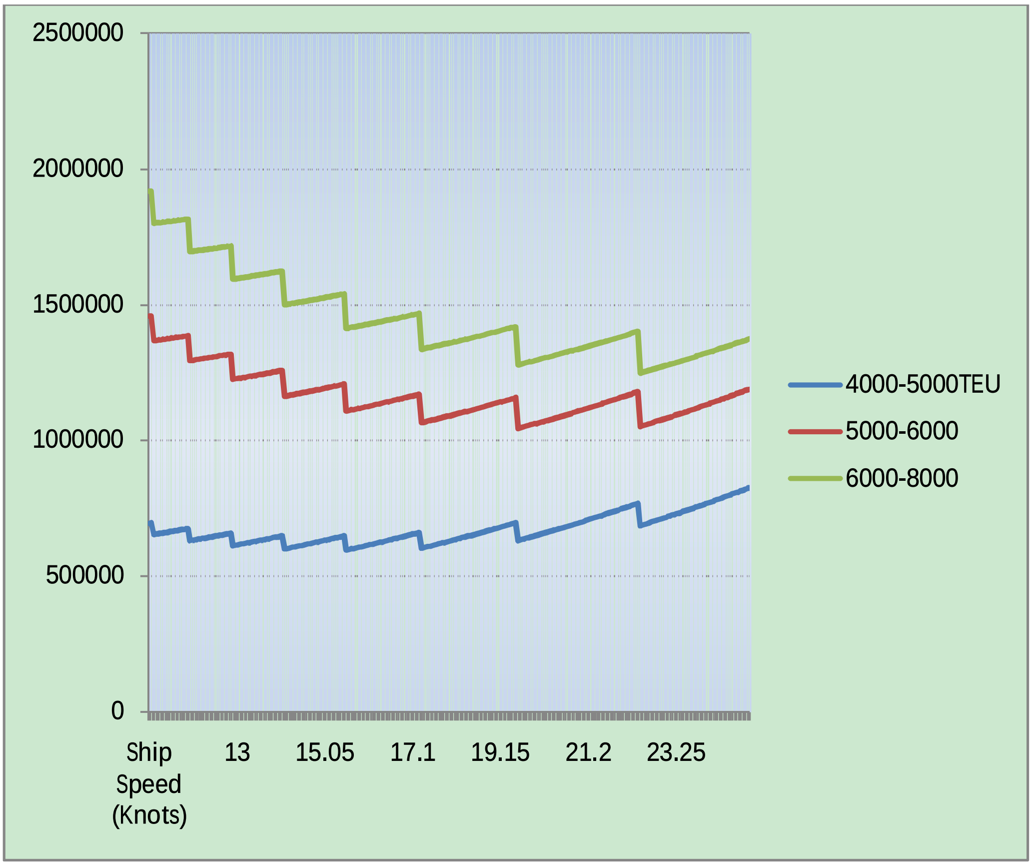

Figure 4-5 Optimal speed and minimal daily cost (US$) for different size of container ships

Figure 4-5 shows that a comparatively higher optimal ship speed is obtained for a larger container ship in order to get a minimal daily cost for the liner service maintaining a weekly service frequency. Thus, fewer ships are deployed for obtaining minimal daily cost if the fleet chooses larger container ships. However, if the shipper's demand does not increase, there will be more unused capacity from use of the larger container ships.

Optimal deployment strategy for routes of more than one emission standard

After August 2012, the area covering 200 nautical miles from coasts of the United States will become Emission Control Area. According to table 4-4, for the period from August 2012 to January 2015 and the period from January 2015 to January 2020, there will be different emission standard requirements and bunker requirements on the route of AWE2 container line service: one emission requirement for the global area such as Coast of Japan and Pacific Ocean, another requirement for the new Emission Control Area. Bunker prices will be different for the two areas even in the same service route. (After January 2020, the emission standard for the global area are becoming close to that of the Emission Control Areas and the bunker prices for the two area are very close, so the optimal strategy for this future period is discussed and analyzed in the section of the thesis before)

Period from August 2012 to January 2015

From August 2012 to January 2015 according to table 4-4, the route of AWE2 container liner service require bunker grade of IFO180 which contains maximum sulphur content of 35000ppm for the global area, and the container liner service requires bunker grade of MDO which contains maximum sulphur content of 10000ppm. Thus we obtain the independent variables for our mathematical model:

B_p = 718.12 (Applying the bunker price in 2012)

B_{pe} = 972.54 (Applying the bunker price in 2012)

D = 21929 (Distance excluding emission control area on AWE2 service route)

D_e =1695 (Distance passing through emission control area on AWE2 service route, containing port of Savanhah, New York and Boston)

Distance calculated by: www.dataloy.com

C_o =10803.57 (for year 2012)

Applying our model for the service route passing through emission control area, we utilize the Microsoft Excel Solver and obtain the optimal decision variables:

V =15.66

V_e =14.61

n =11

and we get a tight constraint (formula (12) with total roundtrip time of 77days(including 63.44 days sailing in global area and 5.25 days sailing in emission control area.

Based on our assumptions discussed before, the results imply that under the new IMO MARPOL Annex VI regulation and during the period from August 2012 to January 2015, container liner service of COSCO AWE2 should deploy 11 vessels of a single vessel size of 4506 TEU and set its fleet sailing speed at 15.66 knots in global area and speed at 14.61 knots in emission control area in order to get a maximal daily profit. Table 4-6 presents the optimal deployment strategy comparing to current deployment strategy of COSCO AWE2

Table 4-9 Comparison for deployment strategies of AWE2 with bunker price at 718 US$/mt for global area and bunker price at 972 US$/mt for emission control area

Strategy	Optimal	Current
Vessel deployed	11	9
Fleet speed* (Knots)	15.65/14.61	19.59
Daily cost(US$) excluding port charge	602322.4	639592.3
Daily port charge (US$)	90857.14	90857.14
Total(US$)	693179.54	730449.44
Differencial(US$)		37269.9
Cost per TEU per roundtrip(US$)	1386.35908	1460.89888

The fleet speed in table 4-8 represents the engine setting speed. The effective speed is 92% of the theoretical speed. The operation TEU is 3500 for a Cosco Nagaya(78% of total capacity), using data collected from Cosco America Inc.

The optimal strategy suggests that the ship uses two sailing speeds on the route, with sailing speed in emission control area (US's Coast) of about one knots less than that in global area. Theoretically, the slowing down at the US's Coast will not influence the service frequency of the container linear service because the ship was of long time accelerating prior to entering US's Coast and there is no port for calling during Westbound when returning to the initial starting port Qingdao. Actually, there are many factors influencing the real moment sailing speed for the ship, including weather condition, previous port operations, ship emergency and port or canal congestion. In order to keep the sailing schedule reliable, the drivers should adjust the ship speed often during the voyage accordingly. Our optimization result in this section provides a general idea for the optimal ship speeds and suggested differences of the speeds between global area and emission control area commonly.

Period from January 2015 to January 2020

While from January 2015 to January 2020 according to table 4-4, the route of AWE2 container liner service requires bunker grade of IFO180 which contains a maximum sulphur content of 35000ppm for the global area, and the container liner service requires a bunker grade of MGO which contains maximum sulphur content of 1000ppm. Thus we obtain the independent variables for our mathematical model:

B_p = 918.76 (Applying the bunker price in 2015)

B_{pe} = 1226.48 (Applying the bunker price in 2015)

D = 21929 (Distance excluding emission control area on AWE2 service route)

D_e =1695 (Distance passing through emission control area on AWE2 service route, containing port of Savanhah, New York and Boston)

Distance calculated by: www.dataloy.com

$C_o = 10803.57 \cdot (1+0.066)^3 = 13086.96$ (for year 2015)

Applying our model for the service route passing through emission control area, we utilize the Microsoft Excel Solver and obtain the optimal decision variables:

V =14.19

V_e =13.42

n =12

and we get a tight constraint (formula (12) with total roundtrip time of 84 days(with 69.97 days sailing in global area, 5.72 days sailing in emission control area).

Based on our assumptions discussed before, the results indicates that under the new IMO MARPOL Annex VI regulation and during the period from January 2015 to January 2020, container liner service of COSCO AWE2 should deploy 12 vessels of a single vessel size of 4506

TEU and set its fleet sailing speed at 14.19 knots in global area and speed at 13.42 knots in emission control area in order to achieve a maximal daily profit, while the total daily cost of the container liner is US$712991.3 per day. Comparing this the optimal strategy for the period from August 2012 to January 2015discussed in previous section, the optimal speed is still decreased while the bunker price increase, even though the ship operation cost increase at a rate of 6.6% per year simultaneously.

Our model and results provide the optimal ship speed and number of ship deployed based on estimated bunker price. Our approach is general and so the ship operator or shipping company could apply our model to any future real bunker price.

Chapter 5

DISCUSSION

Transit time

In chapter 3, we made the assumption that “Demand (TEU) per week from every port on the route does not change. Therefore if the container line maintains the same service frequency, the daily revenue of the company will be the same based on this assumption.” We made this assumption for the research purpose of developing our mathematical model for general study for the impact of fast rising bunker cost on container liner operations. However, the logistics demands from shippers are fluctuating every week as it is always sensitive to the effects of the world economy. While we idealized this demand fluctuating related to external factors for research purpose, another issue related to our optimum operation strategies should not be overlooked and is worth further discussion.

Considering that if a container liner slows down the vessel speed and adds more vessels into the service route in order to maintain the same service frequency, the total roundtrip and then the transit time will be increased.

The transit time in container ship industry does not have restrictive standards and shipping companies have initiative to adjust it between plausible ranges. The transit time from ports to ports varies for different shipping companies because different container liners have different ports of calling and calling sequence on its route. The transit time by international shipping is much longer than that for air transportation so the cargos for international shipping are generally withstanding transit time of more than several weeks.

To measure the service quality for a container liner, the most important criteria is the service frequency which is considered as the core sign for a container liner. The second most important one is the schedule reliability, meaning that container liner has to stick to its published sailing schedules for customers. After these, the shippers will balance the freight rate and transit time according to their characters of cargos. Some shippers claimed they could deal with extra 3.5 days and it could be an acceptable trade-off, if the container liner could improve schedule reliability [16]. However, significantly adding transit time will start to present problems in respect of adding cost of inventory. If there is another container liner providing the same route service and does not optimize the fleet speed upon a fast rising bunker price at the same pace, the container liner that makes the change of fleet speed may face pressure from competition.

Appendix B presents the current transit times for deploying 9 vessels, transit times when deploying 11 vessels and transit times when deploying 12 vessels of Cosco AWE2 container liner service respectively.

The average transit times (days for port to port) for the three deployment strategies are:

22.269 days for deploying 9 vessels, 27.218 days for deploying 11 vessels and 29.692 for deploying 12 vessels.

From the perspective of liner operator

For an operator of container lines, the economic benefit to be had from the optimal strategy of slowing down ship speeds is obvious as we studied in previous chapter, especially under the enforcement of IMO MARPOL Annex VI. However, it is important for the liner operator to clearly understand whether their customers are sensitive in response to increased transit time or not, and to what extent of the increased transit time would be accepted by their customers. The liner operator should also know very well about the market demand and the character of the cargos on its route. After thorough market research, strategy could be made referring to the indication by our mathematical model and optimal results from the viewpoint of operation research.

Particularly, as obtained by our mathematical models in previous chapter, the liner operator could save approximately 5% to 10% of its cost by implementing the optimal speed strategy while detailed saving figures are based on specific bunker price. Thus it will be a practical way for the liner operator to decrease its freight rate within the margin they save from slowing speeds in order to compete for prospective customers.

What's more, when we look at Figure 4-2 or Figure 4-3, the local optimal point on the right hand side next to the global optimal point is very close to the global optimal point from the way looking at total daily cost of the container liner, as illustrated in Table 5-1:

Table 5-1 Comparisons between local optimal results and global optimal results

Bunker price	Vessel Speed(Knots)	Number of vessel deployed	Total daily cost(US$ excluding port charge)	Cost growth rate from the optimal	Total roundtrip time(days)
718US$/mt	15.58	11	594847	0	77
	17.35	10	602620	0.013067226	70
	19.59	9	629207	0.057762752	63
1395US$/mt	14.14	12	948317	0	84
	15.6	11	959156	0.011429722	77
	17.35	10	990673	0.04466439	70
	19.59	9	1061188	0.119022437	63

The figures marked blue are the global optimal results obtained by our model in the previous chapter, and the figures in yellow are the current deployment strategy for Cosco AWE2 container liner service. When the bunker price reaches at US$718/mt, the total daily cost by deploying 11 vessels is slightly less than that by deploying 10 vessels (difference is US$7773), but total daily cost of deploying 10 vessels is much less than that of deploying 9 vessels (a difference of US$26587). However, the increasing of total roundtrip time is the same of 7 days whenever one more vessel is added to the fleet. And the transit time is proportional to total roundtrip time. Thus, if the customers of container liner service are sensitive to transit times, the liner operator could choose to add number of vessel from 9 to 10 instead of 11as first step, and then make further decision based onthe market. Similarly for a bunker price at US$1395/mt, liner operators could choose to add number of vessel from 9 to 10 or 11 instead of the optimum of 12, due to that there is big saving from deploying 10 vessels instead of 9 vessels, and big saving from deploying 11vessels instead of 10 vessels, but comparatively very small saving from deploying 12 vessels instead of 11 vessels, with the same increasing rate of transit time while adding number of vessel by one.

From the perspective of shipper and the entire supply chain

As soon as the transit time increases, in-transit inventory cost increases. This cost includes cargo capital cost and obsolescence, which is directly paid by shippers, and finally indirectly carried by the entire supply chain.

In this section, we incorporate the inventory cost into our optimization model. According to TE Notteboom (2006), these additional inventory costs due to longer transit times can be broken into two parts: (1) opportunity costs (3%–4% per year) and (2) economic depreciation (typically 10%–30% per year for consumer products)[17]. And according to Bergh, I. (2010), inventory cost can be measured by using the Internal Rate of Return (IRR)- the expected return on capital if utilized for other investments (the alternative cost principle). The IRR can be much higher than the typical lending rate that banks quote, possibly in the order of 10–40% per annum depending on the profitability of the particular line of business [18]. In addition, Andrew Traill (2010) used 20% as the IRR in order to calculate inventory cost[16]. On average, our thesis uses 20 %(of the cargo value) per year for inventory cost.

What's more, according to previous research, Notteboom (2006) applied a value of $40,000 for Belgian import TEU and $14,000 for Belgian export TEU[17]. Cariou (2011) used a value of $27,331 for a TEU [19]. We assume the cargo value of a full-loaded TEU is US$27,000 for the full cycle of AWE2 service. And according to Cosco America Inc, there is average of 3300 full-loaded TEU for eastbound and 2000 full-loaded TEU for westbound, which is 75% of operation capacity-3500TEU of Cosco Nagoya on average.

Thus, defining C_I as inventory cost per vessel per day (US$):

$$C_I = \left(27000 \cdot 0.23 / 365\right) \cdot 3500 \cdot 0.7 = 41683.56$$

in the scenario for Cosco AWE2 container liner service

Incorporating C_I into our mathematical model, the objective function (Formula 7) is revised to be :

Minimize

$$\left\{ C_I + C_o + \frac{R}{360} \cdot \left[\frac{r \cdot \left(r+1\right)^m}{\left(r+1\right)^m - 1} \right] + \frac{B_p \cdot (K_1 \cdot V^3 + K_2) \cdot \dfrac{D}{0.92 \cdot V \cdot 24}}{\dfrac{D}{0.92 \cdot V \cdot 24} + \sum_{i=1}^{p} T_i} \right\} \cdot n \qquad (16)$$

with related constrains the same.(Formula 8,9,10)

Applying Microsoft-Excel Solver, we obtain the optimal deployment strategy shown in table 5-2.

Table 5-2 Optimal deployment strategy by model incorporated with in-transit inventory cost

Model incorporated with Inventory Cost	Optimal deployment strategy for route of single emission standard	
Period	January 2012 to August 2012	After January 2020
Bunker price	US$718.12/mt	US$1395/mt
Operation cost	US$10803.57 per vessel per day	US$18014.61 per vessel per day
Optimal ship speed (Knots)	19.56	17.34
Number of vessel deployed	9	10
Total daily cost(excluding port charge)(US$)	1003708	1407031

Though the inventory cost per day per vessel is approximately four times the daily operation cost per vessel, there is no indication from our model that the vessel speed should be increased from 19.56 knots in order to decrease transit time from the economic perspective of the entire supply chain. And in the future, there is also high probability that slowing down the container liner ships' speed could save cost of the entire supply chain due to fast rising bunker prices even when the inventory cost is incorporated.

The optimal deployment strategy from our model incorporated with inventory cost is an extremely conservative decision in slowing down ship speed, meaning that the ship operator will undertake all the expense in the supply chain incurred by fast rising bunker price. However in practice in liner shipping sector, it would not be surprising if many carriers were indeed more concerned with cutting their own costs and changing their own schedules and service parameters to suit their own needs first, foremost, and in some cases at the expense of their customers.

The lower transportation costs may not necessarily be reflected in the rate the shippers have to pay, as the rate is a result of supply and demand. There will be equilibrium between shippers and carriers. However, at least under the enforcement of IMO MARPOL Annex VI, slowing down the vessel speed will be a beneficial step according to our study from the standpoint of operation research for container liners.

Capacity utilization

Besides of saving cost from marine fuel consumption according to our study from the view of operation research, slowing down of the ship speed also has another advantage for the liner operator in the current market. As the indication from our mathematical model, in order to maintain the same service frequency, a container liner has to add vessels when it slows down its ship speed. This measure will help the liner operator to take capacity out of the market, which has been crucial to improve rate levels and uphold capacity utilization.

In our model, the volume of cargo (TEU) transported per unit time does not change (due to same service frequency requirement). Therefore, the volume of cargo transported per roundtrip increases in proportion with the time of one roundtrip. And the time of one roundtrip increase in proportion with the number of vessel deployed due to the slowing down of the speed. Thus the volume of cargo transported per roundtrip increase in proportion with the number of vessel deployed. Consequently the added vessels will not impact the capacity utilization for one roundtrip of the existing vessels and that the added vessels' capacity utilization for one roundtrip will increase from zero (if the capacities are out of the market) to the same level as the existing vessel theoretically. Ultimately the capital cost and new operation cost of the added vessels are covered by the revenue of the container liner service. And the total daily profit could be even higher than that by the former deployment strategy before new vessel added (New deployment strategy with more vessel added obtains a lower total daily cost for the container liner, and the daily revenue does not change). All these are realized by optimization of the ship speed and bunker consumption as studied by our model in previous chapter.

According to French-based liner shipping expert AXS-Alphaliner, the idled capacity of container ships has I increased from 595,000 TEU at the end of 2011 to about 676,000 TEU currently. (Generally there are always idled container ships for shipping companies in the world). What's more, Table 1-1 shows that the capacity of container ship has an increasing rate of 8.2% over the next two years according to the orderbook. So effectively absorbing extra capacities is significantly important for the sustained development and management for a container liner.

Particularly referring to our study, the daily capital cost for the vessel such as Cosco Nagoya (size of 4506TEU) is US$ 15950.7 calculated by formula 5. Thus, adding one vessel to the container liners will help Cosco reduce useless capital cost of US$ 15950.7 per day.

Cost of CO2 emission

Another significant benefit by slowing down vessel speed is the reduction of CO2 emission.

Maritime transportation is accountable for 2.7% of the world CO2 emissions. And according to Psaraftis(2009)'s study[23], containerships are the top CO2 emissions producer in maritime fleets. As the goal of environment-friendly shipping is high on the agenda of the IMO, the European Commission and many individual coastal states, reduction of emissions, from greenhouse gases (GHG) is an important and urgent target.

CO2 emission is directly related with fuel consumption of vessels, the relation can be found in a CO2 emission factor. According to Psaraftis(2010), the most commonly used emission factor for CO2 is 3.17 [24]. This means that 3.17 tons of CO2 is produced by each ton of bunker fuel consumed. Thus we obtain the formula describing the daily volume of CO2 emissions E of container liner AWE2:

$$E = 3.17 \cdot \left\{ \left[\frac{(K_1 \cdot V^3 + K_2) \cdot \dfrac{D}{0.92 \cdot V \cdot 24}}{\dfrac{D}{0.92 \cdot V \cdot 24} + \sum_{i=1}^{p} T_i} \right] + F_{ca} \right\} \cdot n \quad (17)$$

In formula (17), F_{ca} is the daily bunker consumption rate for an auxiliary engine. These bunker fuels are always MGO and used for powering the ship's work such as electricity besides of sailing. This fuel consumption always occur no matter the ship is sailing on the sea or berthing at port. And there is a constant bunker consumption rate for auxiliary engine of container ship. Particularly for Cosco Nagoya, the bunker consumption rate for auxiliary engine is 6 mt/day. (Data collected from Cosco America Inc.) This cost component is included in the operation cost in our study in Chapter 3 and Chapter 4.

According to equation (17), we obtain the daily volume of CO2 emissions for AWE2 at different ship speeds as shown in Table 5-3: (Assuming only one speed is applied on the container liner AWE2 route)

Table 5-3 CO2 emission versus different deployment strategy

Strategy at bunker price of US$1395/mt	Vessel speed(Knots)	Number of vessel deployed	Total daily cost(US$ excluding port charge)	Total daily CO2 emission(tons) of container liner AWE2
Global optimum	14.14	12	948317	1457.6
Local optimum	15.6	11	959156	1539.8
Local optimum	17.35	10	990673	1669.6
Local optimum	19.59	9	1061188	1887.9

Table 5-3 shows that the global optimal deployment strategy (12 vessels) reduces 23% of daily CO2 emission from current Cosco AWE2 deployment strategy (9 vessels).

The concept of a carbon tax is an environmental tax levied on the carbon content of fuels which makes the CO2 savings quantifiable. It is a form of carbon pricing. As published by IMO, the actual spot price for one ton of CO2 is US$ 25 [25].

Accordingly, Figure 5-1 illustrates the CO2 emission costs versus ship speed and number of vessel deployed for Cosco AWE2 container liner service.

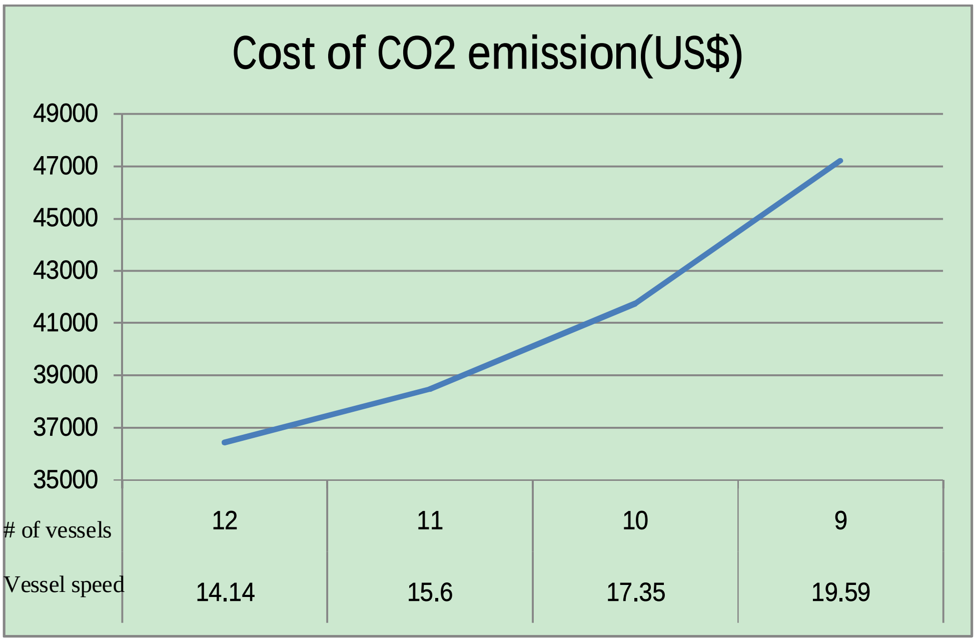

Figure 5-1 CO2 emission costs versus ship speed and number of vessel deployed for Cosco AWE2 container liner service

The CO2 reduction is proportion to bunker consumption reduction. The CO2 emission reduction due to slowing down the ship speed is an acceptable advantage that will be more important in the future when legislations on ship pollution might be tightened. If anything, the cost of bunkers is to be higher and possible future CO2 emissions costs will add to this [18].

Chapter 6

CONCLUSION

International Marine Organization issued the Revision of MARPOL Annex VI in 2008 in order to prevent and significantly decrease the emission from marine shipping. Due to the new regulations, bunker prices for container ships will increase dramatically in the future because ship operators have to change their bunker fuel grade to higher quality ones with lower sulphur contents. Besides of this, the market price of marine fuel oil has been fast rising and consequently the bunker cost composes approximately three quarter of the total cost for a container ship in operation today. Our thesis works on optimization of the ship speed and deployment problem for a specified container liner (Cosco AWE2) serving the transpacific route which will be typically influenced by the Revision of MARPOL Annex VI from the year 2012. Four periods representing the different steps of the enforcement of the Revision of MARPOL Annex VI are analyzed respectively by our study. Detailed bunker prices are estimated according to different time periods and emission control areas.

We developed mathematical models with the objective of minimizing the total daily cost of the container liner, assuming that total daily revenue does not vary based on same service frequency. And the decision variables are ship speeds and number of ships to be deployed in the entire container liner. The independent variable for the optimization problems is the bunker price influenced by the new regulation. Our study incorporates an empirical expression to describe relationship between the bunker consumption rate and ship speeds. Regressions are conducted by real data to obtain an accurate expression to describe this relationship. Two models are devised. The first one is for optimizing the single speed for the container liner and number of vessels deployed in the entire service route one unique emission control regulation is effective for the entire route. According to the Revision of MARPOL Annex VI, the time periods effective for this scenario are period from January 2012 to August 2012 and period after January 2020. The second model is for optimizing two speeds of ship for the container liner and number of vessel deployed in the entire service route. The two speeds are optimal for different segments of the entire route respectively according to different emission control requirements, as the U.S. coasts are going to be emission control area which has a stricter limitation of sulphur content of marine fuel oil to be consumed compared to other global area after August 2012. According to the Revision of MARPOL Annex VI, the time periods effective for this scenario are period from August 2012 to January 2015 and period from January 2015 to January 2020.

The two mathematical models are convex nonlinear optimization problems with global optimum and several local optimums by the constraints that specify the range of the operational speeds of ship and the integer character of number of ships deployed. Analysis finds that local optimums are always reached by constraint of the service frequency is tight.

By solving our mathematical models, our study obtains several optimal results (Assuming the Cosco AWE2 service route and port of calling, weekly service frequency and average vessel capacity of 4506 TEU):

From January 2012 to August 2012: Optimal ship speed is15.58 knots with optimal 11 vessels deployed.

From August 2012 to January 2015: Optimal ship speed is15.66 knots in global area and optimal speed is 14.61 knots in emission control area (within 200 nm off U.S. coast), with optimal 11 vessels deployed.

From August 2015 to January 2020: Optimal speed is 14.19 knots in global area and optimal speed is 13.42 knots in emission control area, with optimal 12 vessels deployed.

After January 2020: optimal speed is 14.14 with optimal 12 vessels deployed.

The saving from the optimal strategy compared to the current practice is approximately 5% to 10% depending on different bunker price. Our mathematical models can be easily applied by different container liner parameters, such as ship capacity, service frequency, bunker consumption rate, service route and bunker price in order to obtain particular and accurate optimal strategy for different ship companies in the world. Generally speaking, our mathematical model provides beneficial indications and references for ship operators from the view of operation research.

What’s more, our study performed sensitivity analysis and shows that when the bunker price increases, the optimal ship speed will decrease, which is very much likely to happen for the transpacific route due to the Revision of MARPOL Annex VI. Additionally, we show that a comparatively higher optimal ship speed is obtained for a larger container ship. This is beneficial for both shipping companies and shippers. Because the new ship in building is on the trend of increasing capacity and faster speed can decrease the port-port transit time which consequently help the shipper to decrease inventory cost and provide the ship company more chances to increase freight rates.

With respect to our optimal results, slowing down and adding more vessels to current container liner will be a common trend upon the new emission regulations. There are one negative impact and two positive impacts from this adjustment for further consideration from the view of entire supply chain.

The negative impact is the transit time will be increased even not serious. And from the perspective of shipper, the inventory cost will be increased. In case of this issue, the ship operator should clearly understand whether their customers are sensitive in response to increased transit time or not, and to what extent of the increased transit time would be accepted by their customers. The liner operator should know very well about the market demand, the character of the cargos on its route, as well as the situation of market competition. In this scenario, the ship operator could low down the freight rate into the range within cost saving by slowing down ship speed. And it is the ship operator's choice to choose the second optimal strategy because there is always a big saving from the third optimal strategy to the second optimal strategy however a comparatively small saving from the second optimal strategy to the global optimal strategy as illustrated by our mathematical model. However, we also show that even though the inventory cost per day per vessel is approximately four times of the daily operation cost per vessel, while the inventory cost is incorporate into our model and by performing re-optimization, there is no indication that the vessel speed should be increased from 19.56 knots (the current speed for Cosco AWE2) in order to decrease transit time from the economic perspective of the entire supply chain. And our mathematical model shows in future, slowing down the container liner ships' speed could still save cost of the entire supply chain due to fast rising bunker price and the new emission regulation even when inventory cost is considered. The optimal deployment strategy by our model incorporated with inventory cost is the extremely conservative decision in slowing down ship speed since it assumes the ship operator will undertake all the expense in the supply chain incurred by fast rising bunker price. There will be equilibrium between shippers and carriers. However at least, under the enforcement of IMO MARPOL Annex VI, slowing down the vessel speed will be a beneficial step from the standpoint of operation research for container liners. And in future, it will be a wise to design new ship engines having wider and different range of operational speeds for serving different cargos which have different degrees of sensitivity to transit time.

The first positive impact by slowing down ship speed is improving the capacity utilization. While slowing down the ship speed means new ship to be added into the fleet in order to maintain the same service frequency. Thus idle capacity will be utilized and related daily capital cost will be covered. Our study shows that adding one vessel to the container liners will help Cosco reduce useless capital cost of US$ 15950.7 per day. The other positive impact by slowing down ship speed is reduction of CO_2 emission which is very significantly meaningful and is also one the original intention by MARPOL Annex VI. Our study shows that the optimal strategy of 12 vessels (speed of 14.14 knots) will reduce 23% of daily CO_2 emission from current Cosco AWE2 deployment strategy (9 vessels, speed of 19.59 knots).

The thesis made the speed of container ship and number of ship deployed as the decision variables. Future research could add the port selection and ship capacity as decision variables, or more sophisticated analysis for container ship of bigger capacity. As shown in Table 1-1, the newbuidlings are on the trend of bigger capacity.

Another opportunity for future research is the study of transit time impact on the profit of container liners. Even though our study performed some quantative analysis in the transit time impact, it was from the viewpoint of inventory cost which could be consider as an upper limit of negative impact for ship operator. It would be very useful for future research to perform detailed analysis to measure how much the transit time will influence the profit of a container liner. Then some detailed expression measuring the effect of transit time could be incorporated into our model.

As our thesis focused on a transpacific route, study on the impact of revision of MARPOL Annex VI for other routes or short sea routes such as short sea transportation within 200 nm off U.S. coast could be another research arena. What's more, answering the question of whether the increasing bunker price due to the revision of MARPOL Annex VI make the international container ship linear reduce number of ports of call in U.S. coast, or make the short sea transportation shift to road and rail on specific short sea shipping routes along U.S. coast could be another important line of research.

References

[1] Li, Y. (2011, October 31). *Shipping industry research report*. Retrieved from National Trust website: http://www.natrust.cn/doc/uploads/20111107070900.pdf

[2] Yao, Z. S., Ng, S. H., & Lee, L. H. (2011). A study on bunker fuel management for the shipping liner services. *Computers & Operations Research*, *39*, 1160–1172.

[3] Lloyd's Register. (2008, September). *Container ship speed matters*. Retrieved from Lloyd's Register Marine Service website: http://www.martek-marine.com/downloads/119/0/SLOWSTEAMINGFUELEFFICIENCYANDTHEENVIRONMENTv6.pdf

[4] International Maritime Organization. *Revised MARPOL Annex VI*. Retrieved from http://www.imo.org

[5] Nottebooma, T. E., & Vernimmen, B. (2009). The effect of high fuel costs on liner service configuration in container shipping. *Journal of Transport Geography*, *17*, 325–337.

[6] Ronen, D. (1982). The effect of oil price on the optimal speed of ships. *Journal of Transport Geography*, *33*(11).

[7] Brown, G.G., Graves, G.W., & Ronen, D.(1987). Scheduling ocean transportation of crude oil. *Manage Sci, 33(3)*.

[8] Fagerholt, K., Laporte, G. & Norstad, I. (2010). Reducing fuel emissions by optimizing speed on shipping routes. *J Oper Res Soc, 61(3).*

[9] Baird, A. (2006) Optimizing the container transshipment hub location in Northern Europe. *Journal of Transport Geography, 14,* 195-214.

[10] Retrieved from Containerisation International website: http://www.ci-online.co.uk/

[11] Kehoe, J., & Woxenius, J. SKEMA, (2010). *Assessment of the impact of the application of new sulphur limits to the Mediterranean and the Atlantic European Seas* (Grant Agreement No. TREN/FP7/TR/218565/"SKEMA" Deliverable: D 4.4.2).

[12] Retrieved from http://www.bunkerworld.com

[13] Retrieved from http://www.coscon.com

[14] HSH Nordbank, Ernst & Young, & Econum. (2009). *Operating Costs 2009-A study on the operating costs of German container ships*.

[15] Delhaye, E., Breemersch, T., Vanherle, K., Kehoe, J., Liddane, M., & Riordan , K. European Commission DG Environment, (2010, August 18). *COMPASS The COMPetitiveness of EuropeAn Short-sea freight Shipping compared with road and rail transport* (Service Contract: 070307/209/545506/SER/C3).

[16] Traill, A. (2010, February 15). *Understanding the impact of slow-steaming*. Retrieved from http://www.ifw-net.com/freightpubs/ifw/opinion/understanding-the-impact-of-slow-steaming/20017748957.htm

[17] Nottebooma, T. E. (2006). Time Factor in Liner Shipping Services. *Maritime Economics & Logistics*, *8*, 19–39.

[18] Bergh, I. DNV. (2010). Optimum speed – from a shipper's perspective. *Container ship update*, *2*, 10-13.

[19] Cariou, P. (2011).Is slow steaming a sustainable means of reducing CO2 emissions from container shipping? *Transportation Research Part D, 16*, 260-264.

[20] Retrieved from http:// www.alphaliner.com

[21] Marintek. , Econ Centre for Economic Analysis , Carnegie Mellon University & DNV, IMO, (2000). *Study of greenhouse gas emissions from ships.*

[22] Psaraftis, H.N. and Kontovas, C.A. (2009a) CO2 Emissions Statistics for the World commercial fleet. *WMU Journal of Maritime Affairs 8(1)*, 1-25.

[23] Psaraftis, H. N., & Kontovasand, C. A. (2009, October). S*peed reduction as an emissions reduction measure for fast ships*. 10th international conference on fast sea transportation, Athens, Greece.

[24] Psaraftis, H.N. and Kontovas, C.A.(2010) Balancing the economic and environmental performance of maritime transportation. *Transportation Reaserch Part D, 15,* 458-462.

[25] IMO,. *Main events in imo's work on limitation and reduction of greenhouse gas emissions from international shipping*. Retrieved from website: http://www.imo.com

[26] G. C. Manning. (1956). *The theory and technique of ship design*. Cambridge, Massachusetts: MIT Press.

[27] J Corbett, J. J., & Winebrake, J. J. (2009, January). *Impacts of speed reductions on vessel-based emissions for international shipping*. Paper presented at 88th annual meerting of the transportation research board, Shoreham, Blue Room, Washington, DC. Retrieved from http://www.trb.org/marineboard/AM09/270Corbettetal.pdf

[28] Christiansen,M., Fagerholt,K., Nygreen, B. and Ronen, D. (2007).*Maritime transportation*. In: Barnhart, C. and Laporte, G. (eds). Handbooks in Operations Research and Management Science:Transportation. North-Holland: Amsterdam, 189–284.

[29] Boutsikas, A. (2004). *The bunkering industry and its effect on shipping tanker operations*. (Master's thesis, Massachusetts Institute of Technology)Retrieved from http://dspace.mit.edu/bitstream/handle/1721.1/33580/63534102.pdf

[30] Norstad, I., Fagerholt, K., & Laporte, G. (2011). Tramp ship routing and scheduling with speed optimization. *Transportation Research Part C, 19,* 853–865.

[31] Wong, H., Hsieh, S., & Wang, C. (2007, July). Optimizing Containership Size and Speed: Model Formulation and Implementation. *WSEAS TRANSACTIONS on BUSINESS and ECONOMICS*, *4*(7), 853–865.

[32] Boffey, T. B., Edmond, E. D., Hinxman, A. I., and Pursglove, C. J. (1979), Two Approaches to Scheduling Container Ships with an Application to the North Atlantic Route. *Journal of the Operational Research Society, 30(5),* 413-425.

[33] Powell, B. J., Perakis, A. N. (1997). Fleet deployment optimization for liner shipping: An integer programming model. *Maritime Policy and Management 24(2),* 183–192.

[34] University of Turku, The Centre for Maritime Studies. Ministry of Transport and communications Finland , (2009). *Sulphur content in ships bunker fuel in 2015, a study on the impacts of the new imo regulation on transportation cost.*

[35] Swedish Maritime Administration (2009). *Consequences of the IMO's new marine fuel sulphur regulations.*

[36] ENTEC. Maritime Coast Guard Agency. (2010). *Impact Assessment for the revised Annex VI of MARPOL.*

[37] Institute of Shipping Economics and Logistics.German Shipowners' Association and Association of German Seaport Operators (2010) *Reducing the sulphur content of shipping fuels further to 0.1 % in the North Sea and Baltic Sea in 2015: Consequences for shipping in this area*.

[38] ECSA. University of Antwerp, Institute of Transport and Maritime Management Antwerp (ITMMA). (2010) *Analysis of the Consequences of Low Sulphur Fuel Requirements*.

[39] AEA. EU Commission. (2009) *Cost Benefit Analysis to support the Impact Assessment accompanying the revision of Directive 1999/32/EC on the Sulphur Content of certain Liquids Fuels*.

[40] SKEMA (2010) *Task 2 and 3 Impact Study on the future requirements of Annex VI of the MARPOL Convention on Short Sea Shipping.*

[41] European Maritime Safety Agency. (2010) *The 0.1% sulphur in fuel requirement as from 1 January 2015 in SECAs - An assessment of available impact studies and alternative means of compliance*.

[42] U.S. Environmental Protection Agency. *Designation of North American Emission Control Area to Reduce Emissions from Ships*. Retrieved from website: http://www.epa.gov/otaq/oceanvessels.htm

Appendix A

Record of bunker consumption rate versus ship speed for Cosco Nagoya

Revolution of main engine(RMP)	Theorotical speed(knots)	Effective speed(knots 8% slip)	Distance (miles/day)	Bunker consumption rate(mt/day)
100.4	25.25	23.23	557.53	133.4
95	23.89	21.98	527.55	113
94	93	21.75	521.99	110
23.64	23.39	21.52	516.44	107
92	23.14	21.29	510.89	104.1
91	22.89	21.06	505.33	101.2
90	22.64	20.82	499.78	98.4
89	22.38	20.59	494.23	95.6
88	22.13	20.36	488.67	93
87	21.88	20.13	483.12	90.4
86	21.63	19.9	477.57	87.8
85	21.38	19.67	472.02	85.4
84	21.13	19.44	466.46	83
83	20.87	19.2	460.91	80.7
82	20.62	18.97	455.36	78.4
81	20.37	18.74	449.8	76.2
80	20.12	18.51	444.25	74.2

Data source: Cosco America Inc.

Appendix B

Transit time for Cosco AWE2 container liner service

Current transit time f Cosco AWE-2 container liner service

From\To (Days)	Qd	Sh	Nb	Yo	LC	Sa	No	NY	BO
Qingdao		2	3	6	18	23	27	30	32
Shanghai			1	4	16	21	25	28	30
Ningbo				3	15	20	24	27	29
Yokohama					12	17	21	24	26
Lazaro Cardenas						5	9	12	14
Savannah	40	42	43	46			4	7	9
Norfolk	36	38	39	42				3	5
New York	33	35	36	39					2
Boston	31	33	34	37					
								Ave.	22.269

Data source: http://www.ci-online.co.uk/

Transit time when deploying 11 vessels of Cosco AWE-2 container liner service

From\To (Days)	Qd	Sh	Nb	Yo	LC	Sa	No	NY	BO
Qingdao		2.4444	3.6667	7.3333	22	28.111	33	36.667	39.111
Shanghai			1.2222	4.8889	19.556	25.667	30.556	34.222	36.667
Ningbo				3.6667	18.333	24.444	29.333	33	35.444
Yokohama					14.667	20.778	25.667	29.333	31.778
Lazaro Cardenas						6.1111	11	14.667	17.111
Savannah	48.889	51.333	52.556	56.222			4.8889	8.5556	11
Norfolk	44	46.444	47.667	51.333				3.6667	6.1111
New York	40.333	42.778	44	47.667					2.4444
Boston	37.889	40.333	41.556	45.222					
								Ave.	27.218

Transit time when deploying 12 vessels of Cosco AWE-2 container liner service

From\To (Days)	Qd	Sh	Nb	Yo	LC	Sa	No	NY	BO
Qingdao		2.6667	4	8	24	30.667	36	40	42.667
Shanghai			1.3333	5.3333	21.333	28	33.333	37.333	40
Ningbo				4	20	26.667	32	36	38.667
Yokohama					16	22.667	28	32	34.667
Lazaro Cardenas						6.6667	12	16	18.667
Savannah	53.333	56	57.333	61.333			5.3333	9.3333	12
Norfolk	48	50.667	52	56				4	6.6667
New York	44	46.667	48	52					2.6667
Boston	41.333	44	45.333	49.333					
								Ave.	29.692