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MSc in International Shipping, Finance and Management

Cargo shipping and scheduling optimization for crude oil transportation

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Cargo shipping and scheduling optimization for crude oil transportation

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CERTIFICATE OF THESIS PREPARATION

“I hereby declare that this particular thesis has been written by me, in order to obtain the Postgraduate Degree (MSc) in International Shipping, Finance and Management, and has not been submitted to or approved by any other postgraduate or undergraduate program in Greece or abroad. This thesis presents my personal views on the subject. All the sources I have used for the preparation of this particular thesis are mentioned explicitly with references being made either to their authors, or to the URL’s (if found on the internet).”

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Contents

Table of Figures and Tables

Abstract

This thesis aims to apply mathematical techniques to facilitate decision making for shipping companies providing crude oil transportation. Focus is given on the development of a mathematical model solving a challenging problem for the shipping industry with practical operational constraints and characteristics. In particular we study a cargo shipping and scheduling problem for crude oil transportation taking into consideration time window constraints and operational synchronization constraints.

At first, we examine the significance of crude oil transportation worldwide. To do so, the largest importers of crude oil worldwide are considered. More specifically, attention is paid to the imports of China and the USA over the last years and how their demand for crude oil has been affected by the multiple crises which still harm the economy and the seaborne trade. In addition, due to the extremely high demand from the European countries, the countries from which the EU imports the demanded amount of crude oil are going to be examined and there is also going to be an effort to make some conclusions based on the data and the indexes which are going to be collected. Of course, the appropriate research also for the other participants of the trade; the exporters of crude oil should also take place. As a result, on the introduction part, there is going to be a presentation and an analysis about "the slice of the cake" that each great exporter has on the crude oil trade. Finally, due to the much harmful effects of the economic crisis period, which COVID19 has created, it will further be examined how much the pandemic has affected the crude oil prices worldwide during the last year and then a comparison of the impacts on them will be presented.

Next, we review research on ship routing and scheduling and related problems during the new millennium and present main methods for solving them. From the Literature review it is revealed that the routing and scheduling problems for shipping companies are of great importance. As a result, our research focuses on a routing and scheduling problem in which a maritime company has the obligation to transport crude oil between three loading ports and nine discharge ports. Each port belongs to a country that has a major role in the crude oil transportation industry, either as an importer or as an exporter. The objective function of this problem is the maximization of the shipping company's profits. More specifically, the company has on its disposal four different

sizes of tanker vessels that can be used in such a way, in order to maximize the difference between its revenues and its costs.

The mathematical model for the problem considered is developed, subject to multiple operational constraints. As a result, the constraint of time horizon is considered necessary. The time horizon in this scenario can also be called as planning horizon. Furthermore, another requirement is the port precedence that should take place, so as the objective function will be at the maximum level. For this reason, there have already been three different contracts set, which declare which discharge ports can each port serve. So, the optimal solution of this problem consists of the optimal precedence between the ports of each route and also the best possible allocation of the routes between the four vessels of the existing fleet.

Finally, the final conclusions of the thesis will be cited, including the results and deductions of the case study. The aim of these case studies is optimal decision making in the crude oil transportation industry and as a result the last part of this thesis' conclusion will be the improvement of this target.

Chapter 1: Introduction

International trade plays a vital role in the global economy worldwide. A major part of international trade consists of seaborne trade. More specifically, the 80% of goods traded internationally are transported by sea. [1]Despite the fact that, due to technology progress many other forms of transportation have been developed in recent years, the seaborne transportation of certain types of goods is still more preferable compared to other modes of transport. For this reason, the shipping industry is considered as one of the most significant industries in our days. As a result, the maritime companies are continuously trying to face the competition inside the industry and maximize their profits as much as possible.

The problems of cargo shipping and scheduling reflect the effort of the maritime companies that should be made in order to be able to survive into high levels of competition. The last 20 years we have observed a general increase of the total capacity of the vessels. In January 2021, the total fleet capacity worldwide presented an increase of 81 million dwt more in contrast with the previous year and it was equal to 2.1 billion dwt.[2] Furthermore, in 2000 the total oil tanker vessels' capacity was equal to 268 million dwt, while in 2020 their total oil capacity was 601 million dwt.[3] In addition, in 2021, it has been calculated that the Bulk Carrier vessels have a share of 43% of total capacity worldwide, while in 2010 their share was equal to 36%. [4]

As a result, the importance of the seaborne trade significantly increases, and many allocations take place by the shipping companies in order to be able to adapt to the high demand for goods transportation. The studying of these types of problems assists to the further examination and observance of the methods followed by the companies of the maritime sector, in order to respond to the seaborne trade.

[1] https://unctad.org/
[2] https://unctad.org/
[3] https://www.statista.com/
[4] https://unctad.org/

1.1 Research Questions

The shipping industry provides a great assistance to every country in the world to be able to trade many and different kinds of commodities. These commodities can usually be either in a dry or in a liquid form. The transportation of dry cargo (grain, coal, iron ore etc.) is made by Bulk Carrier vessels and the transportation of liquid cargo can be from Tanker vessels (crude oil, chemical products etc.). However, due to the containerization era that we are living into, many different commodities can now be transported from containers, regarding their size, type and their form. On this assignment, we focus on the crude oil transportation worldwide. As a result, the first research question to be answered in this thesis is:

1) What is the significance of crude oil transportation worldwide?

The answer of this question is analyzed on the Introduction part of our thesis. Firstly, we examine the main crude oil imported countries worldwide. Then, we further analyze the demand of some of these importers in the last years and during periods of economic crises. Also, at this part, we also make a research for the countries by which some great importers (EU countries) obtain the requested amount of crude oil. In addition, we also examine the highest crude oil exporters worldwide and their contribution to the crude oil transportation industry. Finally, we examine the ups and downs of crude oil prices during the last years, in order to understand how much the crude oil transportation does is affected and can also affect the global economy.

The examination of crude oil transportation can present many similarities with other commodities' transportation. Despite the fact that the used vessels in each case are totally different, the optimization of the shipping plan in many cases is quite similar. The shipping companies wish to maximize the amount of money from a contract for cargo transportation. However, something like that is not so easy as it may sound. As a result, each time a request for cargo transportation arrives at a maritime company, the managers of the company have to design a shipping plan, in order to examine how profitable is for the company to undertake the requested transportation and if so, what is the method to take full advantage of this contract and make the highest possible profits. As a result, the second research question to be answered in this thesis is:

2) Which are the methods which assist us in finding the optimal shipping plan?

In the literature review we examine most of the methods that can be used in order to create a shipping plan that can be as much profitable as possible for the company. What we found in our research on several papers, is that there are plenty of models that can provide great assistance regarding the decision making related to sea transportation of a commodity. On the other hand, the methods that can be examined and formulated to answer these types of problems are fewer. In other words, in our thesis' literature review we further analyze most of the models and methods used regarding the shipping planning and the decision making in sea transportation of many types of cargo and we also examine the efficiency of many of them.

For our case study, we have chosen to examine the transportation of crude oil between several ports around the world. Our objective is to maximize the profits for a shipping company, that . In other words, our aim is to find the optimal solution, according to which , the maritime company will enjoy the maximum possible revenues and will also have the obligation to pay the minimum possible costs. Thus, the third research question to be answered in this thesis is:

3) What is the optimal shipping plan for a shipping company that needs to fulfill a set of contract cargoes for the transportation of crude oil?

The creation of this optimal shipping plan requires the collection of the appropriate data, which will assist us to allocate the amounts of costs and revenues at each route. As a result, the fourth question to be examined by our thesis is:

4) Which data should be collected in order to solve the optimization of the crude oil sea transportation problem?

In order to analyze and formulate the problem of our case study, we collected plenty of data that are extremely significant for us to find the optimal solution. More specifically, we gathered data which mainly are operation costs, bunker costs, freight rates, distances (in days and in nautical miles) etc., which we consider as necessary for our problem. Every platform that we use has real data and the reason behind our decision of these specific platforms is that we want our problem to be realistic and in accordance with real life sea transportation problems. More specifically, the platforms which we chose to collect the data from are:

- Clarksons Research Portal

- Q88: Commercial Shipping Management Software
- SEA DISTANCES.ORG
- Worldsale.co.uk.

1.2 The importance of Crude Oil Transportation in the Shipping Industry

Over the years, crude oil has been one of the highest demanded products for transportation in the shipping sector worldwide. Traditionally, China is the country with the highest demand for barrels of imported crude oil annually in the world. [5]Typically, pipelines and trucks can provide a safe and reliable method of oil transportation through most of the countries around the world, but due to the higher capacity of the vessels, shipping is maybe the most preferable way to transfer oil in higher capacities. As a result, in the shipping industry the manufacturing companies try to create vessels which are better adapted to the transportation of oil in all the world and under more difficult circumstances.

China has the highest demand for oil over the last years and because of that, the whole oil production industry is affected a lot from the imports of China annually. As a result, the whole shipping industry is expected to be greatly affected by the yearly demand of oil by China as well as other countries with high imports of oil. In addition, in the year of 2018, 2038 million metric tons of crude oil have been transported by seaborne trade[6]. Furthermore, it is also extremely important that even though pipelines continue to evolve rapidly to the transportation needs of crude oil, seaborne transportation of oil seems to be preferred more and more over the last few years.

More analytically, it is very important to refer to the countries with the most imports of crude oil in the world. Moreover, after China, high demand present also the USA, India, Japan, South Korea, the Netherlands and Germany referred in order based on imports' quantity.

[5] Statista. 2020. *Statista - The Statistics Portal*. [online] Available at: <https://www.statista.com/>
[6] Statista. 2020. *Statista - The Statistics Portal*. [online] Available at: <https://www.statista.com/>

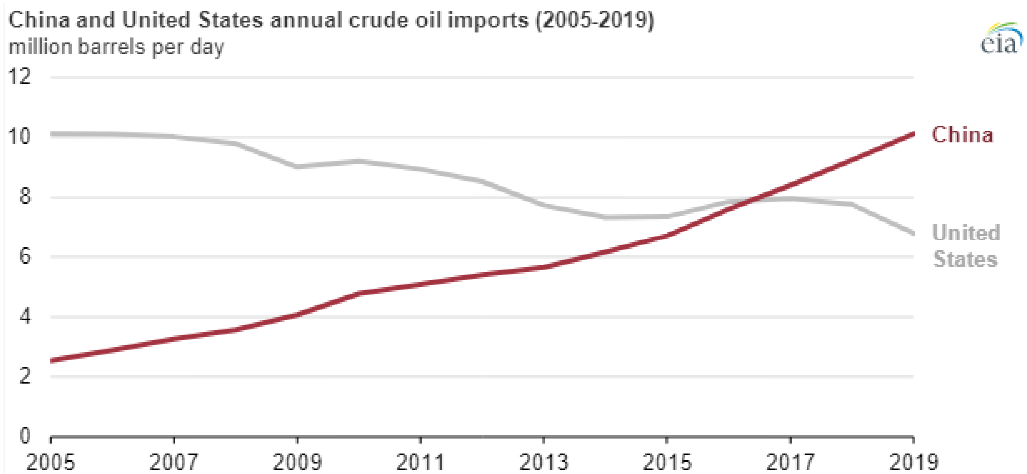

Figure 1: USA and China - crude oil imports[7]

Figure 1 demonstrates that for the last 15 years, China continually increases its demand for crude oil, in contrast with the US. Of course, from 2005 until 2007 we can see that the United States seem to have a steady demand for oil and the total imports of the country are almost 10 million barrels per day. However, after 2007 and mainly due to the world economic crisis of 2008, the imports of the US have decreased quite a lot until 2015 in the number of almost 7,5 to 8 million barrels per day. It is quite logical for this dramatic reduction in oil imports to negatively affect the whole shipping sector, creating many economic problems for many companies which operate mainly with tanker ships. However, during the very bad economic situation in the US and in most of the European countries, China seems to take advantage of the current at the time market condition (after 2008). An extremely fast increase of its imports with a steady rise from 2005 and during and after the crisis has led to China taking a much larger piece of the trade of crude oil by sea, making it the biggest importer of crude oil in the world. The difference of imported barrels per day between China and the US has reached almost 3 million and will likely further increase.

[7] https://www.eia.gov/

Europe

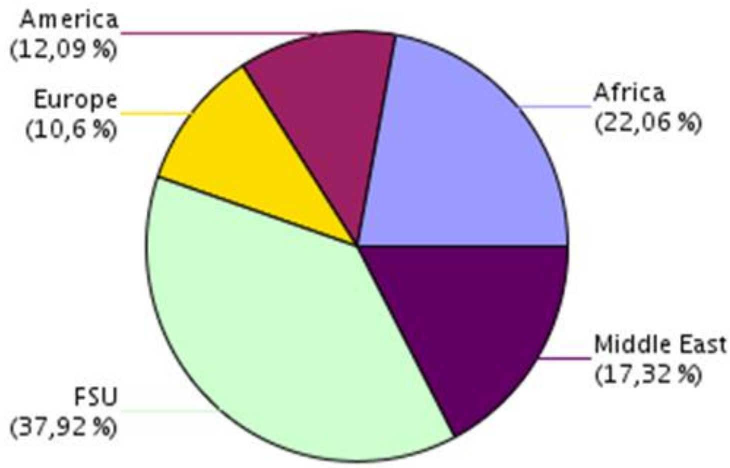

Figure 2: Sources of oil imports in Europe[8]

All the European Union countries as it is quite logical have higher demand for crude oil than China. Of course, it is not wise to compare the total imports of 28 countries with just one country. However, the fact that the EU as a sum has an extremely high demand for oil has to be taken into account and under serious consideration. Furthermore, as we mentioned above, the countries of the EU which have the most imports of crude oil belong to Central Europe (Germany, Netherlands). This is not by fortune, as the countries with the best economic results during and after the crisis (2008) belong to this geographical part of Europe. That proves that the worldwide economic situation affects a lot the shipping sector and also the supply and demand of quite a lot of products.

More specifically, according to the data we found which are publicly available by European Commission, Directorate-General for Energy (©European Communities, 2005), in 2005 the total imports of crude oil for the EU were around 4,5 billion barrels in total. Afterwards, in 2009 the total imports were around 4,05 billion barrels, presenting a fall of almost 500 million barrels of oil demanded (©European Communities, 2009), probably mainly because of the world economic crisis which this period had started to harm European countries. In 2012, oil imports are almost

[8] https://ec.europa.eu

the same with 2009, around 4,03 billion barrels (©European Communities, 2012). After 2012, the imports of oil seem to be in a decreasing mode, as we can observe that in 2014 the total imports are almost 3,8 billion barrels (©European Communities, 2014) and for 2019 the total imports are almost the same, presenting a small decrease of almost 30 million barrels (©European Communities, 2019).

A conclusion of all these data is maybe that the imports of crude oil in the EU decreased by a high percentage especially after the economic crisis began and it seems that the last few years might be the worst of the last decade, in terms of the demand for crude oil. However, we should also mention that after further examination, according to Figure 2, we can observe that the countries of the EU mainly import crude oil by almost 38% in 2019 by the FSU countries (post-soviet states), which traditionally have very high production of crude oil. Afterwards the main providers of crude oil to the EU are Africa and the Middle East and at the end there are countries from America (mainly the US) and from Europe (Norway).

To sum up, the EU tends to prefer to import crude oil from countries which all these years have great production and also have many stocks of crude oil. However, the methods of production of crude oil have been developed a lot during the last years. As a result, many countries which have many stocks and sources of crude oil and it is considered difficult until now to extract them, will have in the near future higher exports in all around the world. A great example of a country which belongs to this category is Venezuela.

Of course, in a trade the existence of the importers cannot stand without the exporters. As a result, the exporters play a vital role in the crude oil transportation. The countries which are considered the biggest exporters of oil are actually the countries which have the most stocks of oil and they can produce plenty of it. So, the countries which with the current methods of extraction of crude oil can produce high quantities of it, have the advantage in this industry area and they gain a lot of money from this business.

Over the last years, Saudi Arabia has made a great and powerful name in the industry of oil extraction and production. Of course, they are considered worldwide as the leaders in this part and as it is logical, it makes sense that they are the biggest exporters of crude oil in the world. More specifically, as we can observe from Figure 3(Workman, D., 2020) during 2019 Saudi Arabia is responsible for the 13,3% of exported oil worldwide, receiving $133,6 billion. A sum which is extremely high and assisting the country to make great investments and to develop also industries which are linked with different products. Furthermore, a very big slice of the oil exports' "cake" receives Russia. Russia, according to the same examination which we mentioned above, in 2019 is responsible for 12,1% of the oil exports worldwide, making $121,4 billion.

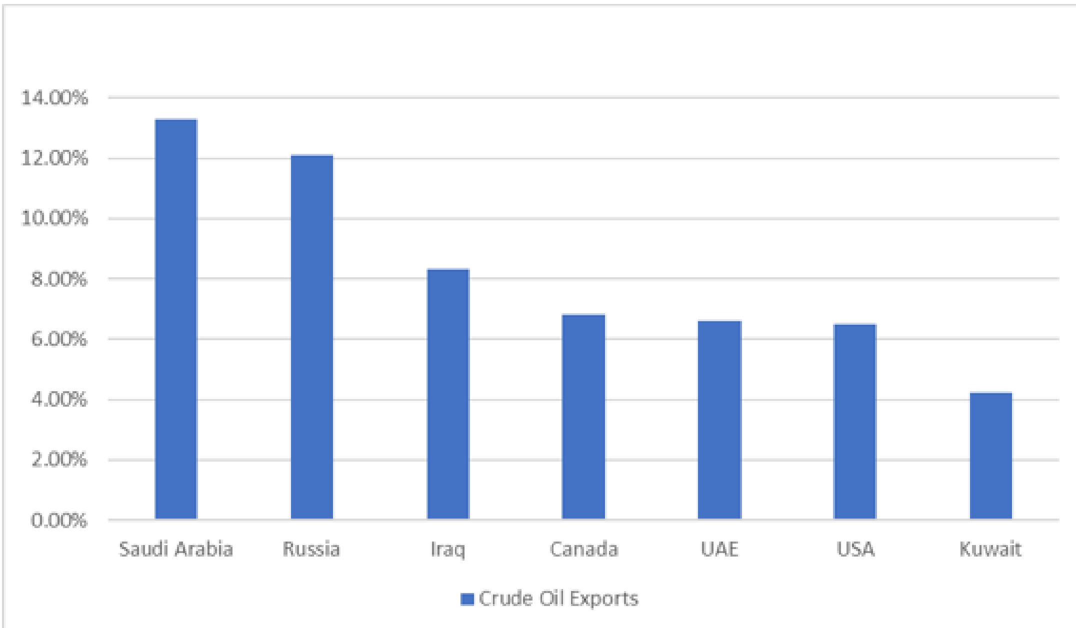

Figure 3: Crude Oil Exports

Afterwards, we can see that in 3rd place worldwide that Iraq with 8,3% of total oil exports gains $83,3 billion. Canada which is considered in our days a very important county in the oil extraction gains $68,1 billion by making 6,85% of total oil exports and UAE making $66,1 billion for 6,6% of total oil exports. The USA is responsible for the 6,1% of total oil exports and receives $61 billion and at the end of the top 7 countries we can observe Kuwait with 4,2% of total exports to receive $42 billion.

By observing the amounts of money that each country receives, we can say that the worldwide industries have invested quite a lot of money in crude oil extraction and trade. Something like that shows the importance of it in the whole world. It is not random at all that from the past, all the societies were showing great importance and attention to find sources and stocks of oil to the area which they used to live. As a result, in our days we can easily say that in the sea transportation of oil there have been invested money which are more than the total GDP of many countries, which are not quite small at all and they are considered developing or recently developed in the economic sector.

From the past, crude oil prices are considered one of the best indicators of the economic situation worldwide. So, when the oil prices fall down, then the economy seems to worsen in many industrial sectors worldwide. Of course, there are always some exemptions, but in general the prices of the oil show the current situation of the economy. Price of oil is nothing else than the price of a barrel of a benchmark crude oil. So, after further research we collected the oil prices of many well-known regions from countries which are considered the best exporters, which we mentioned further above.

Due to COVID19 pandemic the situation of the economy worldwide is going from bad to worse. Unfortunately, we are not able to predict when and if the economy will ever be in a better condition again. The oil prices were affected a lot through these months and they actually fall a lot worldwide. As a result, no matter the country of extraction of the crude oil and its initial price before the pandemic, we observed a general fall. In fact, because of globalization, if a country which has a vital role in an economic or industrial sector gets into crisis, then that can affect plenty of other countries and markets in the whole world.

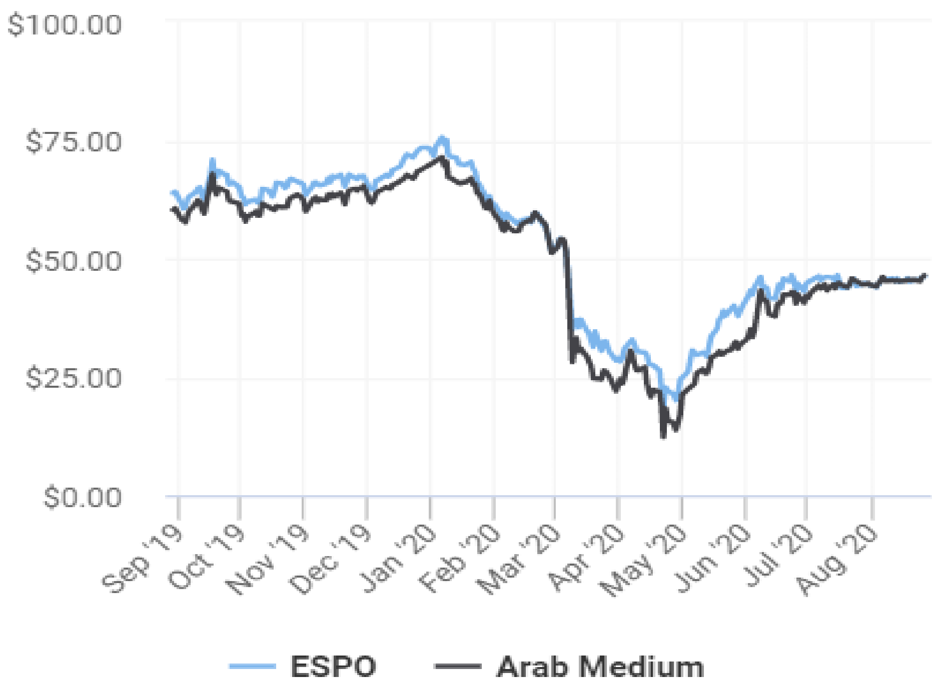

Figure 4: Crude oil price of ESPO and Arab Medium[9]

In Figure 4, the data which we collected represent the oil prices of Arab Medium from Saudi Arabia and ESPO from Russia during the period of 09/2019 until now (08/2020). Saudi Arabia and Russia are actually the two biggest exporters worldwide for many years. As we can see, the prices are almost on the same level from the beginning of the period which we examine until the end of it. The initial price is almost $75 per barrel for both countries. However, after the 2020 had arrived, due to the pandemic which until now continually creates problems to each and every business sector, the prices started decreasing. As a result, on the 1st of April the oil price of Arab Medium was $24,51 per barrel and for ESPO at the exact same date the price of each barrel was $28,31. However, the decrease of the oil price had not stopped yet. On the 22th of April, the price of the oil of ESPO was $18,41 and on the 27th of April the oil price per barrel for Arab Medium was $15,23. Despite that, since May we can observe a slightly better situation of the oil price for both of the countries, which shows that the crisis might be to an end or a parodic pause.

[9] https://oilprice.com/

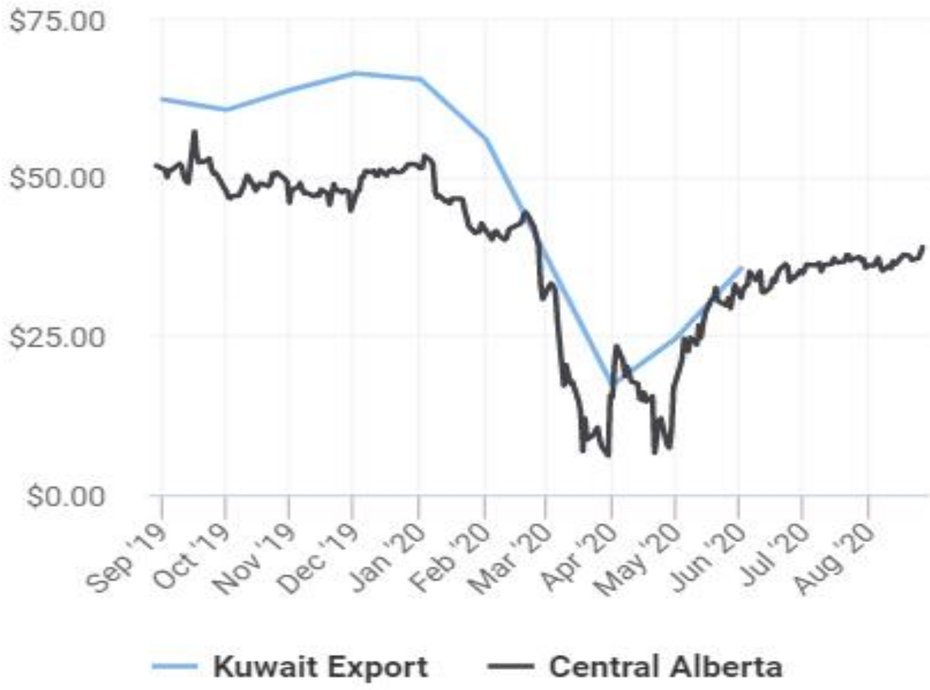

Figure 5: Crude oil price of Kuwait Export and Central Alberta[10]

Figure 5 presents the impact of the economic crisis in the crude oil price outside Europe. More specifically, Central Alberta from Canada and Kuwait Export experienced a decrease in their oil prices at the same time period. Also, again the lowest oil prices were represented during April and May as in Russia and Middle East. However, again the situation seems to follow a different path after May and the prices since then have started to grow again, creating euphoria in the industry.

In this thesis, we study a scheduling problem in crude oil shipping that concerns pickups and deliveries from various origins (loading ports) to various destinations (discharge ports). Cargoes are derived from long-term contracts with cargo owners. Time windows are considered, during which the loading or unloading of the cargo must be performed. The operator controls a heterogeneous fleet of ships that are available to transport the cargoes. The goal is to maximize profits for transporting the set of cargoes considering multiple operational constraints.

[10] https://oilprice.com/

The rest of the thesis is organized as follows: in the next section, we present the relevant literature review. Next, we consider the ship scheduling problem in detail and present the mathematical model for the problem studies. It is followed by a description of the linear programming methodology applied and a computational study that includes the description of the case study, computational results and discussions of the results. Finally, conclusions and some thoughts about future research in the field are presented.

Chapter 2: Literature Review

2.1 Crude Oil Transportation

Crude oil transportation is a subject that concerns many people in the shipping industry worldwide. As a result, there are many papers that we managed to find, in which there have been some similar research such as ours. With most of these papers, we came to similar conclusions concerning the route optimization problem of crude oil transportation. More specifically, it is extremely important to study carefully the fluctuate characteristics of the crude oil transportation and afterwards to evaluate punctually the critical events (Fei, Y., Chen, J., Wan, Z., Shu, Y., Xu, L., Li, H., Bai, Y., Zheng, T., 2020). As it has been observed through the years, the crude oil transportation tends to fluctuate a lot, affecting sometimes more than one economic industry. As a result, we should be able to learn further the characteristics of it, which tend to present higher levels of fluctuations.

Furthermore, as we are going to further present in the part of Introduction of our thesis, the crude oil prices fluctuations tend to affect a lot the countries dependent on the import and export of crude oil worldwide through the years (Yu, H., Fang, Z., Lu, F., Murray, A., T., Zhang, H., Peng, P., Mei, Q., Chen, J., 2019). So, the connection of the crude oil prices and the maritime sector is very strong and during periods of crisis this connection can be more obvious. An interesting example of this connection was presented at 2007-2009 global financial crisis and 2012-2014 Eurozone crisis, when the volatility co-movement between oil and liner shipping companies' stock returns increased (Maitra, D., Chandra, S., Dash, S., R., 2020).

As we mentioned before and we are going to analyze further in the following chapters, the optimization of crude oil transportation has been taken into serious consideration, because it presents a great opportunity to the shipping companies to reduce their costs and maximize their total profits. In one of our case studies we will examine which is the optimal amount of crude oil for each route that we are going to set. However, great significance also presents that in contrast with all the available methods of transporting crude oil for long distances, the possible one is via Very Large Crude Carriers. On the other hand, the safest method is considered to be the transportation via pipelines. (Wang, Y.; Lu, J., 2015).

Due to the fact that the maritime sector faces great volatility, during periods of great crises, it is affected a lot. This is a problem that the maritime companies should face, i n order to survive and more specifically, the managers of the company should adapt the needs of the companies in accordance with the current economic situation every time. So, a very important characteristic that each shipping company should have is the quality of adaptation. As a result, because of the very high competency of this industry, the maritime companies should schedule with great punctuality their programs and organize their transportations, in order to be able to survive on a difficult period. (Más, R., Pinto J., N., 2002). In other words, the most important part of this business will always be transportation. However, the better organized it can be, the more profitable the company is going to be in the near future.

The crude oil transportation however is not connected only to the tanker vessels. The last few years we have observed a great increase in the liner shipping industry. As we mentioned in a previous paragraph, during crises the connection between the two of them become greater. So, in the logistics operation, the crude oil transportation plays a vital role. More specifically, the global supply chain management in the oil industry is actually affected a lot by the transportation of crude oil. So, any downward or upward movement of the transportation of crude oil slope can be considered extremely profitable or disastrous. (Cheng, L., Duran, M., 2003). Of course, that proves the importance of the crude oil transportation worldwide and also the fact that more and more sectors inside the shipping industry (liner shipping) try to get into this type of business, as it is considered one of the most important ones for many years.

2.2 Strategic Optimization Problems in Shipping

2.2.1 Fleet composition problem

The fleet composition of a shipping company is considered one of the most important factors of its success in terms of profits in the maritime industry. The inclusion of this characteristic in the shipping transportation problem is supported by Assad (1988), Bodin and Golden (1981), Bodin et al. (1983), Ronen (1983) and Ronen (1988). There are two categories which can characterize the type of the fleet composition. The first one is the homogeneous category. In this kind of composition, the fleet consists of vessels that are identical in all the important aspects. These important aspects can differ for each type of a maritime problem. However, the most significant of them are the capacity of the vessels, the speed of the vessels and the size of vessels, in terms of width, length and draught.

On the other hand, the opposite category which is also the second one among the two possible ones, is the heterogeneous composition of a fleet. Here, the main difference is that the fleet has vessels which don't have similar characteristics between them and also tend to differ, mainly on the important aspects which we mentioned in the previous paragraph. Logically, the type of the fleet composition can determine the whole type of a route transportation problem. So, it is considered necessary, in order to get the optimal solution on the examined case study, to have the fleet composition specified from the beginning.

Therefore, any decision among the size and the composition of the fleet, plays a very significant role in the determination of which vessels are actually available for the completion of some specific routes. This has been further analyzed also by Hoff et al. (2010), examining the industrial characteristics of the fleet composition to the maritime and also to the road-based transportation. As a result, during the last 20-30 years we have observed high amounts of money invested for the purchase of a vessel in the shipping industry. Due to the large uncertainty and volatility that the maritime sector faces within the last years, the shipping companies make a huge effort to design their fleet in such a way, in order to be able to face any difficulties that may arise.

The high uncertainty of the demand creates a lot of problems in each shipping company worldwide. Zeng and Yang (2007) have proposed an IP model which determines the optimal fleet and the routing of the vessels. This model has been extended by Álvarez et al. (2011) and provides a great assistance to the shipping companies, in order to face the high uncertainty of the future demand for multiple time periods in the sea transportation industry. More specifically, this model is a MIT model for the multi period deployment and fleet composition problem. This model is extended into a robust optimization one, in order to help the shipping companies to decide upon several options that they might have so as to face the demand volatility.

More analytically, this model calculates for the maritime companies, the risk probability for each of the options regarding mainly the use of the vessels of their fleet. In other words, the model examines the risk in terms of an numerical degree for the shipping company in several significant options such as the purchase of a new vessel, the sale of an existing one, the lay-up or the scrap of another vessel of its fleet, the chartering in or out and also the deployment of their active vessels to several contracts and geographical markets worldwide.

In addition, Fagerholt et al. (2010a) examined a support methodology which would be able to evaluate and examine a set of several strategic decisions through a simulation that contains the optimization of the ship routing and scheduling problem. However, on this model and its methodology the fleet composition and size are not taken into consideration. Despite that, many authors consider that this model is very similar to that of Zeng and Yang (2007) and also to the extended one of Álvarez et al. (2011). Also, because of the high seaborne trade of crude oil in the maritime industry, Cheng and Duran (2004) examined a similar application , regarding the crude oil transportation worldwide, taking into account the optimal control and discrete event simulation.

2.2.2 Optimal fleet design

One of the first works and observations done in the area of the optimization of fleet was done by Dantzig and Fulkerson (1954). They conducted an experiment in which they were trying to minimize the number of tanker vessels inside a specific set of schedules which had to be performed. This kind of problem that Dantzig and Fulkerson tried to deal with, can be considered as a transportation problem. Afterwards, Cho and Petrakis (1996) examined a similar problem, about the design of optimal liner routes, by taking into account the fleet size. However, in this case study, the problem had to do with the container and not with the tanker industry. This problem was solved by Linear Programming and the columns were representing every possible route that has been set. Also, a Mixed Integer Programming was taken into consideration for the extension of this model.

In addition, Xinlian et al. (2000) and Bendall and Stent (2001) examined similar problems with Cho and Petrakis (1996), which mainly have to do with the optimal number of ships and the fleet development plan. Fagerholt (1999) presented a case study, in which he examined the design of an optimal fleet which had to operate into a weekly program in the liner shipping industry. However, this model could not actually be realistic, because the ships of the fleet should have the exact same ship, which is impossible. For this reason, Fagerholt and Lindstad (2000) proposed a new solution algorithm, in which the ships could have different speeds and the solution that could possibly come out, would be much more realistic.

On the other hand, fleet optimization surely is one of the major parts of a shipping transportation problem, but it is not the only one with that great importance. In other words, another very significant design that should be taken into account, is the one of the maritime supply chain. However, many supply chains include sea transportation, but it is also provided with other options of transportation (railway, road, pipelines etc.). Richetta and Larson (1997) created a problem which is an extension of a previous model of Larson (1988), regarding decision making in the optimal size of the fleet and operational planning. More specifically, the problem which they examined to solve by this model had to do with the design of New York City's refuse marine transport system.

Mehrez et. al (1995) examined a real industrial ocean cargo shipping problem, in which dry bulk minerals had to be shipped by the point of their extraction to several customers which had requested them. Of course, on this problem several realistic variables were included, such as size of the fleet of the vessels, several loading and discharging ports, transportation routes and a planning-time horizon which has been agreed in order for the dry bulk minerals to be addressed. Furthermore, a problem regarding the size of the U.S. destroyer fleet is described in Crary et al. (2002) and it was approached via quantitative methods, for more accurate results.

Also, Darzentas and Spyrou (1996), by the "what if" decision approach, they simulated a model regarding the ferry traffic among the Aegean Islands, in which several realistic transportation scenarios took place and further analyzed. Simulation method also used by Imai and Rivera (2001), so as to examine another case study which deals with the optimal planning of the fleet size for refrigerated containers, so as to meet the demand and find the optimal solution. As a result, we can observe that many similar methods and models can be used for the examination of much different shipping transportation problems.

2.3 Tactical and Operational Problems in Industrial Shipping

Romen (1993) has given two specific definitions for the terms of routing and scheduling. Routing according to Ronen (1993) is the assignment of the sequences of ports that a vessel should visit. On the other hand, scheduling is mainly a constraint which according to Romen (1993) the term scheduling is used when the temporal aspect is included into the routing. The scheduling is usually referred to as the parameter of the time horizon in terms of a constraint. The scheduling problems can be separated mainly into three parts. The first one is the problems which have to do with the industrial ship scheduling. In addition, the second category consists of commercial vessel routings and scheduling and the third category deals with ship routing and scheduling in the supply chain.

2.3.1 An Industrial Ship Scheduling Model

The most common objective function in this category of problems is the minimization of costs for the vessels of the fleet. More specifically, this problem consists of the transportation of a specific type of cargo which should be transported from a number of loading ports to a number of discharge ports. In other words ,the optimal solution of these problems presents which routes should be followed and in what sequence each port should be served. On the part of the solution, we can also observe the optimal selection of the vessels of the fleet that are going to be used, in order for the shipping company to have the minimum possible costs for the use of these vessels.

We have observed that the 40% of papers which examine ship scheduling problems, prefer to solve them by Set Partitioning (SP). A standard optimization software can usually solve the SP models. The main advantages of SP models are that the complicated and non-linear constraints can be embodied without any difficulty, while creating the columns. More specifically, in the mathematical formulation of this problem exists an underlying network, in which the designed nodes represent the loading and discharging ports and the arc represents the optimal transportation path between two ports.

Inside the formulation of SP, we can find the sequence that should be followed by the vessels for the visit at each node and also the time from the beginning of service at each node. All of them have been generated in such a manner, so as to reach the minimization of costs. Also, the model also has a binary decision, which determines which vessels will be used for the execution of the routes and which not. In addition, the ship scheduling problems often have a lot of constraints. Because of that and also due to the long duration of each ship voyage and the high uncertainty which exists, the ship schedule cannot be planned for more than a specific number of voyages ahead for each vessel.

2.3.2 Commercial Vessels Routing and Scheduling

Most of the relative problems which examine routing and scheduling of commercial cargo, deal with scheduling problems which have as an objective to minimize the costs of a fixed fleet of ships. These vessels usually have to transfer bulk cargo and as a result mainly the fleet consists of Bulk Carrier vessels. However, Brown et. al (1987) have further examined the transportation of oil in commercial cargo shipping. This work consists of a major oil company shipping crude oil from the Middle East to Europe and North America. Also, each vessel is fully loaded with cargo, regarding their DWT capacity and this constraint is affected by the time of delivery and the loading and discharge ports. These cargoes can be transported either by the vessels of the specified fleet or by spot charters.

This kind of problem can also be solved by an SP model, which is slightly more elastic than the previous above mentioned one. As a result, the solution consists of an elastic enumeration procedure. The same problem is studied by Perakis and Bremer (1992) and an SP model also be formulated in this case. We should also mention that this problem can also be considered as well constrained. Furthermore, a decision-support system was formulated by Bausch et al. (1998) and is an extension of the work of Brown et. al (1987). This problem has a restriction that each vessel can load up to 5 products and also the fleet consists of coastal tankers and barges which transport bulk products in liquid form. The vessels of the fleet can also have up to 7 fixed compartments, in order for the ship to load cargo which has more than one product.

Sherali et al. (1999) examined a problem similar with the problem of Bausch et al. (1998), in which crude oil and several refined oil products should be transported for loading ports of Kuwait to several discharge ports around the world, giving more emphasis on the classification and more details of each vessel. At this point, we should mention that it is extremely significant the fact that many routes which are going to take place on this problem will be real such as a route through the Suez Canal or around the Cape of Good Hope. Furthermore, a similar application with that of Bausch et al. (1998) was examined by Scott (1995), which deals with transportation of several refined oil products, but with a different solution approach.

More specifically, in this model the used application is called Lagrangian relaxation and assists on the generation of better schedules. For the selection of the optimal schedule, Scott (1995) uses a novel refinement of Benders Decomposition. With this method a very difficult Integer Programming Problem is separated into two compartments, so as the optimal solution to be reached easier. Also, Fagerholt and Christiansen (2000a) examined a similar problem with an SP model approach. On this problem each fleet has a flexible cargo hold and also the scheduling of the ships composes the multi-ship pickup and delivery problem within specific time windows. However, a constraint on this problem is that ports remain closed at night and on the weekends. In addition, the time windows can be multiple and the vessel is able to remain on the loading and discharge ports for a few days. With uncertainty taken into account, the results after several calculations show that the lustiness of the schedule increases when the price of the transportation costs is also increased.

Furthermore, Cho and Perakis (2001) created an improved model that the one of Ronen (1986), On this problem, there is a short-term scheduling problem for the transportation of bulk and semi-bulk commodities. Each ship can visit a number of discharge ports, but can load only in one loading area. However, in this case a transportation of cargo to a discharge port can be split between more than one vessel. Finally, an application for inland water transportation was developed by Vukadinovi´c and Teodorovi´c (1994). This application provides great assistance to the dispatcher to make the best possible decision about the number of picked up and dropped off barges at river ports. The same problem was also examined afterwards by Vukadinovi´c et al. (1997). But on this problem, loaded barges must be assigned to pusher tugs at each loading port.

To sum up, these kind of developed models on these problems make an effort to help the dispatcher to decide what is more profitable for him so as to ship his cargo.

2.4 Tactical and Operational Problems in Tramp Shipping

This category of problems is examined due to the existence of many small transp operators in the shipping sector. Usually, this business of transportation includes a contract of affreightment, which is the transportation of a specific amount of cargo in a specific time horizon between predetermined specific ports. A tramp ship scheduling problem was examined by Appelgren (1969,1971) via a DW approach. The problem is considered as SP. In this problem the objective function is the maximization of the tramp shipping profits. In addition, each vessel is allowed only cargo.

The revenues of each cargo are equal to the cargo quantity multiplied by the rate per unit of cargo. The profits can be generated by the operation of the vessels and also by the service of cargoes by spot charters. The problem becomes more realistic due to the fact that it is allowable for the company to lease some of the vessels of its fleet during the time horizon of the problem. In addition, another work done in the area regarding decision support systems in the bulk industry has been done by Kim and Lee (1997), by formulating the problem into a set packing one. Finally, Fagerholt (2003) developed a model which solves a problem regarding both tramp and industrial shipping, making it even more complicated.

Time Horizon Constraint in a Maritime Problem

Another important part of a shipping transportation problem which should be clearly defined from the beginning of a sea transportation problem is the time horizon. More specifically, of whether the routes that should take place, have to be completed within a specific time horizon (Ronen, 1988). The decision of whether this kind of constraint and variable should be included on the completion of the routes within it, plays a vital role to the whole problem. In other words, the optimal solution can be a lot different if the constraint of time horizon is used.

In addition, there are two different characteristics of a maritime problem in which the time horizon is defined. The first one is that the routes must be completed within the time horizon. The second one is that the routes should not be completed within it. However, there is also the type of problems in which the time horizon does not exist and as a result, these problems are considered as undefined, in terms of this constraint's existence. The time horizon inclusion on a shipping transportation problem is also called plan horizon, due to the fact that within it the shipping company should make the appropriate decisions.

Port Precedence Requirement in a Maritime Problem

Furthermore, another important requirement that can be included on a maritime transportation problem is the port precedence one. The inclusion of this requirement is supported by Desrochers et al. (1990), Ronen (1983) and Ronen (1988). This characteristic is included more often in liner shipping problems. At first by taking into account this requirement, the demand is considered as pick-up and the delivery as interwoven. So, the main idea of this, is that precedence is implied in case that the vessel should be empty at an already defined port and also that the transshipment cannot be allowed at any case.

2.5 Tactical and Operational Problems in Liner Shipping

Liner shipping industry can present a lot of differences by other types of maritime sectors. On liner shipping, the main decisions examined, concern the fleet size, mix and development, the cargo booking and mainly the route and schedule design. As it has been observed, the container sector has presented a great development during the last years and as a result, the containerization of the commodities' transportation becomes a phenomenon, which we meet more often. This can be observed even 20 years ago, by the difference of the container vessels' percentage in the total fleet worldwide. More specifically, in 1995 this percentage was equal to 5,9% and in 2001 it was equal to 9.0% (ISL 2001).

The transportation problem concerning the liner shipping has been examined by the works of Perakis and Jaramillo (1991) and Jaramillo and Perakis (1991). This work has been solved by an LP model formulation. However, there also exists an extension of these problems by Powell and Perakis (1997). The objective of this problem is the minimization of the operating and layup costs for the vessels of the fleet and it is formulated through an IP model. At this point, we should mention that this model has been examined and formulated also in real liner shipping transportation problems, which makes it even more realistic.

2.6 Ship Routing and Scheduling in Supply Chains

The sea transportation of a commodity, in some cases can be a part of the supply chain. A problem of inventory routing was examined by Christiansen (1999), which deals with company-owned plants which produce and also consume ammonia. So, enough capacity of ammonia should remain for consummation and also the stock in the plants should not exceed the storage capacity. However, on this problem, the amount of loaded capacity at each port and the number of calls at each port are not predetermined from the beginning. The time horizon of the problem, the number of calls and the loaded material at each case are determined by the production plan of each port. This problem can be separated into two more subproblems which are a scheduling problem for each vessel and an inventory management problem for each port. The overall problem can be solved by a Dantzig-Wolfe (DW) decomposition approach (Christiansen and Nygreen 1998a). Another approach of solution for this problem is a mix of an LP model with an iterative improvement heuristic (Flatberg 2000).

On the other hand, Fox and Herden (1999) formulate an MIP model in order to schedule the transportation of ammonia from the production plants to eight specific ports of Australia.

Furthermore, Christiansen and Nygreen (2001) examined an extension to their own previous model, by taking into account the uncertainty that exists in the industry, making the problem even more realistic and by adding a pair of soft inventory limits within the hard ones. Also, an inventory routing problem is also examined by Ronen (2002) by an MIP model. Finally, a transshipment problem is also examined by Shih (1997) for the transportation of coal and as an objective function has been set for the minimization of procurement, transportation and holding costs. An extension to this problem was generated by Liu and Sherali (2000) via an MIP model.

2.7 Naval Routing and Scheduling

This category covers mainly the area of navy and Coast Guard and not commercial vessels. In these applications the time horizons are usually lengthier. The most important objective is the assignment of the vessels of the fleet to a set of predetermined and specific tasks. A problem which belongs to this area was presented by Nulty and Ratliff (1991) regarding the problem of scheduling the U.S. Navy's Atlantic Fleet. Through an IP model formulation , the major objective of this problem is the satisfaction of all the requirements.

In addition, a similar problem of the U.S. Coast Guard was further examined by Darby-Dowman et al. (1995). In this case, the objective is very similar and has to do with the satisfaction of each constraint and requirement. However, the method used for the solution of this problem is an SP model. In addition, a similar problem for the U.S Coast Guard was also analyzed by Brown et al. (1996), but on this examination, the application of penalties was taking place, making the problem even more realistic. The solution of this problem was claimed by an elastic MIP model.

According to Psaraftis (1988), the scheduling problem which should be faced by U.S. Military Sealift Command is the preparation of mobilization situations. The main objective is the allocation of cargo in the specified destination. However, there are also some constraints on these kinds of problems, which should be satisfied. These usually are the ship capacity, the compatibility of cargo, ship and port and also the pickup and delivery time windows.

Chapter 3: Case Study

3.1 Problem Description

In the problem of our case study, we represent a shipping company, which has to transfer crude oil from three loading ports to several destination ports around the world. More specifically, we have to execute three specific contracts which state the discharge ports that each loading port is able to serve. The vessels of our fleet which are going to execute these sea transportations are four. A Panamax vessel, a Suezmax vessel, an Aframax vessel and VLCC vessel. The three loading ports which we have chosen to base our contracts on are: Novorossiysk in Russia, Montreal in Canada and Jeddah in Saudi Arabia. All of the chosen countries from which crude oil will be exported, are considered major crude oil exporters worldwide.

On the other hand, we have set for our problems nine different discharge ports. Of course, as with the chosen crude oil exporting countries, also the crude oil importing countries are considered very significant importers of crude oil during the last years. The nine discharge ports that we have decided to base our problem on are: Mumbai from India, Singapore from Singapore, Shanghai from China, Busan from South Korea, New York form USA, London from England, Hamburg from Germany and Rotterdam from Netherlands.

Summarizing from the above, the maritime company which we represent, has made an agreement with some of its clients which are located in a major crude oil exporting country, to transport crude oil from the previously mentioned loading ports to the above mentioned discharge ports which belong in very important crude oil importing countries, in which some specific customers of our company's clients will receive the requested merchandise.

Table 1: Freight rates for each route and demand for each discharge port

Demand	70,000	50,000	50,000	50,000	60,000	45,000
Freight Rates	Mumbai	Singapore	Shanghai	Busan	New York	London
Jeddah	8.31	11.78	17.50	17.57	17.11	12.81

Montreal	24.55	30.87	33.7	32.03	8.52	12.33
Novorossiysk	14.97	18.47	24.24	24.31	17.44	13.16

Table 2: Freight rates for each route and demand for each discharge port

Demand	40,000	50,000	55,000	50,000	44,000	45,000
Freight Rates	Hamburg	Rotterdam	Tokyo	Singapore	Hamburg	Rotterdam
Jeddah	13.56	13.19	19.17	11.78	13.56	13.19
Montreal	12.54	11.58	31.43	30.87	12.54	11.58
Novorossiysk	13.91	12.41	25.92	18.47	13.91	12.41

On Tables 1 and 2, we can observe the requested amount of crude oil that each discharge port has in terms of tons. The freight rates on the below rows are expressed in terms of $ per transported crude oil ton. However, the reason that the ports of Singapore, Hamburg and Rotterdam in Table 2 are presented two times each and their demand is different, is because these ports are the only ports among the total nine discharge ports which can be served by two different contracts and more specifically, by more than one loading ports.

Table 3: Loading and discharge ports

Loading ports	**Discharge ports**			
Jeddah	Mumbai	Singapore	Shanghai	Busan
Montreal	New York	London	Hamburg	Rotterdam
Novorossiysk	Tokyo	Singapore	Hamburg	Rotterdam

On Table 3, we can observe in detail, which discharge port can each loading port serve. As it is obvious, each loading port can serve up to four loading ports. Due to the fact that the discharge ports are nine, the ports of Singapore, Hamburg and Rotterdam can be served by two loading ports and more specifically, by Montreal and Novorossiysk. However, each contract is unique and every port's demand should be totally satisfied.

On the other hand, the execution of each route has some significant costs for the maritime company. At this point, it is very important for us to mention that we are going to represent the roles of tramp operators. More specifically, the operating cost and voyage cost of each vessel is charged to the part of the shipowner, which we are going to represent. The two main costs that in this problem that we take into account in the formulation of our model, in order to find the optimal solution are the Bunker costs for the voyage execution and the Operating costs.

Table 4:Vessels' costs and descriptions

Type	Year	DWT	Speed	Consumption	Total Operating Costs (/day)
Panamax	2016	74000	14.4	26.2	9,230
Aframax	2016	110000	14.2	27	10,020
Suezmax	2018	150000	14.9	44.8	11,140
VLCC	2011	320000	15.9	100.9	12,790

On Table 4, we can observe the most important details of each vessel of the maritime company's fleet that has been selected to execute the routes, which we further mentioned above. More analytically, on Table 4 the vessel's details which are referred are the age, the operating costs, the bunkers consumption in tons per day and the average speed of each one of them. The consumptions will be useful for the calculation of the bunker costs that each vessel has. At this point, it should be mentioned that each vessel, regarding its size and because of the consumption of bunkers that it consumes daily, will need different amounts of bunkers in order to be able to travel the whole distance each time. As a result, to sum up, as voyage cost, we will take into account the bunker costs, which will be calculated only once for each tanker vessel of the fleet.

Table 5:Average price of VLSFO Bunkers

Bunkers VLSFO	Rotterdam	New York	Singapore	Shanghai	Average Price
	$402.00	$425.00	$433.00	$419.50	**$419.88**

More specifically, as we can see further from Table 5, as a bunker price we have chosen to set an average price that arises from four very significant bunker prices in the shipping industry. As a result, the average price of each VLSFO bunker is going to cost $419.88. This amount of price can be considered as very realistic. As a result, for the calculation of the bunker costs we are going to multiply the days that each is going to sail with the average bunkers VLSFO price and with the consumption of VLSFO of each vessel. On the other hand, the operating costs will be calculated with the multiplication of the total operating costs that we have already found with the days that each vessel is going to sail. The days are calculated by the multiplication of the average speed of each vessel with the distance between each port that we have found.

We are going to conduct the case study for three different time horizons separately. The first planning horizon will be one year, the second one will be six months and the third one is going to be nine months. In other words, in order to examine which is the optimal time horizon we will conduct the experiment for 360, 180 and 270 days. Afterwards, we will assume that our fleet consists of two VLCCs, an Aframax and a Suezmax vessel and we will formulate the same experiment so as to compare the objective function and the results that will come upon. Finally, we will run the experiment one last time separately for each planning horizon mentioned above, but the fleet again will be different and is going to consist of a Panamax, a VLCC and two Suezmax vessels. By comparing all the results and the optimal solutions, we will be able to understand which fleet planning and time horizon is considered more optimal for the company.

3.2 Methodology

The problem considered is going to be formulated as a Mixed Integer Linear Programming (MILP) model . In the linear programming models, we meet problems in which a linear objective has to be minimized or maximized, in accordance with a set of appropriate linear constraints which have been set in relation with the problem. This model provides more efficient solution techniques and also a higher amount of information which are more reliable, regarding the sensitivity of the optimal solution. The optimal solution in our case study is the minimization of the costs for the company which we are going to represent.

There are three main parts in order to solve a problem via the method of linear programming. The first part is the definition of the problem by gathering the necessary input data, which will assist us to develop the model. Afterwards, on the second part we have to set the appropriate constraints, regarding the problem and test the solution. The last part consists of the total analysis and implementation of the results. By this way, we are going to find the optimal solution among all the feasible ones. As a result, the solutions that can be presented in a problem are many, but some of them satisfy the constraints and all the criteria of the problems in a better way than the others. The solution which provides the highest level of satisfaction to all the constraints which have been set, is considered the best possible one and we call it the optimal solution.

Linear Programming is a mathematical technique and it is identified as one of the most well designed in decision making. That’s the reason it is highly recommended in decision making in the sector of management, in order to choose the most profitable solution. The main assumption that has to be made in order to formulate a linear programming model is that all data are accurate. However, in an optimal shipping plan such as ours, we are also able to assume that each cargo of our problem can be split into two or more compartments and also into whatever fractions that we desire. Also, the cargo can be packed into each compartment. All these assumptions are made always in accordance with the criteria of our problem and to the restrictions which have been set.

An integer programming problem is a mathematical problem that is used for optimization of a solution of a problem. The main constraint of integer programming problems is that the decision variables which form the optimal solution are set as integers. As a result, the form that they take can be either 0 or 1. In many cases the term can also be referred to as integer linear programming, in which the constraints are the variables are linear. However, in case the integer decision variables are not discrete, then the problem can be called mixed integer programming.

An integer linear program in canonical form is expressed as:

$$\begin{array}{ll} \text{maximize} & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\ \text{subject to} & A\mathbf{x} \leq \mathbf{b}, \\ & \mathbf{x} \geq \mathbf{0}, \\ \text{and} & \mathbf{x} \in \mathbb{Z}^n, \end{array}$$

and an ILP in standard form is expressed as:

$$
\begin{array}{ll}
\text{maximize} & \mathbf{c}^{\mathrm{T}}\mathbf{x} \\
\text{subject to} & A\mathbf{x} + \mathbf{s} = \mathbf{b}, \\
 & \mathbf{s} \geq \mathbf{0}, \\
 & \mathbf{x} \geq \mathbf{0}, \\
\text{and} & \mathbf{x} \in \mathbb{Z}^n,
\end{array}
$$

where (c, b) are vectors and (A) is a matrix, where all entries are integers. As with linear programs, ILPs not in standard form can be converted to standard form by eliminating inequalities, introducing slack variables (s) and replacing variables that are not sign-constrained with the difference of two sign-constrained variables.

The tool that we use in order to solve the problem in our Case Study is OpenSolver, which is an Excel VBA add-in that extends Excel's built-in Solver with more powerful solvers.[11] OpenSolver offers a range of solvers for use in Excel, including the excellent, Open Source, COIN-OR CBC optimization engine which can quickly solve large Linear and Integer problems. In other words, OpenSolver has been created to assist on finding an optimal solution among all the feasible ones, when the constraints are multiple and highly complicated. At this point, it should also be mentioned that OpenSolver provides a menu which assists on the relaxation of an integer program.

OpenSolver allows the user to define 'parameter' cells which are the cells that the user is going to change between successive solves, by making the appropriate selection from the Quick Solve mode, which is on the parameter's menu. With the help of this mode, the problem can be solved more quickly and provide a solution to the user in a very short period of time. This has been created mainly for Linear Programming problems. As a result, plenty of the problems that usually require a lot of time to be solved, can be solved via this mode very quickly. Finally, OpenSolver also allows the user to pass extra parameters to the solver, by creating a named table to the spreadsheet.

3.3 Mathematical model

In the mathematical description of our problem the each transported cargo of crude oil is represented by the index i. Regarding the ports between crude oil is going to be transported

[11] https://opensolver.org/

between, there is a node i, which denotes the loading port and there is also a node n+1, which depicts the corresponding discharge port. The symbol of n presents the f transported crude oil in each route, during a specific time horizon which is going to be set. A s a result a set of pick up nodes can presented as: $N^P = \{1,2, \ldots, n\}$and on the other hand a set of delivery nodes can be presented as $N^D = \{n+1, n+2, \ldots, 2n\}$. The set of pick up nodes is separated into two more sets, $N^C$and N^O, which is determined by the contracts, regarding the transported crude oil.

The vessels of the shipping company's fleet on our problem, are presented by the symbol by the symbol V. In addition, each ship is connected with a network (N_v, A_v). Each vessel can visit, including the artificial origin and the artificial destination, the N_v, which is the set of nodes that can be visited by the ship. In our problem, the origin and destination points are loading and discharge ports. Furthermore, the arc that presents the precedence of each route is depicted on the mathematical formulation by the symbol A_v. The precedence of the routes is actually the order that each vessel should visit the predetermined ports of each route.

Very significant to also to be mentioned is that the capacity of the vessel depicted as K_v and the total sailing time of each vessel as T_{ijv}. As a result, $\{T_i, \bar{T}_i\}$ is the time window, which in other words shows the earliest and the latest time of each route. Also, $Q_i$represents the quantity of the transported crude oil in tons. In addition, the revenues are presented as $R_i$and the total costs, in which are included the operational and the voyage costs are presented as C_{ijv}. Finally, the decision variables, from which the optimal solution is designed are: 1) the binary flow variable x_{ijv}, which can be either 1 or 0, regarding the use of a vessel v on a route or not, 2) the l_{iv}regarding the total amount of transported tons of crude oil on board and finally, 3) t_{iv}, regarding the time at which the use of the vessel starts from the node i.

In addition, for our problem we have set some specific constraints that are going to determine the optimal solution and the objective function. Each constraint that we chose to set is based on real life sea transportation of crude oil and provide great assistance to the designation of the optimal shipping plan for the maritime company that we represent on this specific problem. More specifically, the objective function and the constraints, which should be satisfied in our problem are:

$$\max \sum_{v \in V} \sum_{(i,j) \in Av} (R_i - C_{ijv}) * x_{ijv} \,, \quad (1)$$

$$\text{s.t.} \quad \sum_{v \in V} \sum_{j \in N v} X_{ijv} + y_i = 1, \quad i \in N^c, \quad (2)$$

$$\sum_{j \in Nv} x_{o(v)jv} = 1, \quad v \in V, \quad (3)$$

$$\sum_{j \in Nv} X_{ijv} - \sum_{j \in Nv} X_{ijv} = 0, \quad v \in V, \; i \in N_N \setminus \{O(v), d(v)\}, \quad (4)$$

$$\sum_{i \in N_v} x_{id(v)v} = 1, \quad v \in V \quad (5)$$

$$x_{ijv}(I_{iv} + Q_j - I_{jv}) = 0, \quad v \in V, \; i \in N_v^P, \; (i,j) \in A_v, \quad (6)$$

$$x_{j(n+j)v} \; (I_{iv} + Q_j - I_{(n+j)v}) = 0, \quad v \in V, \; j \in N_v^P,$$

$$(i, \; n+j) \in A_v, \quad (7)$$

$$0 \leq I_{iv} \leq K_v, \quad v \in V, \; i \in N_v^P, \quad (8)$$

$$x_{ijv}(t_{ijv} + T_{ijv} - t_{jv}) \leq 0, \quad v \in V, \; (i,j) \in A_v, \quad (9)$$

$$\sum_{j \in N_v} x_{ijv} - \sum_{j \in N_v} x_{(n+i)jv} = 0, \quad v \in V, \; i \in N_v^P, \quad (10)$$

$$t_{iv} + T_{i(n+i)v} - t_{(n+i)v} \leq 0, \quad v \in V, \; i \in N_v^P, \quad (11)$$

$$T_i \leq t_{iv} \leq \overline{T_i}, \quad v \in V, \; i \in N_v, \quad (12)$$

$$y_i \in \{0, 1\}, \quad i \in N^c, \quad (13)$$

$$x_{ijv} \in \{0, 1\}, \quad v \in V, \; (i,j) \in A_v. \quad (14)$$

The objective function (1) maximizes the difference between the revenues with the costs of the operating vessels of our fleet. Constraint (2) presents the already agreed by contract crude oil can be transported by a ship in the existing fleet. In addition, constraints (3-5) state the flow that a vessel is going to have on a route while sailing. Furthermore constraints (6-7) show the loading on board at each pickup and delivery node each time and constraint (8) states that the capacity of the vessel should be higher than the amount of crude oil transported tons loaded on board. Constraint (9) shows the symphony between routes and each schedule and program , while constraint (10) states that a vessel visiting a loading port, should also visit the associated and predetermined on the same route discharge port. Each requirement and necessity related to the precedence, according to which the vessel should first visit a loading port and then the discharge ports is determined by constraint (11). Finally, the constraint (12) shows the time window and the constraints (13-14) represent the binary requirements, which can be either 1 or 0, regarding the use of a vessel or not.

However, some of the previous mentioned constraints above, are nonlinear and as a result, we should transform them into linear, in order to be able to conduct our case study. More specifically, the nonlinear constraints, which should be transformed are the constraints (6), (7) and (9). Constraints (6-7) present a track of loading cargo on board at each loading and discharge port and constraint (9) will show the compatibility between routes and planned program. As a result, the linear formulation of these constraints is:

$$x_{ijv}(I_{iv} + Q_j - I_{jv}) = 0, \quad v \in V,\ i \in N_v^P,\ (i,j) \in A_v, \tag{6}$$

$$x_{j(n+j)v}\ (I_{iv} + Q_j - I_{(n+j)v}) = 0, \quad v \in V,\ j \in N_v^P,$$

$$(i,\ n+j) \in A_v, \tag{7}$$

$$x_{ijv}(t_{ijv} + T_{ijv} - t_{jv}) \leq 0, \quad v \in V,\ (i,j) \in A_v, \tag{9}$$

3.4 Computational Results

Searching for the optimal composition of our fleet and for the time horizon, which will bring the highest profits to the shipping company, we made some experiments keeping as constant the loading and discharging ports and the number of the vessels and changing the type of them and the time horizon from half to one year. So, we came up with nine different scenarios in which we chose three different time horizons, six, nine and twelve months, and three different fleet compositions. In the first there will be a Panamax, a Suezmax, an Aframax and a VLCC, in the second there will be a Suezmax, an Aframax and two VLCCs and in the last one there will be a Panamax, two Supermaxes and a VLCC. In every scenario of the above every single one from the twelve contracts that are selected is completed successfully. Moreover, we set that every vessel from the point that it loads or discharges a cargo sails immediately to the next destination and when it reaches the last one it remains there.

The results that came up from running the model are presented below:

<u>360 days – 4 different types of vessel</u>

Panamax: Jeddah – Singapore – Jeddah – Busan

Suezmax: Montreal – Hamburg – Novorossiysk – Singapore – Jeddah – Mumbai – Novorossiysk – Hamburg – Novorossiysk – Tokyo – London – Montreal -Rotterdam – Novorossiysk -Rotterdam

Aframax: Jeddah – Shanghai

VLCC: Montreal – New York

Profits: **$6,039,552.88**

<u>270 days – 4 different types of vessel</u>

Panamax: Jeddah – Singapore – Jeddah – Busan

Suezmax: Montreal – Hamburg – Novorossiysk – Singapore – Jeddah – Mumbai – Novorossiysk – Hamburg – Novorossiysk – Tokyo – London – Montreal -Rotterdam – Novorossiysk -Rotterdam

Aframax: Jeddah – Shanghai

VLCC: Montreal – New York

Profits: **$6,023,349.71**

180 days – 4 different types of vessel

Panamax: Jeddah – Singapore – Jeddah – Busan

Suezmax: Montreal – Hamburg – Novorossiysk – Singapore – Jeddah – Mumbai – Novorossiysk – Hamburg – Novorossiysk – Tokyo – London – Montreal -Rotterdam – Novorossiysk -Rotterdam

Aframax: Jeddah – Shanghai

VLCC: Montreal – New York

Profits: **$6,023,349.71**

360 days – 2 Suezmaxes on the fleet

Panamax: Montreal – New York – Jeddah – Singapore – Jeddah – Mumbai – Jeddah – Shanghai

1st Suezmax: Novorossiysk – Hamburg – Novorossiysk – Tokyo

2nd Suezmax: Montreal – Hamburg – Novorossiysk – Rotterdam – Novorossiysk – Singapore – Jeddah – Busan – London – Montreal – Hamburg – Novorossiysk – Rotterdam

VLCC: -

Profits: **$6,237,366.76**

<u>270 days – 2 Suezmaxes on the fleet</u>

Panamax: Montreal – New York

1st Suezmax: Novorossiysk – Hamburg – Montreal – Rotterdam – Novorossiysk – Rotterdam

2nd Suezmax: Montreal – Hamburg – Novorossiysk – Singapore – Jeddah – Busan – London – **Novorossiysk** – Tokyo – Mumbai – Jeddah - Shanghai

VLCC: -

Profits: **$5,984,271.13**

<u>180 days – 2 Suezmaxes on the fleet</u>

Panamax: Montreal – New York – Montreal – London – Jeddah – Singapore – Jeddah – Mumbai – Jeddah -Shanghai – Jeddah - Busan

1st Suezmax: Novorossiysk – Tokyo

2nd Suezmax: Novorossiysk – Singapore – Novorossiysk – Rotterdam – Hamburg – Montreal – Hamburg – Rotterdam

VLCC: -

Profits: **$6,424,050.30**

<u>360 days – 2 VLCCs on the fleet</u>

Suezmax: Montreal – Rotterdam – Novorossiysk – Tokyo – London – Novorossiysk – Rotterdam – Hamburg – Jeddah – Mumbai – Jeddah – Singapore

Aframax: Jeddah – Busan – Jeddah – Shanghai

1st VLCC: Montreal – New York

2nd VLCC: -

Profits: **$5,313,401.78**

270 days – 2 VLCCs on the fleet

Suezmax: Montreal – Hamburg – Novorossiysk – Singapore – Jeddah – Singapore – Jeddah – Busan – New York – Montreal – London – Novorossiysk -Rotterdam – Jeddah – Mumbai – Novorossiysk – Singapore – Tokyo

Aframax: Jeddah – Shanghai

1st VLCC: -

2nd VLCC: -

Profits: **$5,447,903.61**

180 days – VLCCs on the fleet

Suezmax: -

Aframax: -

1st VLCC: -

2nd VLCC: -

Profits: -

In this case it wasn't possible for the model to give us a feasible solution.

The scenario with the highest profits for the shipping company is that when the time horizon is 180 days and the fleet will be composed by a Panamax, two Suezmaxes and a VLCC and the total profits will be $6,424,050.30.

From the results that we got we can easily understand that a Suezmax vessel is preferable for completing these contracts as it enjoys the best ratio of freight rates to costs. On the other hand, the type of vessel that it is not chosen to execute any route is the VLCC as it is a vessel with high operational costs and in our case, with these small amounts of cargoes to be carried brings almost every time negative income. However, if it finds a contract to carry larger amounts of cargo and sails almost full, it is sure that it would generate more income than every other vessel. Another observation that we made from our findings is that the greater the time horizon is the more routes will be executed from the Suezmax vessel leaving the other vessel completing very few or even no contracts.

In some cases, it might be possible to charter a vessel from the spot market to transport a single cargo. We introduce a binary variable $y_i$that would be equal to 1, if cargo i is transported by a spot charter, and zero otherwise, and an associated cost $CS_i$for doing so. In this way the objective function (constraint (1) of the mathematical model would be transformed to:

$$\max \sum_{v \in V} \sum_{(i,j) \in Av} (R_i - C_{ijv}) * x_{ijv} - \sum_{i \in N^c} CS_i \, y_i \, ,$$

An extra constraint should be added:

$$\sum_{v \in N} \sum_{j \in N_v} x_{ijv} \leq 1, \; i \in N^0$$

.

Chapter 4: Conclusions

Crude oil has played an important role in the development of the economies in the last two centuries making it one of highest demanded products for transportation in the shipping sector worldwide. In the last two decades we see that China is the country with the highest number of barrels of imported crude oil annually in the world, followed by the USA, India, South Korea, Japan, Germany and the Netherlands. After the year 2008 and the financial crisis, we observed that apart from China all the other main importers of crude oil significantly reduced their imports, demand, negatively affecting the oil price and the shipping sector in general. A similar phenomenon seems to happen again in the first half of 2020 due to COVID 19 where the oil prices went to significant low levels, April 2020, however, it seems to follow a different path after May and the prices since then have started to grow again, creating euphoria in the industry.

In this thesis we applied linear programming to assist decision making in crude oil transportation. To do so, we conducted a thorough research among relative published papers. We found out that crude oil transportation is one of the most important procedures as it has been researched a lot by many industry's professionals because it presents a great opportunity to the shipping companies to reduce their costs and maximize their total profits. The most important reason that this phenomenon is studied so thoroughly is that this industry faces great volatility, especially in periods of crisis like the one we live due to the COVID 19 pandemic, and the managers should adapt quickly in the current situations in order for their company to survive.

To develop our model at first, we selected some contracts, supplying crude oil from three loading ports to nine discharging ports, all chosen ports were selected by the fact that they are the most important ports of the countries with the greatest exports and imports respectively. We created twelve contracts for transporting crude oil to these nine destinations, three of them would receive crude oil from two different loading ports. After that, the first challenge that we faced was the composition of the fleet as it is very important in order to define a shipping route. There are many differences between vessels but the most significant of them are the capacity of the vessels, the speed and the size, in terms of width, length and draught. So, as we faced no restrictions about the size as all ports selected are reachable even by the largest vessels, we composed our fleet using a Panamax, a Suezmax, an Aframax and a VLCC vessel, having a variety from a small vessel to a very large one, and made some scenarios about which will be used setting as fixed the number of them, which is four.

Furthermore, after selecting the major characteristics of our model we had to set the objective function and set the constraints that will structure our model. Starting with the objective function, we found out from our research that the most common one is the minimization of costs for the vessels of the fleet. However, here being able to find the actual freight rates from Worldscale.co.uk we changed the objective function to maximization of profits, calculating them by multiplying the freight rates with the transported amount of cargo and deducting the bunkering costs and operational expenses. Also, we set a large amount of constraints regarding the fleet capacity, the amount of cargo transported, the time horizon and some binary decision variables, the optimal solution presented which routes should be followed and in what sequence every port should be served. From the literature review we found out that due to the high uncertainty that exists in the shipping industry and the long duration of a ship voyage it is wise not to plan the ship schedule for more than a specific number of voyages. So, for this reason in our model we set the time horizon up to one year.

We observed that the optimization of this problem would be achieved in a time horizon of six months and the most preferable vessel to use is a Suezmax, as it produces the highest returns. From this we understand that there is no preferable vessel for every route. It depends a lot on the freight and the amount of cargo that will be transported and this makes in some cases smaller vessels to have a strategic advantage on the larger ones, even though it is not the obvious choice.

Concluding, in this thesis we tried to answer some basic questions regarding the shipping industry. The first one is what is the significance of crude oil transportation and we found out that it is one of the most transported products in the world as it is essential for every modern economy as even countries that do not produce it use it to produce energy. The second question that we answered here is which are the methods that assist us to find the optimal shipping plan. This the most difficult question that we had to answer as the shipping industry is very complicated and it is affected by many exogenous factors. We tried through the study of the literature review to be as precise as possible covering as many aspects of the problem we could. This led us to the third question which is what the optimal shipping plan for a shipping company needs to fulfill a set of contract cargoes for the transportation of crude oil. The creation of this optimal shipping plan requires the collection of the appropriate data, which will assist us to allocate the amounts of costs and revenues at each route. As a result, the fourth question to be examined by our thesis is which data should be collected to solve the optimization of the crude oil sea transportation problem. To analyze and formulate the problem of our case study we gathered data such as operation costs, bunker costs, freight rates, distances (in days and in nautical miles) etc., which we consider as necessary for our problem. Every platform that we use has real data and the reason behind our decision of these specific platforms is that we want our problem to be realistic and in accordance with real life sea transportation problems.

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