UNIVERSITA' DEGLI STUDI DI PADOVA

Dipartimento di Ingegneria Industriale DII

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Corso di Laurea Magistrale in Ingegneria Meccanica

Speed Optimization and Environmental Effect in Container Liner Shipping

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Anno Accademico 2016/2017

ABSTRACT

This thesis deals with the speed optimization problem concerning a fixed container ship route. The objective of the model is to maximize the operator's daily profit. The literature provides many models concerning the speed optimization in container line shipping, which either maximize the profit or minimize the costs. However, such models take into consideration a fixed transport demand hence fixed revenue. Consequently, the effect of freight rate, which is a representative value of the market condition, is not taken into account by the current models. The thesis addresses the optimization problem considering a non-fixed transport demand. In order to do that, the optimization problem contains three linked decision variables: the speeds along the legs, the number of ships deployed and the service frequency. In addition, the thesis analyses the effect of the bunker price and the effect of the daily fixed operating costs on the optimal solution.

Another novelty introduced by the thesis concerns the inventory costs. Such costs, as well as the bunker price, influence the optimal speeds along the legs. The effect of inventory costs is to adopt a higher speed along the legs on which these costs are higher.

In addition, the model can calculate the CO_2 emissions produced by the fleet employed on the considered route. The thesis also deals with the impacts of two speed reduction policies, which are the implementation of a bunker levy and a speed limit policy.

In the beginning of the thesis, we provide a review regarding the shipping industry, the emissions in the seaborne transport and the slow steaming practice.

ACKNOWLEDGEMENTS

Firstly, I would like to thank my supervisor at DTU, Professor Harilaos N. Psaraftis. Although the topic was a novelty for me, you were very patient with me when we started the thesis. Moreover, you have been always helpful, replying to all my emails and helping me to gather the data required in the developing of the thesis. I would also like to thank my supervisor in Italy, Professor Daria Battini, and the University of Padova for making this period abroad possible. Finally, I thank Dr. Jan Hoffmann of UNCTAD and Mr. Dimitrios Vastarouchas of Danaos Corporation for providing me the data required in order to complete my thesis.

I am very grateful to my family for supporting me in these five years without any pressure. On the contrary, you have pushed me to do my best without spending all my time studying. I think that is the best example of "efficiency" I have ever seen in five years at university. Besides, you have let me free to take my decisions, making meanwhile some mistakes.

Finally, I would like to thank my friends. I am referring to all the people I have met in these years, with which I have hanged out. I would really like to thank you one by one but it is impossible. I have enjoyed my time spent at the Università di Trento, Università di Padova and DTU thank to you. Particularly, I am very grateful to my childhood friends. Studying at the University could be very stressful sometimes but you have been always ready to support me, putting a pinch of madness in my life. I am here writing my master thesis also thank to you.

FIGURES

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CHAPTER 1
INTRODUCTION

1.1 MANAGEMENT SCIENCE AND OPERATIONS MANAGEMENT

Management Science (MS) is closely connected to Operations Research (OR) and is a discipline that regards the application of advanced analytical methods as decision-making tool. Typically, OR problems are composed by objectives, such as determining the maximum or minimum of a function, and constraints, which determines the limits within variables, can range. In this way, mathematical tools can tackle real-world issues. OR employs mathematical tools provided by many field of mathematics such as statistical analysis, mathematical modelling and mathematical optimization; in fact, it is often considered as a sub-field of mathematics. In the same way as lots of others discipline, the modern field of OR arose during wartime, precisely during the Second World War: Great Britain employed it to plan military operation and to optimize the utilization of limited resources. Subsequently OR has occupied about engineering, financial field, management and many other sectors. Since MS can be employed on practical applications, it overlaps with other disciplines: among these, there is Operations Management (OM). OM regards designing and controlling of processes in the production of goods or services ensuring that business operations are efficient and effective: i.e. OM uses OR to employ as few resources as needed in order to satisfy costumers' requirements. OM deals with management problems such as order quantity and production planning: we can say that it is to employ a scientific method to solving management problems. Nowadays, resources shortage and global competition force companies to pay close attention to OM: not only products and services have to be provided to costumers but also the processes used have to be quality. In general, business language, quality refers to costumer's satisfaction, which has a wide significance:

→ Reliability of the product or the service

→ Efficiency of the process

→ Effectiveness of the process

→ Price

→ Environmental effects

→ Social effects

Quoting Frederick Winslow Taylor, a pioneer of OM:” This paper has been written to prove that the best management is a true science, resting upon clearly defined laws, rules, and principles, as a foundation. And further to show that the fundamental principles of scientific management are applicable to all kinds of human activities, from our simplest individual acts to the work of our great corporations, which call for the most elaborate cooperation.”

1.2 PROJECT OBJECTIVES

This thesis regards the speed optimization problem in container liner shipping industry: given a fixed route, through a mathematical model it may provide a decision-making tool to set the sailing speed. The container liner shipping market presents a peculiar characteristic: the carriers provide a specific service frequency on their routes. Such feature links the number of ships deployed on the route to and the sailing speeds on the route’s legs. The main objective of the thesis is to assess whether and how the market condition, that is fundamentally the freight rate value, affect the speed in the containership industry. In order to do so, the model introduces two novelties concerning the speed optimization problem:

- → The transport demand is not fixed
- → The service frequency is an optimization variable

Besides the thesis employs the model to evaluate the effect of other two main parameters that affect the shipping market: the bunker price and the daily fixed operating costs. The model takes into account another significant parameter, which usually is not considered in the speed optimization issues: the inventory costs. Although ship owners do not bear such costs, their impact should be considered as the goods’ owners prefer a faster service than a slower service. Summarizing, the thesis aim is to assess the effect upon the model of the following factors:

- → Freight rate
- → Bunker price

→ Daily fixed operating costs

→ Inventory costs

Subsequently, the thesis deals with the effect of such parameters on the CO_2 emissions produced by the ships and it evaluates how a bunker levy policy and a speed limit policy may influence such emissions. Nowadays, the increasing attention on global warming leads government to regulate emissions, especially in terms of greenhouse gases (GHG) and specifically in terms of CO_2 emissions, in order to curb the environmental effects of these gases. In order to simulate the real industry conditions, the model employs data as realistic as possible.

1.3 PROJECT STRUCTURE

The thesis is divided in two main topics. The first one is the review concerning the features of the container ship industry: namely, it gives the basic knowledge with regard to the characteristics of the vessels, the common rules of the market; moreover, it introduces the CO_2 emissions-issue related to the seaborne trade industry. The second principal topic concerns the model, explaining how it works and providing the results of the simulations. The section provides a briefly description of each chapter treated in the thesis:

→ **Chapter 2:** the second chapter contains the main information regarding the containership industry and the seaborne market. It reports a classification concerning the type of ships and as well as the type of cargoes transported. Moreover, the chapter lists the fuels used in the shipping industry and the type of contract employed with their main traits;

→ **Chapter 3:** the third chapter deals with the environmental issues in the maritime transport industry; specifically, it regards the CO_2 emissions. It explains the evaluation methods to calculate the emissions produced by the word fleet. It reports several statistics concerning the CO_2 emissions, such as the emissions for type of ships and the weight of the maritime transport emissions upon the global pollution. Subsequently, it analyses the feasible measures to curb such emissions and a method to assess their cost efficiency. At the end of the chapter, a comparison between the seaborne transport and the other transport means, concerning their environmental-efficiency is reported;

→ **Chapter 4: t**he fourth chapter introduces the “slow steaming” practice. The reasons beyond his application and the strong impact on the market are approached. Instead, the second part of the chapter addresses the model formulation, introducing the objective function and constraints;

→ **Chapter 5:** the fifth chapter contains all the information regarding the evaluation of the parameters employed in the model, such as the formulation of the fuel consumption function and the calculation of the revenue. Besides, it describes the main characteristics of the routes treated in the thesis;

→ **Chapter 6:** the sixth chapter focuses on the results of the simulation. The chapter reports the most significant results obtained from the model through which the impacts of the market conditions, such as the bunker price and the freight rate, are evaluated. Fundamentally, such chapter is the core of the thesis;

→ **Chapter 7:** the last chapter concerns the conclusions. Basically, the conclusions briefly summarize the results obtained in the chapter 6;

CHAPTER 2
MARITIME TRANSPORT

Ship transport is one of the most important transport means along with aviation and land transport, which comprises both rail transport and road transport. Each of these transport means has its specific features, hence when one selects the proper transport mode for his freight, one has to consider some variables such as speed, costs and the nature of cargo itself. A first significant subdivision with regard to what is transported can be made between:

→ Transport of passengers

→ Transport of goods

As regards the transport of commodities, maritime transport is accountable for 90% of the overall world trade (source: www.ics-shipping.org/shipping-facts/shipping -and-world-trade, 17-11-2016). Therefore, it is evident that ship transport is the most significant factor within the global trade as it makes possible to move goods in every place in the world. This chapter furnishes information concerning structure and composition of the world fleet, focusing on the container sector. The fuels employed and the contracts that are usually adopted in ship transport are analysed, besides it is provided a classification of the costs that a ship owner incurs when his ships are operative. At last, the container fleet's characteristics and the major trade route involved in the containership liner market are studied.

2.1 CARGO AND VESSEL CLASSIFICATION

According to (Stopford, 2009), cargoes can be classified at two different levels. The first classification sorts goods in six groups which represent six specific industries. Thus, one can analyse a specific commodity within his economy sector and see the relationship among the goods of the same group. For example, if the global energy demand falls, the demand of crude oil as well as the demand of liquefied gas may decrease. Similarly, if the crude oil's price rises, the demand of other energy sources, such as liquefied gas, may probably increase. The six economy sectors in which commodities are grouped are:

→ **Energy trade**: this group includes crude oil, coal, oil products, liquefied gas;

→ **Agricultural trade**: cereal, wheat, barley, sugar as well as refrigerated food are comprised in this category;

→ **Metal industry trade**: it comprises both raw materials and products of steel and non-ferrous industries as mineral ore;

→ **Forest products trade**: this class includes all materials regarding paper industries and wood products as timber and boards;

→ **Other industrial materials**: a wide range of materials are comprised such as cements, chemicals, salt;

→ **Other manufacturers**: this section typically includes high value goods; for instance, machinery, vehicles, furniture;

The second classification subdivides goods with respect to how the shipping industry transports such commodities. Indeed, a commodity is transported in a specific range of quantity, depending on his demand characteristics. For instance, an iron parcel that is an individual consignment of cargo, ranges between 40000 and 100000 tonnes (Stopford, 2009). This characteristic is described by the parcel size distribution (PSD) for each commodity. The PSD essentially describe which is the usual parcel size for a particular commodity. The PSD allows to subdivide commodities in two class depending on the size of parcel:

→ **Bulk cargo**: (parcel >2000-3000 tonne) a commodity is considered a bulk cargo when the typical parcel is big enough to fill a whole ship. The bulk cargoes can be divided in four categories:

  - Liquid bulk: these cargoes require tanker transportation. The main product in such class is crude oil;

  - Major bulk: in the major bulk class are comprised iron ore, grain, coal, phosphate and bauxite. These commodities are transported by dry bulk carrier;

  - Minor bulk: the most important commodities in such group are steel products, cement and non-ferrous metal ores;

- Specialist bulk cargoes: it includes any bulk commodity which require specific handling or storage necessity, such as motor vehicle and prefabricated building;

→ **General cargo**: (parcel <2000-3000) general cargo is a commodity whose parcel size is insufficient to fill a ship. Therefore, this type of cargo is delivered in small consignments and a single ship at the same time transports different general cargo commodities. Moreover, such kind of cargo are often high-value. As the bulk cargo group, it can also be subdivided in several sub-categories:

- Loose cargo: such as individual items and boxes:
- Containerized cargo: this is currently the principal form of cargo transport;
- Palletized cargo
- Pre-slung cargo: items lashed together into standard-size packages;
- Liquid cargo: liquids ship in deep tanks or liquid container;
- Refrigerated cargo: perishable goods which have to be shipped in reefer containers;
- Heavy and awkward cargo

Since for many commodities the parcel size distribution contains both small and big parcels, the commodities cannot be neatly subdivided in these two classes but often the same commodity can belong to both the categories. The classification of commodities in bulk cargo and general cargo allows to divide the shipping market in two categories. These two markets are strictly related to the types of vessel employed and require different types of shipping operation:

→ **Bulk shipping industry**: the principle of this market is “one ship, one cargo” and it is also called tramp shipping. In such market ships have no fixed route, but the visited ports are set depending on the shipper necessity. Carriers in the bulk shipping industry mainly employs tankers and bulk vessels;

→ **Liner shipping industry**: liner ships follow a fixed route and operate a scheduled service. The schedules are typically published on the company’s website where the ports of call are indicated, the route and the duration of the voyage in days. Moreover, shipping companies generally provide a weekly service frequency, that means each port is served once a week. Containerships are usually involved in the liner market.

Therefore, the decision regarding which type of vessel is employed depends on the cargo characteristics. Within the shipping market are employed many different types of ship, the major types present in the international shipping industry are:

- → **Container ship**: container vessels transport commodities which are contained in in standardized containers. The capacity of such ships is measured in twenty-foot equivalent units (TEU) that is the usual size of a container. Container ships are generally faster than bulker carriers and tankers. According to (Equasis, 2015), there are 5174 containerships operating;

Figure 2.1: Picture of a containership

- → **Tanker ship**: tankers are merchant vessel designed to ship liquids or gases, such as ammonia, crude oil, liquefied natural gas and fresh water. Generally, tankers are subdivided in four category depending on the commodity transported: oil tanker, liquefied gas tanker, chemical tanker and tankers for other liquid. The cargo capacity of these vessels is measured in tons. According to (Equasis, 2015) there are 15391 ships of this type;

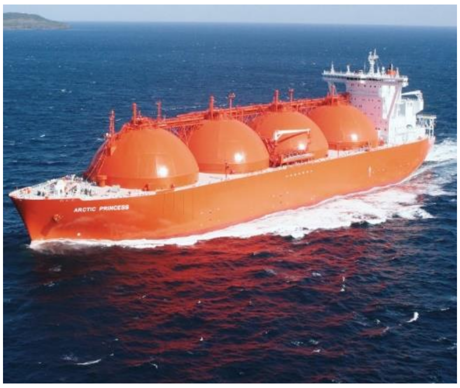


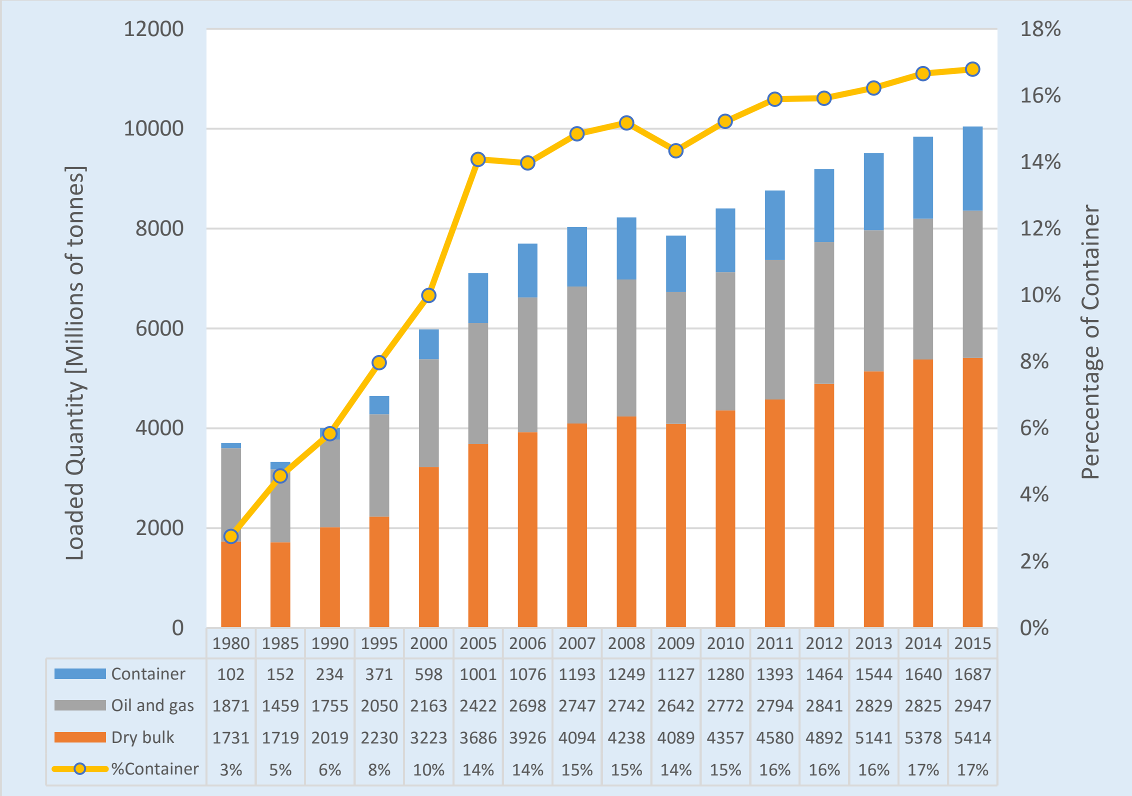
Figure 2.2: Picture of a LNG tanker

- → **Bulk carriers**: they are designed to transport unpackaged bulk cargoes. Bulk carriers have large cargo holds wherein the payload is stored. Bulk carriers are usually loaded and unloaded with either conveyor belts or gantry cranes, depending of the cargo. There are 11289 (Equasis, 2015) bulk carriers in the merchant fleet;

Figure 2.3: Picture of a bulk carrier

Besides, other ships are used in maritime transportation, such as Ro-Ro which is a vessel designed for transporting cars and other wheeled vehicles, general cargo ships and passenger ships.
Figure 2.4 depicts the loaded quantity in millions of tonnes loaded with regard to containers, oil and gas and dry bulk commodities. Besides, the percentage of the containers on the total is also plotted. As one can see, the utilization of containers to transport cargoes has sharply increased from 1980 to 2005. Furthermore, one should take into consideration that typically containers contain high-value commodities, hence if the economic value of transported goods is considered, the container weight on freight market will considerably higher. The rise of container freight is due to him characteristic. Until mid-1960s most general cargoes were shipped loose, such practice forced carriers to spend two-thirds of their time in port for the handling operations. Since the increasing demand of freight transport, carriers were not able to furnish the required service at an economic cost. In order to shrink handling time hence the related costs, carriers started to adopt container to unitize goods. Containers are the unit of containerization system which is an intermodal freight transport method. An intermodal freight transport is a transport system in which are involved multiple transport means, without necessity of handling operation when the freight is moved among the different mode of transportation.

Containers mainly come in two different standardized sizes: twenty-foot equivalent (TEU) containers, which are 6.1 meters long, 2.44 meters wide and 2.59 meters high, and forty-foot equivalent containers, which are wide and high as TEUs but are longer (12.2 meters), that is twice TEU's length. The term "TEU" is commonly used to describe the cargo capacity of a containership or to quantify the transport demand. The paper employs the TEU-size as unit of measurement concerning the transport demand, however there are many other available container's sizes, such as 45 feet high cube, which are employed in the maritime commerce.



	1980	1985	1990	1995	2000	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Container	102	152	234	371	598	1001	1076	1193	1249	1127	1280	1393	1464	1544	1640	1687
Oil and gas	1871	1459	1755	2050	2163	2422	2698	2747	2742	2642	2772	2794	2841	2829	2825	2947
Dry bulk	1731	1719	2019	2230	3223	3686	3926	4094	4238	4089	4357	4580	4892	5141	5378	5414
%Container	3%	5%	6%	8%	10%	14%	14%	15%	15%	14%	15%	16%	16%	16%	17%	17%

Figure 2.4: Goods loaded quantity in 1980-2015 for containerships, tankers and bulk carriers Adapted from: (UNCTAD, 2016), Figure 1.2

2.2 MARINE FUELS

Oil is currently the only significant energy source for maritime industry. Marine fuels are divided in two main classes, which include the different type of fuels:

→ **Distillate fuel oil**: the distillate fuels are manufactured with the vapours produced during the distillation process

- MGO (Marine Gas Oil)
- MDO (Marine Diesel Oil)

→ **Residual fuel oil**: the residual fuels are produced using the residue of the distillation process

- IFO 180 and IFO 380 (Intermediate Fuel Oil): the figure indicate the maximum viscosity measured in centistokes at 50°. Generally, IFO fuels are also called HFO (Heavy Fuel Oil) in literature;
- HFO (Heavy Fuel Oil)

All the marine fuels are produced from refining of crude oil; in fact, their prices are strictly linked to the crude oil price per barrel. MGO is made from distillate only whereas MDO is a blend of heavy fuel oil and gas oil. IFO is a blend of gasoil and heavy fuel oil however it contains less gas oil than MDO. MDO and MGO are considerably more expensive than IFO moreover IFO 180's price is slightly higher than IFO 380's. On 9 November 2016 MGO was sold for 404 [USD/tonne] whereas IFO 180 and IFO 380's prices were 279 and 251 [USD/tonne] respectively. Because of this low price HFO is the most employed fuel in maritime industry, counting about for 84% of the overall marine fuel consumption. However, it is also more pollutant in respect to the distillate fuels. Specifically, MGO maximum sulphur content is 1,5% whereas the maximum sulphur content of HFO is 3,50% (source of figures: www.shipandbunker.com, 08-11-2016). The International Maritime Organization (IMO) has made a decisive effort to diversify the industry consumption away from HFO toward cleaner fuels. In fact, in 2008 IMO adopted a resolution to update MARPOL (MARPOL is the International Convention for the Prevention of Pollution from Ships) annex VI regulation 14, which contains limitation regarding the sulphur content of the fuel used by shipping sector; as of 1.1.2020, sulphur content should not be more than 0,5%. This regulation forces ship owners to use low sulphur fuel oil such as MGO or MDO within the emissions control areas and also limits the sulphur emissions outside these areas. The emission control areas are the Baltic Sea area, the North Sea area, the North American area (covering designated coastal areas off the United States and Canada) and the United States Caribbean Sea area.

An alternative to oil-based fuels is the Liquefied Natural Gas (LNG). LNG is the cleanest fossil fuel and allows to reduce CO_2 emissions as well as pollution by sulphur. In fact, LNG contains both less carbon and sulphur than fuel oil. Moreover, the cost of LNG is about the same of residual fuel oil and it is significantly less expensive than distillate fuels. Currently, several technical challenge has to be faced for employing LNG as a real alternative to fuel oils. The main issues with regards to LNG as a marine fuel are its availability in the bunkering ports and the large space required to storage the fuel on board. In figure 2.5 are reported the utilization percentages of distillate fuels, residual fuels and liquefied natural gas in international shipping. The figure shows a slightly trend from utilization of residual fuel oil toward LNG and distillate fuel oil.

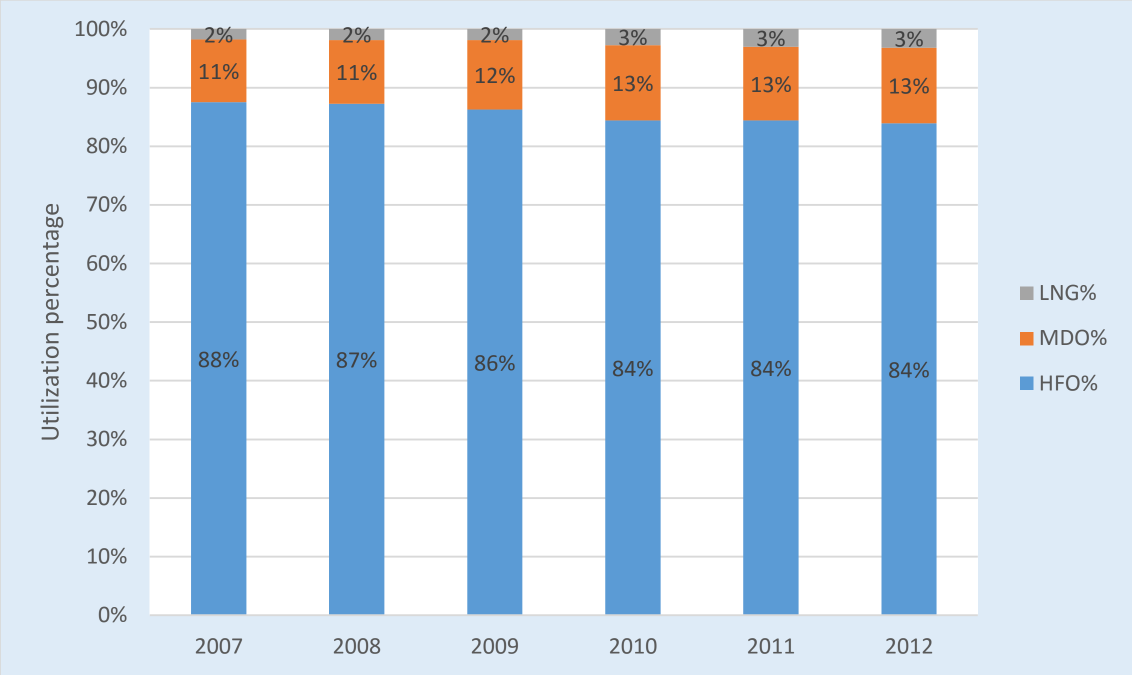


Figure 2.5: Utilization percentage of HFO, MDO and LNG in international shipping[1]
Adapted from: (IMO, 2014), Table 3

2.3 SHIP COSTS

Assessing the daily costs of a ship is not a trivial operation. The costs are largely influenced by type of vessels besides the daily cost may also be different for the same ship type. In fact, the ship costs depend on a wide set of vessel's features such as age of the vessel and the ship's size. The aim of this section is to provide a review regarding the which cost must be considered when the daily ship cost is assessed, without taking into account of all parameters that influence such evaluation. According to Stopford, (2009), the costs of a ship in the maritime cargo market can be classified into five categories as shown in figure 2.3:

→ **Operating costs**: the operating costs are the expenses which must be paid to make the ship be operative, except for the fuel expenditure that is considered separately. These costs are independent whether the ship is in port or at sea whereas they are connected to the operative days of the ship. The principal elements which are comprise in such category are:

[1] See appendix A for the calculations method

- Crew costs: this item includes all the charges concerning the seafarers, such as salaries, pensions and social insurance. Crew costs mainly depend on the number of crew on the ship, which is principally linked to the degree of automation of the vessel. In recent years, the number of seafarers required in order to run a vessel has declined hence this expenditure currently has a small weight upon the overall costs;

- Stores costs: such category comprises all the cost related to consumable supplies such as spare parts, cabin stores and lubricant. Since most vessels have diesel engine the lubricant expense is by the far the most influential cost item for this class;

- Repairs and maintenance costs: this category contains the costs concerning the routine maintenance of the ship as well as the costs related to breakdowns. The difference between these two items is basically that the maintenance is scheduled by the ship owners whereas the breakdowns cannot be scheduled, being random events;

- Insurance costs: all the ships are furnished with an insurance in order to protect the ship owner from casual occurrences. For example, insurances typically cover injuries of crew members, damage of cargoes or damage of the ship's components;

- Administration costs: these costs are due to managing of the fleet;

→ **Periodic maintenance costs**: all merchant ships must be undergone to regular surveys. These surveys assess the seaworthiness of the ship and are carried out when the ship is dry-docked. Generally, it is required to replace some components which do not reach the minimal requirements;

→ **Voyage costs**: the voyage costs are principally related to the fuel expenditure but this class also comprises port fees and canal charges. These costs depend on the speed of the vessel and on the number of port of calls involved during the voyage;

→ **Cargo handling costs**: these costs comprise cargo loading cost, cargo discharging cost and cargo claims. Generally, such costs are expressed as USD per TEU or per tonne and it is a significant expenditure for carriers. These expenses have a heavily impact in liner trades;

→ **Capital costs**: the cost of purchasing the ship is not reported in the company's balance as a single expenditure. Indeed, the cost of the ship is spread over the ship's span time, which is typically equal to 20 years. This practice is generally applied by all accountants for reporting large capital items in the profit and loss account otherwise the company would report a massive loss for every investment. Besides, as reported in (Počuča, 2006), from the purchasing value is subtracted the value of the ship at scrapheap in order to consider the earning for demolishing the vessel. Another name to refer to capital cost is depreciation cost.

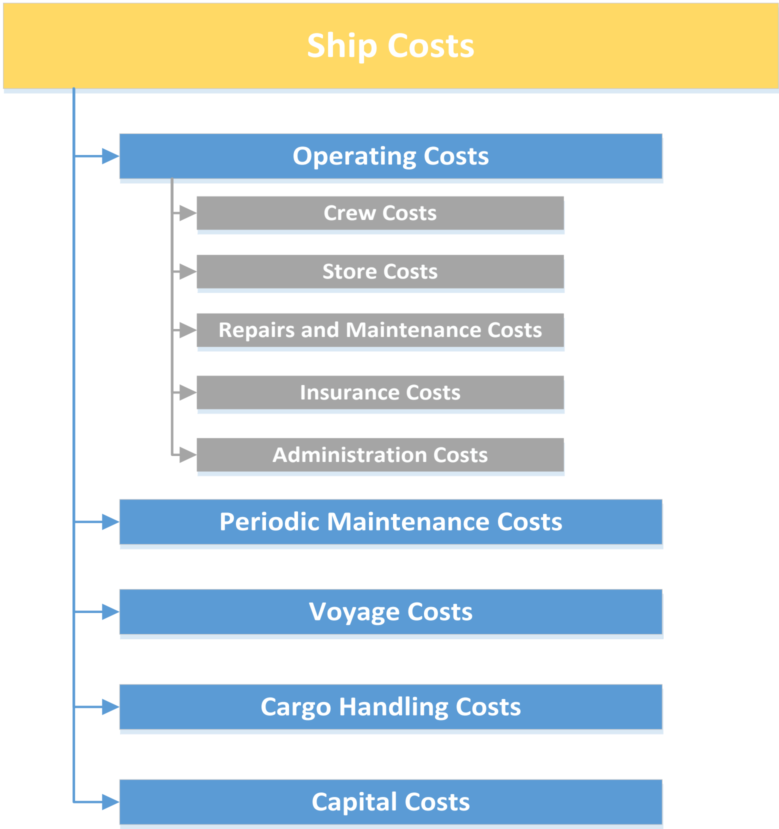


Figure 2.6: Cost classes in maritime cargo market

Therefore, according to (Počuča, 2006), the daily ship cost can be evaluated as follows. In such analysis are exclusively considered the operating cost and the depreciation cost because in the model present in this thesis the handling costs and the voyage costs are separately treated, being dependent by the speed and the service frequency. For this reason, the cost here calculated can be called daily fixed cost as it is the daily cost to deploy a new vessel on the route. The daily fixed cost E can be computed in the following way:

$$DOP = \frac{YOP}{OD} \tag{2.1}$$

Where DOP is the daily operating cost, YOP is the yearly operating cost and OD are the ship's operating days per year. Subsequently the daily depreciation cost DD is calculated as follow:

$$DD = \frac{AD}{OD} \tag{2.2}$$

$$AD = \frac{VS - VSS}{DP} \tag{2.3}$$

Where AD is the yearly depreciation cost, VS is the value of the ship, VSS is the value of the ship at scrapheap and DP is the depreciation period. At last, the daily fixed cost E is the sum of the daily depreciation cost and the daily operating cost:

$$E = DD + DOP \tag{2.4}$$

The result reported in (OpCost, 2014), regarding the daily operating cost, estimates as 7398 [USD/day] the daily operating cost for a container ship of 2000-6000 TEU capacity. (Murray, 2016) estimates such cost as about 10000 USD for vessels with a capacity over 12000 TEU. The daily depreciation cost has to be added to the figure above, as it does not take into account of such cost.

2.4 CONTRACT CLASSIFICATION

The market in which sea transport is bought is sold is called freight market. The contracts in the freight market are called charterer-party and regulate the employment relationship between carriers and shippers (or charterers). The freight rate value depends on the market involved hence freight rates are different for container ships, tankers and bulk carrier. Within the freight shipping industry there are four principal types of contracts (Stopford, 2009):

→ **Voyage charter**: a voyage charter is the transporting of the cargo between two ports. The carrier and the shipper involved set out a contract in which the price for a certain amount of good is fixed, that is the freight rate. The cargo must be delivered in a specific date otherwise if the cargo is delivered after the due date, carrier will pay a demurrage for delay. Contrarily, if the cargo is delivered before the committed date, carrier will receive a despatch payment. The ship owner manages the ship and bears all the costs. The freight rate is the price at which a certain amount of cargo is transported, such as USD per tonne or USD per TEU.

→ **Contract of affreightment**: this contract is similar to a voyage charter but in this case the carrier commits to transport a set of cargo for a fixed price per tonne. The set of cargoes must be delivered in a fixed time interval and the carrier can arrange the details of each voyage in order to use his ships in the most efficient manner. The carrier bears all the costs as in the voyage charter. This kind of contract is especially employed for cargoes in dry bulk market, such as iron ore and coal;

→ **Time charter**: shipper hires the vessel for a specific period of time and is in charge to pay the voyage and the handling costs, such as fuel consumption and port charges. The shipper arranges the details of the voyage, such as the speed and which port are involved but the managing of the ship owner is still carried out by the ship owner who pays for the cost related to the crew and for the maintenance. Generally, the price for hiring a ship is stated as USD per day;

→ **Bare boat charter**: the bare boat charter is a contract similar to time charter but in such contract the charterer obtains full control of the vessel. As a consequence, shipper is in charge to pay the operating costs and the maintenance costs. Basically, the charter has full operational control of the ship but does not own it;

2.5 CONTAINER SHIPS

The container-shipping industry is composed by many trade routes. Container shipping companies, such as Maersk and MSC, provide several freight services and each one of these services is scheduled and visits specific ports, depending on the route. Thereby, routes form a global network which enables to transport commodities from a certain port A to a port B, given a certain price per TEU delivered and within a scheduled time, as shown in figure 2.7. The first ship designed for container transportation was built in 1960, as of that moment the quantity of containerized commodities moved all over the world has rapidly increased. In fact, as of 2009, around 90% (Ebeling, 2009) of cargo worldwide is moved by container ships, excluded bulk cargoes. Therefore, container freight transport can be considered as the international transport mode par excellence with regard to high-value commodities. As discussed in section 2.1, containerization allows to reduce the handling time of cargoes hence the overall costs of freight transport means. The reduction of handling time is a paramount challenge in the freight transport as the continuous increasing in the transport demand.

The freight transport demand is strictly related to the economic growth, which is measured through the gross domestic product (GDP). Despite the economic recession in

2009, when the global containerized trade decreased, in 2015 the global volume of container trade reached the record figure of 175 million TEUs and this value is predicted to increase over 180 million TEUs in 2016 (UNCTAD, 2016). The continuous rise of containerized trade is associated to the globalization of the economic market. Even better, one can say that container ships have been a paramount driver of globalization, allowing transporting goods all over the world at a reasonable price. In this section the characteristics of the major route are discussed, moreover the currently and future composition concerning the container ship fleet is analysed.

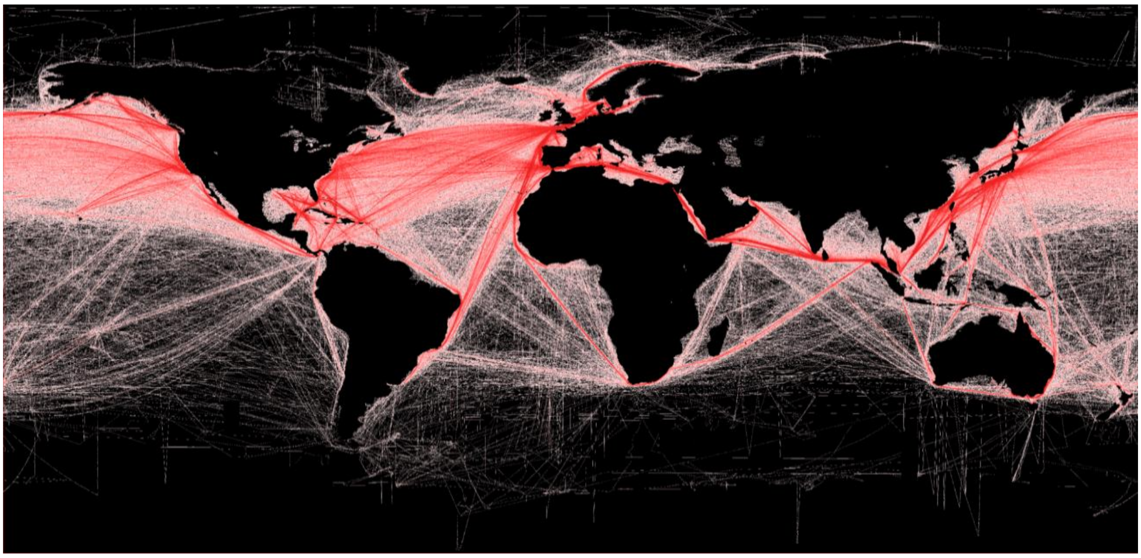


Figure 2.7: Representation of global maritime traffic
Source: (Halpern et al., 2008)

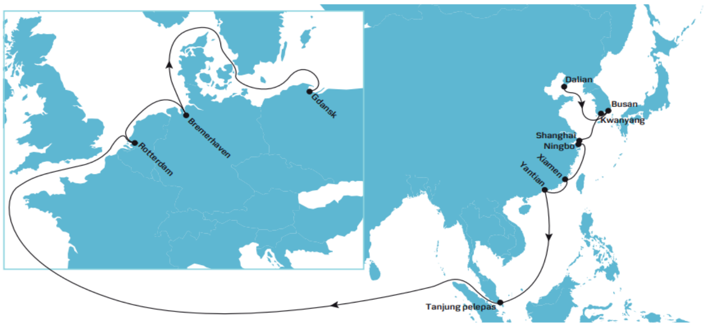
2.5.1 Container Liner Shipping Route Network

In the liner shipping market ships travel along fixed route within a fixed scheduled time, such as the timetable in figure 2.7 which depicts the service provided by Maersk for the Europe-Asia route. The behaviour of a liner ships is thus similar to bus and train services. Currently, there are around 400 liner services in operation, which links the major ports in the world (source: www.worldshipping.org/about-the-industry/liner-ships, 21-11-2016).

AE10 WESTBOUND

SERVICE HIGHLIGHTS

- Fastest transit time in the market to Rotterdam with great coverage of FEA main markets
- Best product in the market to Poland
- Introducing direct Xiamen and Dalian to Gdansk with best-in-class transit time



From	Dept\Arr	ROTTERDAM Netherlands SAT	BREMERHAVEN Germany TUE	GDANSK Poland FRI
DALIAN, China	FRI	36	38	41
BUSAN, South Korea	MON	33	35	38
KWANGYANG, South Korea	TUE	32	34	37
SHANGHAI, China	FRI	29	32	34
NINGBO, China	SAT	28	30	33
XIAMEN, China	TUE	25	28	31
YANTIAN, China	WED	24	26	29
TANJUNG PELEPAS, Malaysia	MON	19	21	24

21/06/2016

Transit times are indicative and subject to change.

Your promise. Delivered.

MAERSK LINE

Figure 2.8: Maersk line's East-West service schedule and route
One can notice the weekly frequency of such service, moreover table also furnishes the voyage duration in days. For instance, every Friday a vessel leaves Dalian's port and it will reach Rotterdam on Saturday, after 36 days.
Source: http://www.maerskline.com/en-sc/shipping-services/routenet/maersk-line-network/east-west-network, 21-11-2016

According to (UNCTAD, 2016) and (Stopford, 2009), the global network, concerning the container shipping trade, can be subdivided in four classes:

→ **East-West lane**: which connects three main economic regions, namely Asia (especially China) the manufacturing centre of the world, and Europe and North America, which are the principal consumption markets. The East-West line can be divided in two sub-class:

  - Mainline: the mainline comprises the transatlantic routes which link Europe to North America, the transpacific routes which connect North America to Asia and the routes between Asia and Europe;
  - Secondary line: which includes the other routes;

→ **North-South lane**: the north-south line links the three major in the North, such as Europe, North America and Far East, with the economies in the South;

→ **South-South lane**: this line connects the economies in the South each other, such as South Africa and South America;

→ **Intraregional lanes**: the intraregional market comprises routes, which bring together ports belonging the same region. For instance, Maersk provides an Intra-Europe service, which allows delivering goods among European ports. Most intraregional lanes use small ships and voyages of few days, such as three or four days;

The global network of shipping market, composed by such international and intraregional lanes, is constantly changing in order to meet the development of new economies, hence depending on the freight transport demand.

Currently, the major trade lane is the East-West route which counts for 42%, whether the overall cargo's flow is considered, as shown in figure 2.9. As stated in (Vad Karsten et al., 2015), containers move along the network, however in order to transport a certain container from A to B more than one service may be involved. One can refer to the transit between two distinct routes as transshipment.

Basically, transshipment means employing more than a service for delivering goods. Such practice requires storing of containers at the transshipment port, moreover loading and unloading activity are necessary when the cargo moves on another route.

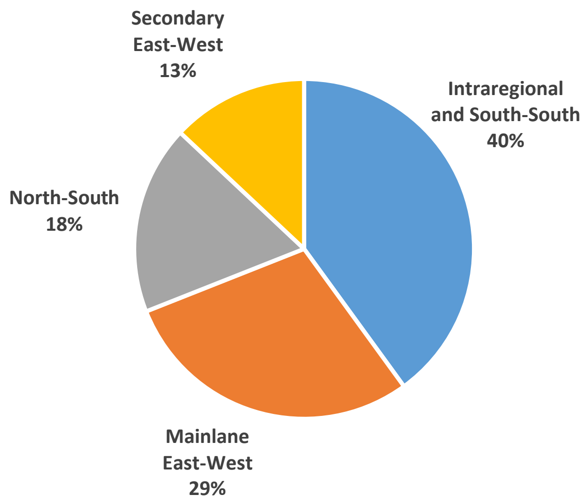


Figure 2.9: Global containerized by route, percentage share in TEU
Adapted from: (UNCTAD, 2016), Figure 1.5

Therefore, transshipment allows to link ports, which are not directly connected by a service, nevertheless, it entails a longer handling time hence higher costs.

2.5.1.1 MAINLANE EAST-WEST

The mainlane East-West is the major liner route and during 2015 through this lane were transported about 52,5 million of TEU (UNCTAD, 2016). The East-West trade lane connects the three major economic centres that are Europe, North America and Eastern Asia (especially China). As depicted in figure 2.10, these three continents are connected by three trade routes: transatlantic lane, Europe-Asia lane, and transpacific lane. The transpacific lane is the primary of them and counts for 46% of the overall container trade on the East-West route, whereas Europe-Asia lane counts for 41% and transatlantic lane counts for 13% (UNCTAD, 2016). Figure 2.11 reports the quantities of TEU moved along the three routes.

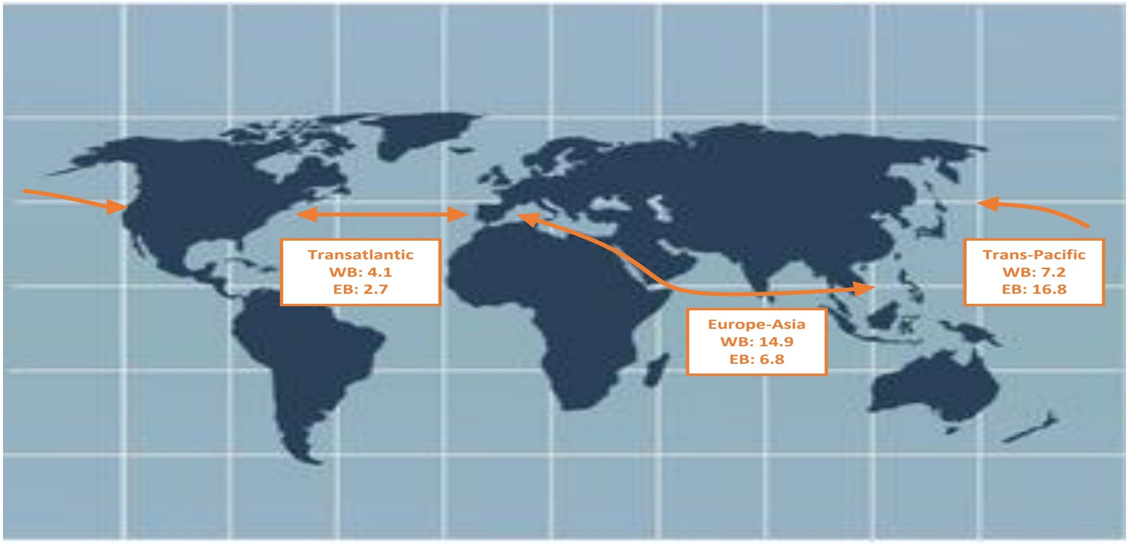
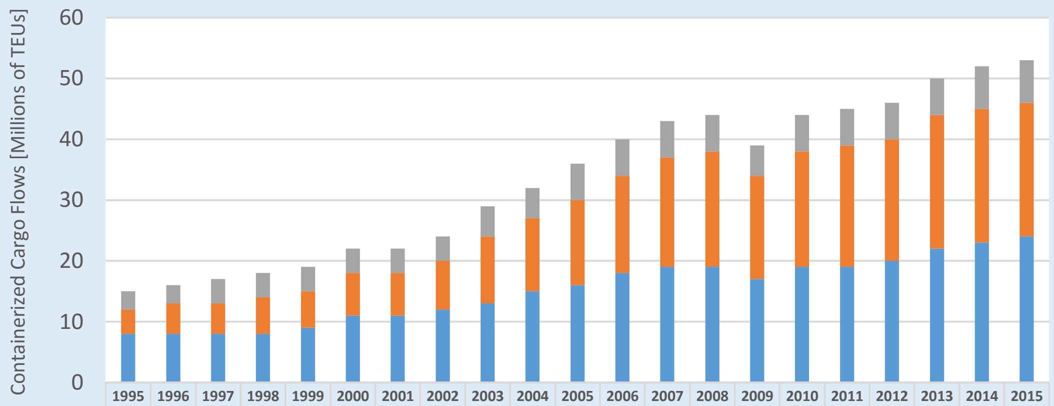


Figure 2.10: Container flows on Mainlane East-West route [million TEUs], 2015
Adapted from: (UNCTAD, 2016), Table 1.7



	1995	1996	1997	1998	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015
Translatlantic	3	3	4	4	4	4	4	4	5	5	6	6	6	6	5	6	6	6	6	7	7
Europe-Asia	4	5	5	6	6	7	7	8	11	12	14	16	18	19	17	19	20	20	22	22	22
Trans-Pacific	8	8	8	8	9	11	11	12	13	15	16	18	19	19	17	19	19	20	22	23	24

Figure 2.11: Containerized trade on Mainlane East-West route, 1995-2015
Adapted from: (UNCTAD, 2016), Figure 1.7

The characteristics of a route, such as the freight rate, are not constant all over the route itself. Indeed, several parameters are heavily influenced by the travel direction, namely, the eastbound direction and the westbound direction with regard to the mainlane East West. The major parameters influenced by the travel direction are the followings:

→ **Freight rate**: freight rates are different and depend on the travel direction. As reported in table 2.1, freight rates are very influenced by the travel direction, especially when the Asian market is involved.;

Imbalance in Freight Rate

Route	Eastbound [USD/TEU]	Westbound [USD/TEU]	Ratio
North Europe-US	800	650	1,231
Far East-North Europe	1200	1900	1,583
Far East-Us	1800	1100	1,636

Table 2.1: Eastbound and Westbound freight rates in the fourth quarter of 2010
Adapted from: (FMC, 2012), Table TE-20, AE-19 and TP-19

→ **Capacity utilization**: the capacity utilization is the percentage of payload carried by a ship in respect to his potential capacity. Especially, in the Europe-Asia lane this value is significantly different in the eastbound direction and the westbound direction. For instance, as reported in (FMC, 2012), in the fourth quarter of 2010 this value was 54% as regards eastbound and 78% as regards westbound;

→ **Number of containers transported**: the quantity of cargoes hauled along a route is different in the two directions. Using the ratio between the number of containers transported westbound and eastbound, one can analyse such significant aspects of a trade route. In 2015 such ratio was equal to 2,33 as regards the transpacific lane whereas it was equal to 2,2 and 1,52 (in this case the ratio is defined as the cargoes transported westbound divide by the cargoes transported westbound) for the East-Asia lane and transatlantic lane respectively (UNCTAD, 2016);

→ **Average value of cargo**: as reported in (Psaraftis and Kontovas, 2013), the monetary value of containers is influenced by the specific trade. Indeed, the paper claims that in the Europe-Asia lane the average cargo values are about double in the westbound direction than in the eastbound direction. As discussed in chapter 4, the cargo value influences the optimal speed of the vessel hence it is significant considering such aspect.

2.5.2 FLEET CHARACTERISTICS

The size of containerships normally refers to the number of TEU-size containers that it is able to carry, which is the vessel's freight capacity. Since the ship dimensions depend on the number of transportable containers by the ship itself, stating the freight capacity also means stating the ship size. Some different classifications depending on the transport capacity are stated in literature; this thesis relies on the nomenclature present in (MAN, 2013) and reported in figure 2.12.

Small Feeder	<1000 TEU
Feeder	1000-2800 TEU
Panamax	2800-5100 TEU
Post-Panamax	5500-10000 TEU
New-Panamax	12000-14500 TEU
ULCV	>14500 TEU

Figure 2.12: Container ship classification depending on the TEU-capacity
Adapted from: (MAN, 2013), Propulsion Trends in Container Vessels: Two-stroke engines

Container ships are relatively faster than tanker ships and bulk carrier. Indeed, as shown in figure 2.13, the average design speed for medium-size and large vessels is about 25 knots. As a consequence, fuel consumption is higher for containerships and the policy of slow steaming has a greater impact for such type of ships than for bulk carrier and tankers. The chapter 4 deals with such topic, analysing deeply which effects slow steaming entails in the liner trade market.

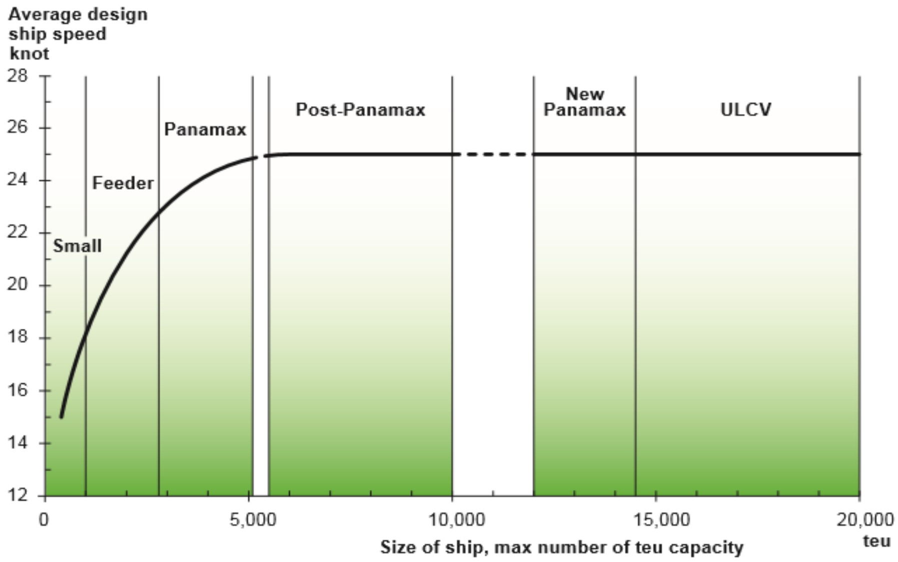


Figure 2.13: Average design speed of container
Source: (MAN, 2013), Propulsion Trends in Container Vessels: Two-stroke engines

According to (UNCTAD, 2016) the global TEU capacity for container ships is about 19,9 million TEUs. Currently as reported in figure 12.13, most containerships have a TEU capacity lower than 4000, however in 2016 the average capacity of containerships in the order book is 8508 (UNCATD, 2016) which is more than double the average vessel size of the current fleet. Therefore, the average size of the container fleet is destined to increase in the next years. Carriers employ larger vessels in order to reduce costs and increase their market share.

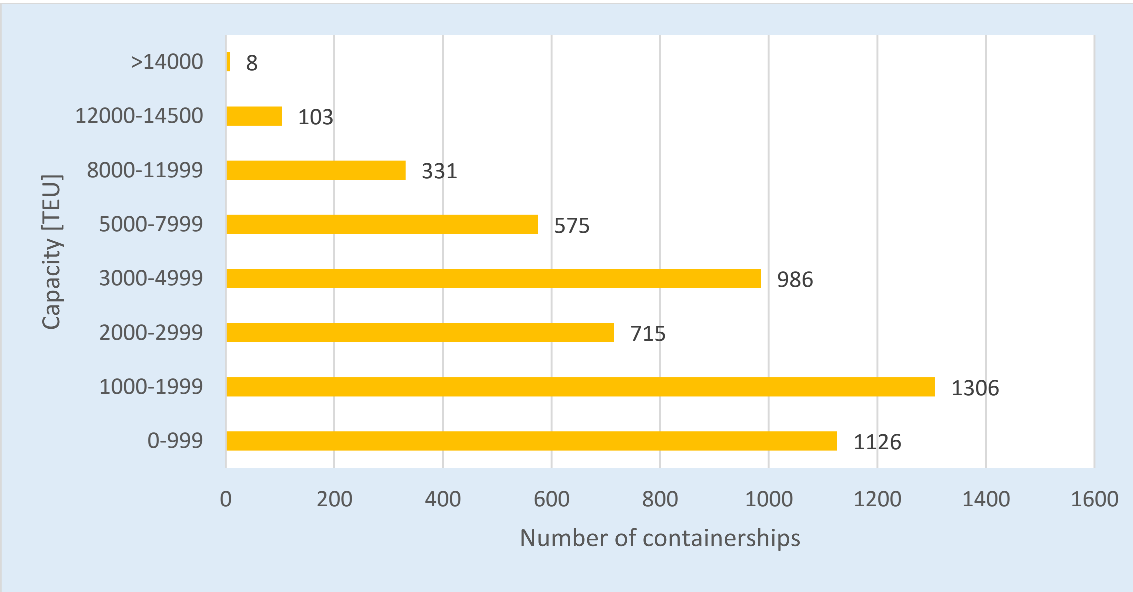


Figure 2.14: Number of containerships for TEU capacity
Adapted from: (IMO, 2014), Table 14

Indeed, according to (Murray, 2016), there are indisputable benefits in using larger vessels. Such study claims that there are three economies of scale in container ship market. Namely, there is a marginal decrease in cost as ship size increases hence larger ships are cheaper than smaller ones. The three economies of scale are related to three costs sources as listed below:

→ **Economy of scale in capital cost**: in 2015 the average construction cost of a containership was 64 million USD, whereas the cost for a vessel with a capacity higher than 13300 was about 140 million USD (Murray, 2016). Dividing the construction cost of a vessel by his TEU capacity it clearly appears the evidence of an economy of scale as shown in figure 2.15;

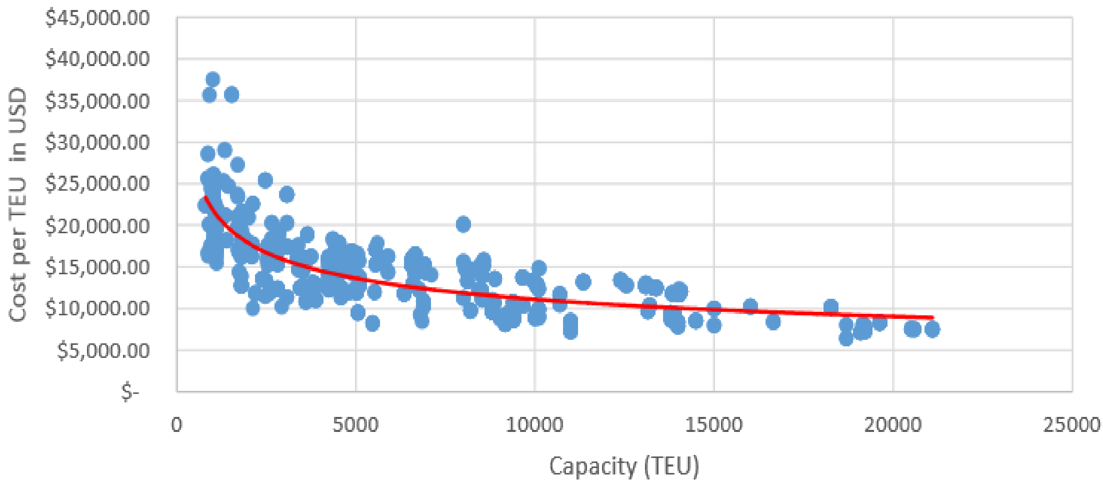


Figure 2.15: Construction cost of a container ship per TEU
Source: (Murray, 2016)

→ **Economy of scale in fuel consumption**: as depicted in figure 2.16, the fuel burned per day for transporting a TEU decreases as the vessel capacity increases. This means that the number of transportable TEU increases faster than the fuel consumption for an increasing ship's capacity;

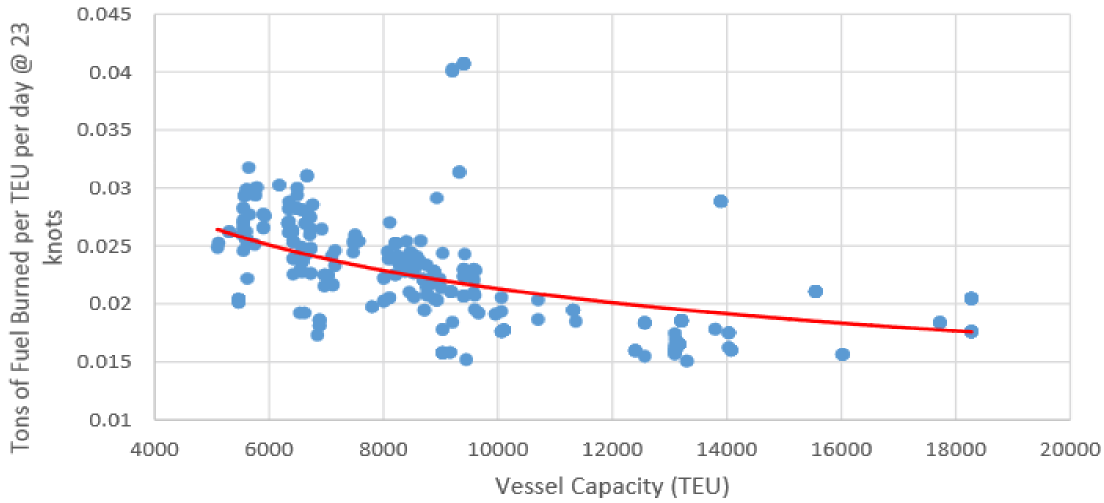


Figure 2.16: Fuel consumption of a container ship at 23 knots per TEU per day
Source: (Murray, 2016)

→ **Economy of scale in operating costs**: in figure 2.17 contains the curves with regard to the daily operating cost per TEU as the vessel capacity varies. Another time, the cost per transported TEU is lower for larger vessels, hence an economy of scale is also present as regards the operating costs;

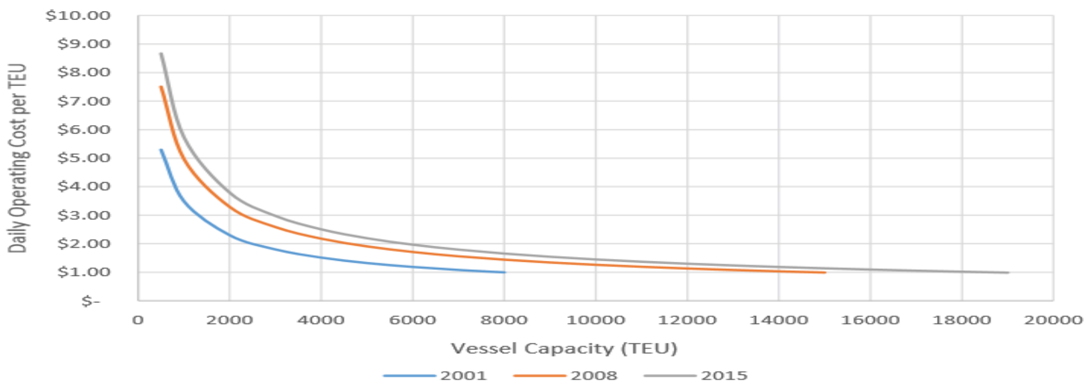


Figure 2.17: Fuel consumption of a container ship at 23 knots per TEU per day
Source: (Murray, 2016)

Despite the presence of such economies of scale, it is not straightforward assessing the actual impact of employing larger vessels into the freight market. Indeed, (UNCTAD, 2016) states that larger ships may shrink the unit costs for carriers, however the overall costs of handling these huge vessels regarding their management and the related logistic system required might outweigh such benefits. For example, employing larger vessels leads to require more transshipment operations and less direct services, as less vessels provide the same transport capacity. Furthermore, the increasing demand of larger containerships entails an amplification of the overcapacity issue, which is addressed in chapter 4.

CHAPTER 3
ENVIRONMENTAL EFFECTS

It is well-accepted that human activities are leading to an increase of the global average temperature as shown in figure 3.1. due to the pollutant gases emissions. Fossil fuels produce the emission of several gases when are burned, some of which are called greenhouse gases (GHGs). These gases are the responsible for the climate change, which will entail many catastrophic consequences, such as rising sea level, loss of bio-diversity, mass migration along with all the predictable consequences concerning international diplomacy and the plausible beginning of new conflicts. In the GHG list are comprised numerous gases such as CH_4 and N_2O, nevertheless the most relevant is surely the carbon dioxide whose chemical formulation is CO_2 (these three are the main GHGs for shipping). Their interaction with the sun light, within the infrared range of wavelength, causes the so-called Greenhouse Effect. Basically, these gases partially absorb the sunlight reflected by Earth. Therefore, a higher content of GHG in the atmosphere implies an increase of temperature, being the average temperature on our planet principally affected by the energy balance of incoming and outgoing solar energy. This physical phenomenon allows maintaining an average temperature on Earth, which permits to establish suitable conditions for life, otherwise this temperature would not be reached.

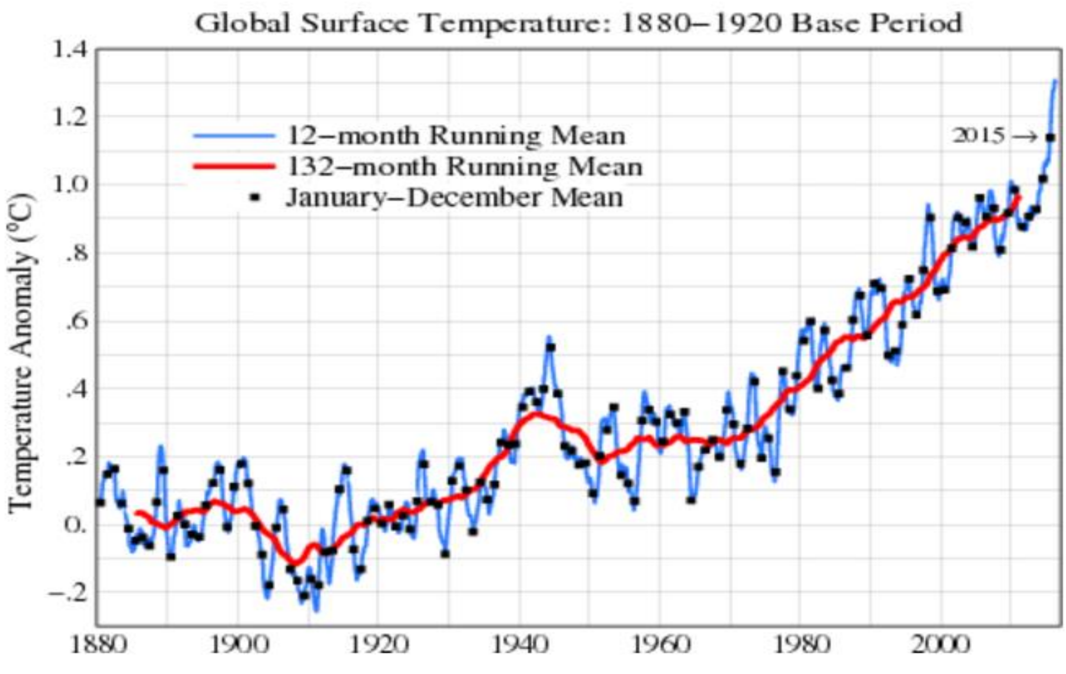


Figure 3.1: Temperature anomaly from 1880 to 1900
Source: www.co2.earth, 31-10-2016

Therefore, such effect it is necessary however the recent increase of GHG in the atmosphere has alarmed the whole scientific world. Since the Kyoto protocol in 1997, the environmental effect of the human activities has been deeply examined and several measures and policies in order to curb the emissions of GHG in the atmosphere were developed. Indeed, in the recent years, a new concept of developing has arisen which considers not only the economic aspects but also the environmental and social effects, as shown in fig 3.2. Such idea is called Sustainable Development.

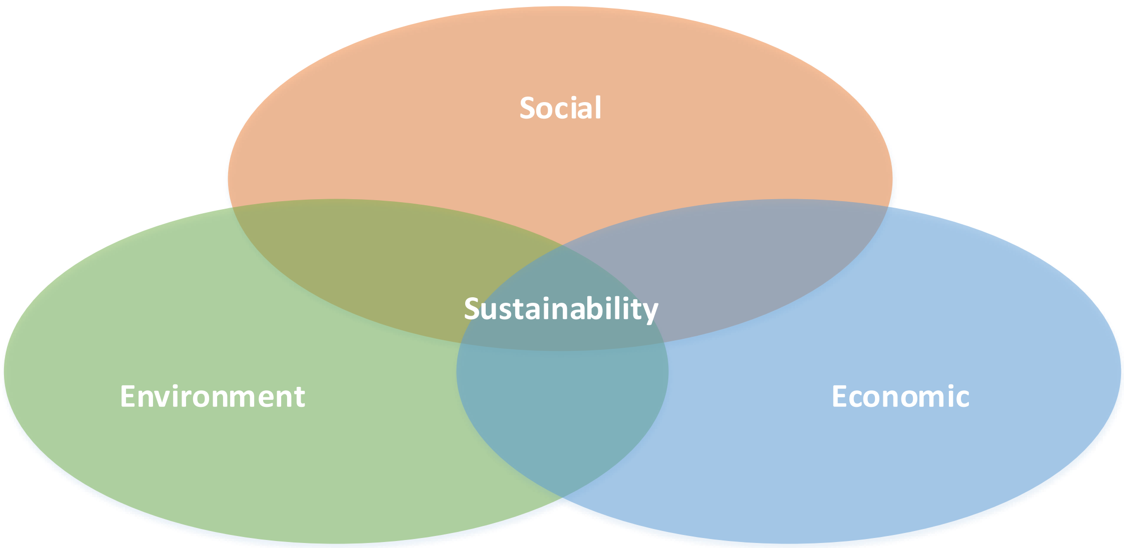


Figure 3.2: Sustainable development
The Venn diagram shows that sustainability involves aspects regarding environmental, economic and social feasibility. Indeed, the new concept of sustainable development evaluates the effectiveness of a project or a product not only taking into account the economic aspect but also its social and ecological impact

This increasing commitment to arrest the global warming led to hold the United Nations Climate Change Conference in December 2015 in Paris. The main aim of such convention, as described in the article 2 of the agreement is: "Holding the increase in the global average temperature to well below 2 °C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5 °C above pre-industrial levels, recognizing that this would significantly reduce the risks and impacts of climate change" (source: Text of the Paris Agreement). Nevertheless, a lot of criticism have surfaced regarding this agreement because there is not a legal commitment but it is all based upon promises (www.theguardian.com/environment/2015/dec/12/james-hansen-climate-change-paris-talks-fraud, 31-10-2016). This section deals with the emissions in the maritime transport and assesses the weight of such transport through several data and statistic, principally reported in (IMO, 2014) and (Psaraftis, 2012). Besides, the measures available as well as the methods to evaluate their economic effectiveness are analysed.

3.1 Evaluation Methods

Before examining all the statistics regarding the emission in maritime transport is meaningful to be aware how these figures are obtained. There are fundamentally two main methods for computing the CO_2 emissions that are produced by a specific transport means (Psaraftis and Kontovas, 2009):

→ **Bottom-up approach**: the emissions are calculated using simulation models calibrated on the ships activity;

→ **Top-down approach**: this method basically computes the total emissions through the fuel sales data;

Estimates vary in respect to which of these two approaches is employed, besides the results are also affected by how data are elaborated and which assumption are made. In figure 3.3 are reported the result of the third IMO study as example of the relevant differences in the results between the bottom-up approach and the top-down approach.

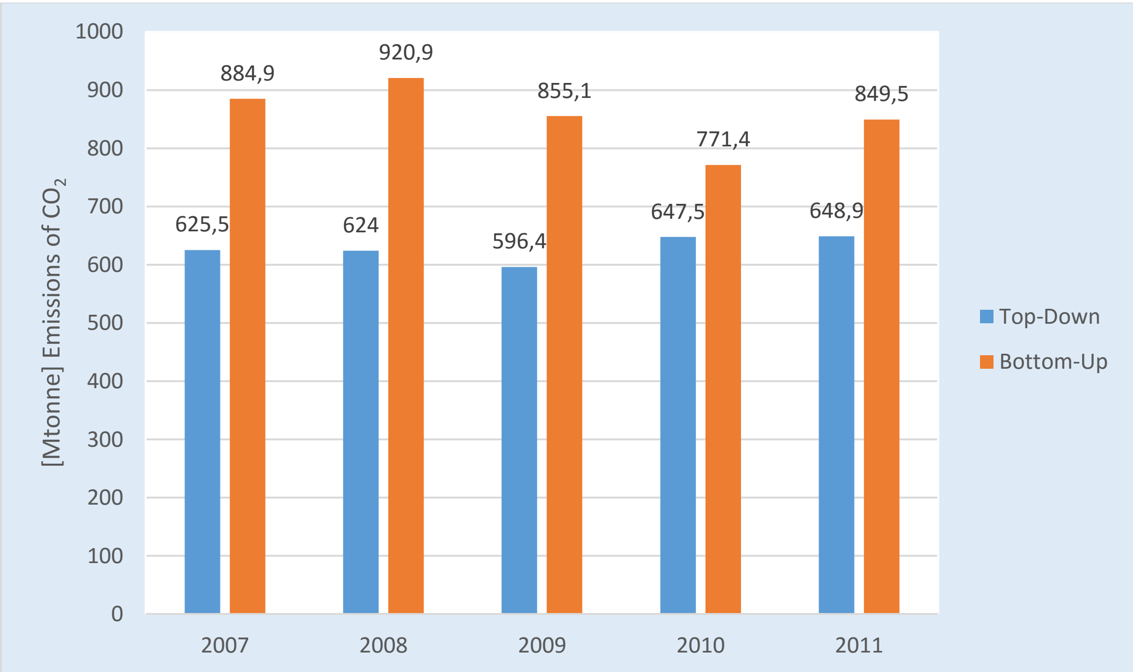


Figure 3.3: CO_2 emissions for the Top-Down approach and the Bottom-Up approach
This graph regards the emissions of the international shipping.
Adapted from: (IMO, 2014), Table 2 and Table 3

3.1.1 TOP-DOWN APPROACH

The top-down approach is based on the fuel sales data, indeed it is also called "fuel-based". Fundamentally, this method consists in computing the emissions multiplying the amount of fuel sold by the CO_2 emission factor. Usually, in the maritime field different type of fuels are used for the main engine and the auxiliary engine. Ships principally use oil-based fuels such as HFO (heavy fuel oil) and MDO (maritime diesel oil). Therefore, if different fuels are taken into account, the total CO_2 emissions, $Emissions_{CO_2}$ [tonne], can be calculated by the following equation:

$$Emissions_{CO_2} = \sum_i FS_i \, EF_{CO_2,i} \tag{3.1}$$

Where FS_i is the amount of fuel sold ith [tonne] and $EF_{CO_2,i}$ is the emissions factor of such fuel. The value of emissions factor for the typical maritime fuel are reported in section 3.1.1. The data regarding the fuel sales are collected from database provided by the Energy Information Administration (EIA), the International Energy Agency (IEA) and the United Nations Framework Convention on Climate Change. For example, the IEA is the data source used in the inventory of CO_2 emissions elaborated by (IMO, 2014). This approach would be the most reliable however the data about fuel sales are sometimes considered not dependable[2]. Indeed, the results obtained from the top-down approach considerably differs from those furnished by the bottom-up approach.

3.1.2 BOTTOM-UP APPROACH

The bottom-up method computes emissions by modelling the fleet activity, indeed this method is also called "activity-based". Namely, this means that some activity data are required, such as travelled kilometres per year or day at sea per year. These activity data are then multiplied by some emission factors such as fuel consumption per km in tonnes or daily fuel consumption in tonnes respectively. Obviously, it is difficult to calculate a proper value of these emission factors hence many uncertainties are present in such studies. For instance, the fuel consumption per day of a vessel is a function of the sailing speed as well as of the payload and other factor therefore in order to compute the daily fuel consumption it is necessary to be aware about the vessel's speed, the payload and other activity features. Moreover, once the daily consumption for the single ship is estimated, by this value it has to be calculated the global fleet's total emissions and this is not a trivial challenge. Indeed, the sailing speed as well as the other activity

[2]The reasons that lead not to rely on fuel sales' data are reported in (Psaraftis and Kontovas, 2009)

characteristics are different for each vessel, moreover these sort of data is not available, especially on a global scale. As a consequence, many assumptions a simplification are required. As an example, (Psaraftis and Kontovas, 2009) provide a study which estimate the CO_2 emissions of world commercial fleet, using the bottom-up approach. In this study, assuming the operative days per year, the time at sea hence the time in port and finally the daily fuel consumption at sea and the daily fuel consumption in port, the yearly emissions are computed for several size brackets and for different types of vessels such as container ships, tanker ships and bulk carriers. Some results of this study are reported and elaborated in the next section. Another example can be (Gkonis and Psaraftis, 2012) into which the emissions of the global fleet of a specific tanker segment are estimated. Such study takes into account that the speed depends on both the bunker price and the freight rate, thus allowing to evaluate how these two factors influence the amount of emissions produced. According to (IMO, 2014), the best estimate for years' emissions for GHG is provided by the bottom-up approach hence the results obtained from such analysis must be considered as benchmarks. Therefore, all the data provided in this thesis refers to the bottom-up method.

3.1.3 EMISSION FACTORS

The emission factors *EF* are fundamentally coefficients that allow evaluating the emission of a certain gas. Multiplying the *EF* by the fuel consumption *FC*, for example in [tonne/day], permits to compute the amount of emissions *E* produced by burning the fuel:

$$E = FC\ EF \tag{3.2}$$

In fact, the *EF* is the number of gas tonnes produced per tonnes of burned fuel. The common values of *EF* are reported in table 3.1 for three different types of fuel, regularly used in maritime transport. However, in some articles a unique emission factor is used for each type of fuel. For instance, this was made in the first IMO GHG study of 2000 (Psaraftis and Kontovas, 2009) wherein the *EF* is equal to 3.17.
Similarly, the emission factors are furnished for each GHG and more in general for each pollutant agent whose environmental impact must be evaluated.

CO_2 Emissions Factors	
Fuel	**Emissions Factor**
HFO	3,021
MDO	3,082
LNG	2,7

Table 3.1: Emissions factor for HFO, MDO and LNG
The EF are in tonne of CO_2 produced per tonne of fuel burned.
Adapted from: (Psaraftis and Kontovas, 2009)

Instead, in (IMO, 2014) a different value for the CO_2 emission factor is provided, which is higher than the previous, as shown in table 3.2, such values are employed in the thesis to evaluate the emissions of the fleet. LNG contains less carbon than the other fuels hence the emissions of CO_2 are lower. Nevertheless, using LNG increases the CH_4 emissions (methane slip is the proper name for methane that is not used as a fuel and basically escapes into the atmosphere) hence the net effect of employing this type of fuel is a reduction by 15% of CO_2eq.

CO_2 Emissions Factors (IMO, 2014)	
Fuel	**Emissions Factor**
HFO	3,114
MDO	3,206
LNG	2,750

Table 3.2: Emission factor provided by the third IMO GHG study
The EF are in tonne of CO_2 produced per tonne of fuel burned.
Adapted from: (IMO, 2014), Page 248

Besides, in order to evaluate the effectiveness of using a specific fuel, it is also necessary to take into account the SFOC's value (Specific Fuel Oil Consumption) for each type of bunker. Indeed, this parameter allows assessing the grams of fuel required to maintain a given power for one hour. This value depends on the vessel's speed, however some values are reported in table 3.3 as indicative values.

SFOC [g/kWh]	
Fuel	**Specific Fuel Oil Consumption**
HFO	215
MDO	205
LNG	166

Table 3.3: SFOC for different fuel type
Data source: (IMO, 2014), Table 24

3.1.4 CARBON DIOXIDE EQUIVALENT

As said in section 3, the main GHG is the carbon dioxide however also the methane CH_4 and the nitrous oxide N_2O are greenhouse gases. These two gases are produced when the fuel is burned as well as the CO_2. Therefore, their influence on pollution must be taken into account when emissions are computed. In order to assess the environmental effect of CH_4 and N_2O is introduced a new concept: the carbon dioxide equivalency *CO_2e*. As claimed in (IMO, 2014) the carbon dioxide equivalency is "a quantity that describes, for a given amount of GHG, the amount of CO_2 that would have the same global warming potential (GWP) as another long-lived emitted substance, when measured over a specified timescale (generally, 100 years)". The GWP expresses the contribution of a gas on the greenhouse effect relatively to effect of CO_2. The GWP is equal to 25 and 298[3] for methane and nitrous oxide respectively, considering a time scale of 100 years. This means that one tonne of N_2O has the same consequence upon the greenhouse effect of 298 tonnes of CO_2.

Table 3.3 reports the CO_2e for each GHG and points out as the carbon dioxide is by far the most influential greenhouse gas, being responsible of the pollution about by 98%. As consequences, this thesis does not consider the pollution derived by N_2O and CH_4, as it remarked in section 4.2.

CO_2e Emissions [Mtonne]

	2007	2008	2009	2010	2011	2012
CO_2	884,900	920,900	855,100	771,400	849,500	795,700
CH_4	5,929	6,568	6,323	7,969	9740	9,742
N_2O	12,152	12,689	11,860	10,615	11,473	10,931

Table 3.4: CO_2e emissions for GHGs in million tonnes produced
This graph regards the emissions of the international shipping.
Adapted from: (IMO, 2014), Table 19

[3] IPPC Fourth Assessment Report, Climate Change 2007-The physical science basis, Table TS.2

3.2 Global Emissions

According to (IMO, 2014) and as reported in table 3.4, maritime transport's contribution on the global CO_2 emission amounts about by 3%. As reported in (Eide et al., 2009), if global shipping was treated as a country, it would be considered the sixth larger producer of GHG all over the world, that is above the Germany's ranking position. Moreover, international shipping is far more pollutant than domestic shipping, weighing for about the 2,2% of the total emissions in 2012. The weight of the shipping transport on the global CO_2 emissions is currently decreasing: in fact, the shipping share was by 3,5% in 2007 whereas his contribution has decreased by up to 2,6% in 2012. Besides, the overall amount of tonnes emitted has decreased, diminishing from 885 million of tonnes in 2007 to 796 million of tonnes in 2012.

Global and Shipping CO_2 Emissions [Mtonne]

	Global	Shipping	Percentage of global	International shipping	Percentage of global
2007	31409	1100	3,5%	885	2,8%
2008	32204	1135	3,5%	921	2,9%
2009	32047	978	3,1%	855	2,7%
2010	33612	915	2,7%	771	2,3%
2011	34723	1022	2,9%	850	2,4%
2012	35640	938	2,6%	796	2,2%

Table 3.5: Global and shipping CO_2 emissions in 2007-2012
International shipping is defined as shipping between ports of different countries, as opposed to the domestic shipping, which is defined as shipping between ports of the same country. These definitions involve that the same ship is usually employed both in domestic and international shipping market. Besides, both fields do not consider military and fishing vessels.
Adapted from: (IMO, 2014), *Table 1*

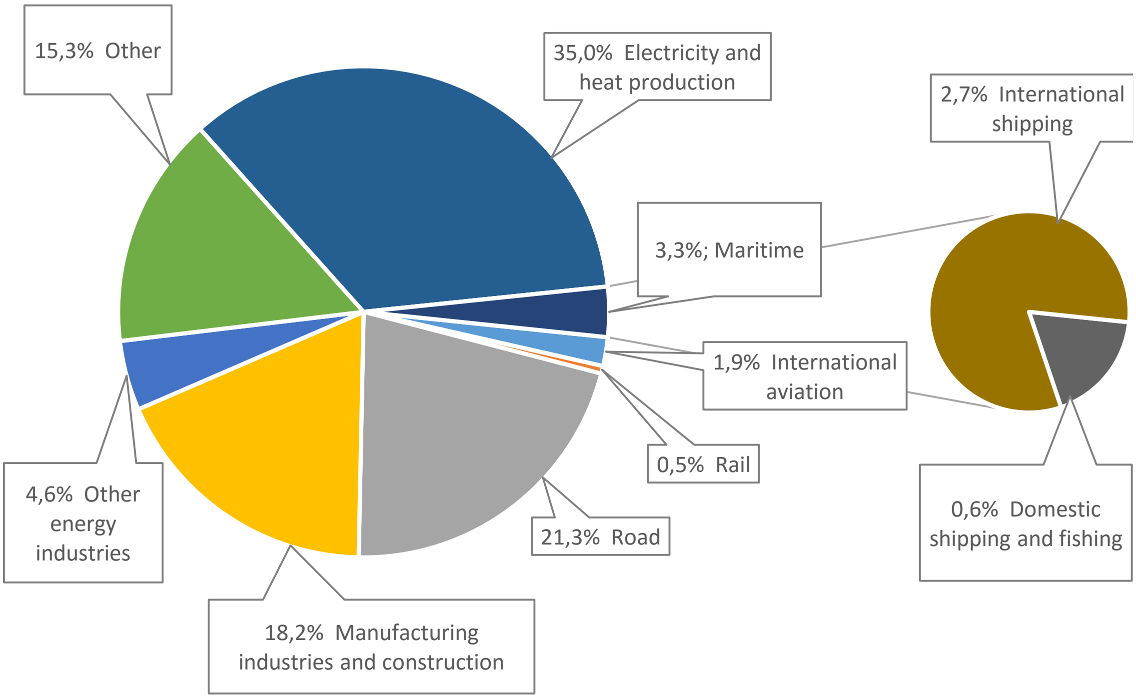


Figure 3.4: CO_2 emissions from shipping compared with global total emissions
Data source: (IMO, 2009), Figure 1-1

This decrease is not correlated to a contraction in the demand for maritime transport services. Indeed, over the last few years the volume of world seaborne shipment has grown, as stated in (UNCTAD, 2015). The cause is likely attributable to use of slow steaming. Slow steaming is a measure adopted by carriers in order to cut fuel consumption and relative costs. Furthermore, the slow steaming practice mainly appeared in order to deal with the depressed market condition due to The section 4.1.3 treats slow steaming in detail; nevertheless, it is sufficient being aware that this practice allows to reduce ships emissions as well as facing the market conditions

Figure 3.4 shows the quantities of emissions per cargo transported regarding the international shipping, called emission-activity index, whereby the fleet's emissions trend can be evaluated, taking into account of his throughput. The emission-activity index decrease proves the previous statement. In fact, despite of the increasing transport demand the international fleet has emitted less CO_2 in the atmosphere hence this implies that the average CO_2 emission per vessel has diminished.

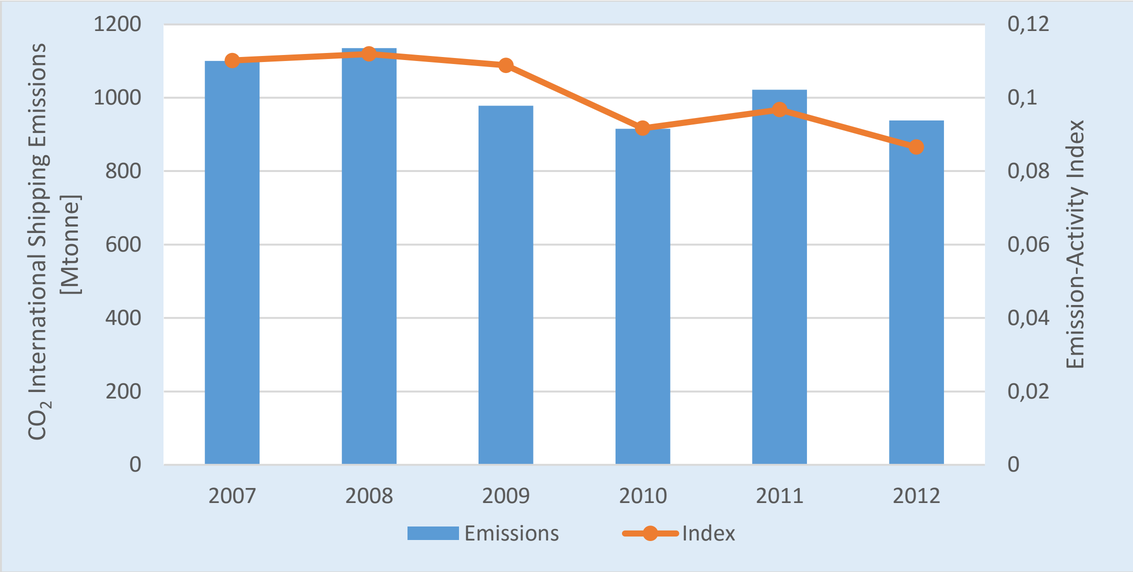


Figure 3.5: CO_2 shipping emissions and emission-activity index
The emission-activity index[4] is the ratio between the emissions of CO_2 produced in Mtonne and the load transported in Mtonne. In 2009 the emissions reduction is caused by a contraction of the demand. Indeed, the index has almost the same value of the previous year hence the emissions contraction is surely due to a reduction in the required services.
Data source: (IMO, 2014), Table 1 and (UNCTAD, 2015), Figure 1.2

3.2.1 International Shipping Emissions

Principally, international shipping emissions are composed by those in three seaborne transport sectors:

→ Container

→ Crude oil tanker

→ Bulk carrier

These three shipping markets are accountable for 63% of the total CO_2 emissions produced by the international fleet, as shown below in figure 3.6. Other influential sources of emissions are chemical tanker, general cargo carriers and liquefied gas tankers.

[4] See appendix B for the calculation method

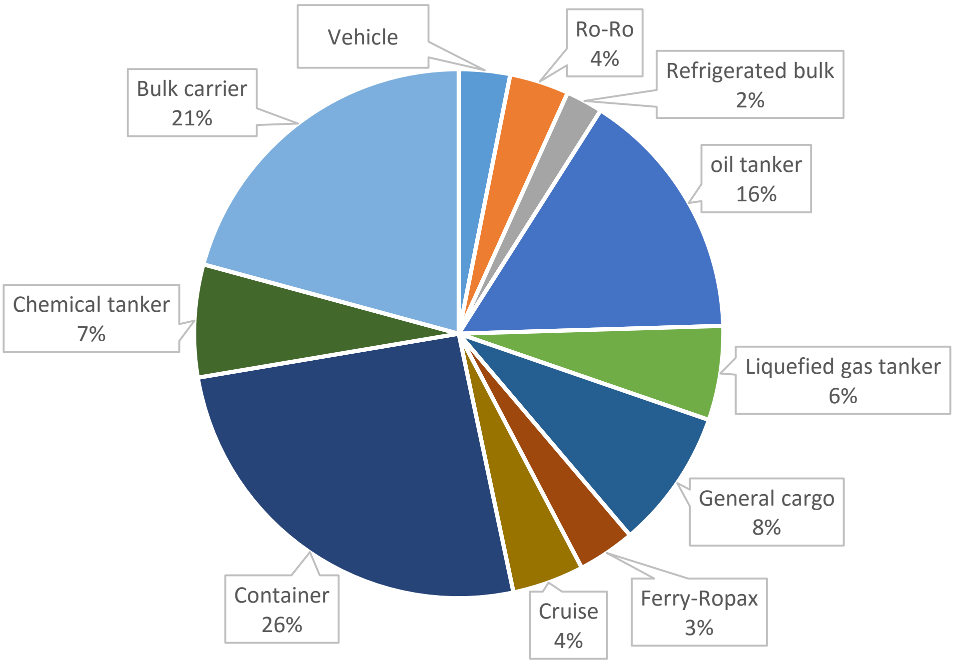


Figure 3.6: CO_2 emissions from international shipping by ship type
Data Source: (IMO, 2014), Figure 27

This section is based upon (Psaraftis and Kontovas, 2009) whose study regards an estimation of CO_2 emissions of the world commercial fleet subdivided into ship-type and size brackets. The article employs the bottom-up approach whereby is compute an interesting parameter regarding the efficiency of container, oil tanker and bunker carriers. Such parameter is the *CO_2 emission efficiency* (IMO, 2009) evaluated in [(gramsCO_2)/(km tonne)] and defined as (Notice, the term efficiency is misleading. Indeed, one would like that such efficiency takes the as low as possible value):

$$CO_2 efficency = \frac{CO_2}{Tonne\ Kilometer} \tag{3.3}$$

Where *CO_2* is the carbon dioxide emitted [gram] and *Tonne Kilometre* is the number of work done measured in cargoes transported [tonne] and leg travelled [km]. All these factors are evaluated for a given period, typically per year. This analysis allows to make some considerations regarding the environmental impact of the international shipping. Moreover, the *CO_2 emission efficiency* values provided in this section are used to furnish a comparison among the shipping transport and the other transport means in section 3.4.
The results of (Psaraftis and Kontovas, 2009) regarding the yearly emissions produced by containerships, crude oil tanker and dry bulk carriers are reported in figure 3.7. Such results show that containership bracket is significantly the most pollutant. In fact, his emissions are about double the emission of the dry bulk brackets (the ratio is equal to 1,78) and almost three times if compared to the crude oil tanker segment's emissions (the ratio is equal to 2,54). The containerships produce higher emissions because of their

higher sailing speed, as discussed in section 4. Indeed, a higher speed entails higher CO_2 emissions.

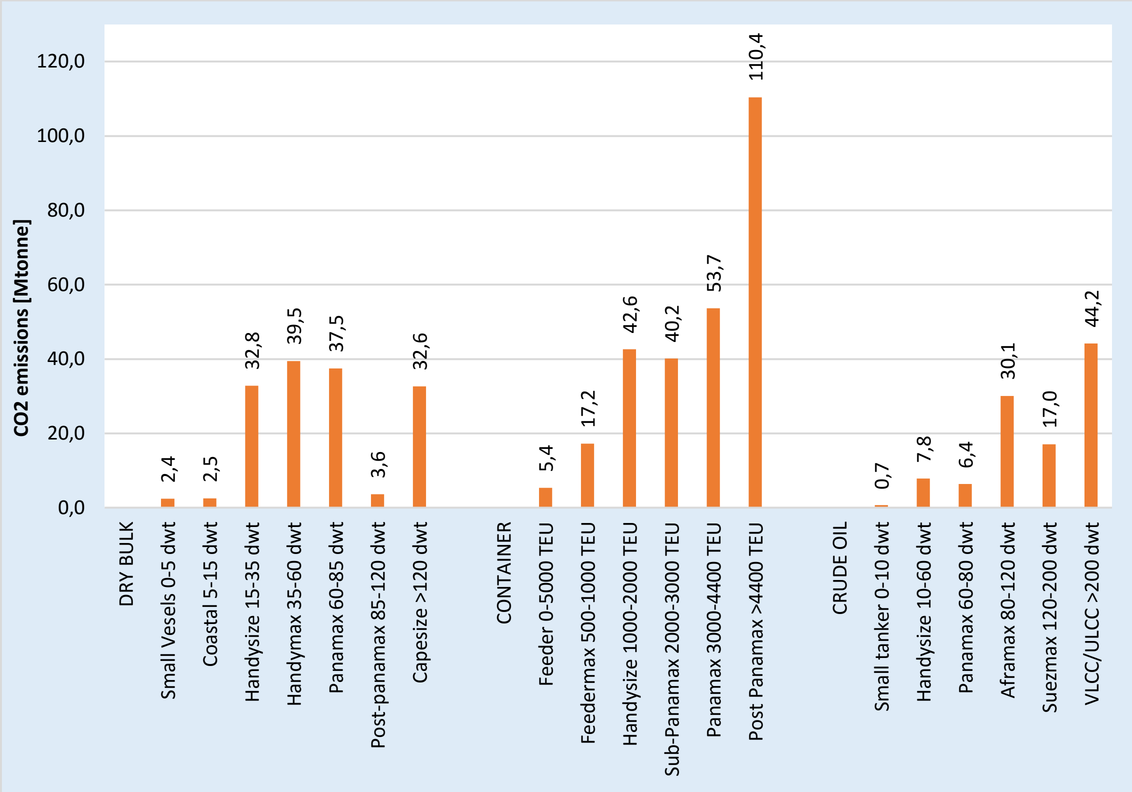


Figure 3.7: CO_2 emissions for size bracket for containerships, oil tanker and bulk carriers[5] Adapted from: (Psaraftis and Kontovas, 2009)

Figure 3.8 reports the emissions percentage for each size bracket within the containership class. Post Panamax vessels produce 41% of the containerships' emissions. Besides, the containerships' size bracket Post Panamax results to be by far the most pollutant, emitting more than the whole tanker group. Finally, the CO_2 emission efficiency values for each class are displayed in figure 3.9. The efficiency for each ship type follows the same trend, being higher for small vessels and significantly lower for large vessels. As regards containerships, the efficiency trend is less sharply compared to the trend of dry bulk ships and crude oil ships. This observation is correlated to the economy scale discussed in section 2. In fact, the CO_2 efficiency is connected to the ship's fuel consumption since the emissions are correlated to the fuel consumption through the emission factor. Therefore, a lower value of the emissions efficiency implies a lower fuel consumption per work done. In brief, larger ships are more efficient as regards both economic reasons and environmental reasons.

[5] The dwt (dead weight tonnage) are expressed in thousand tonnes

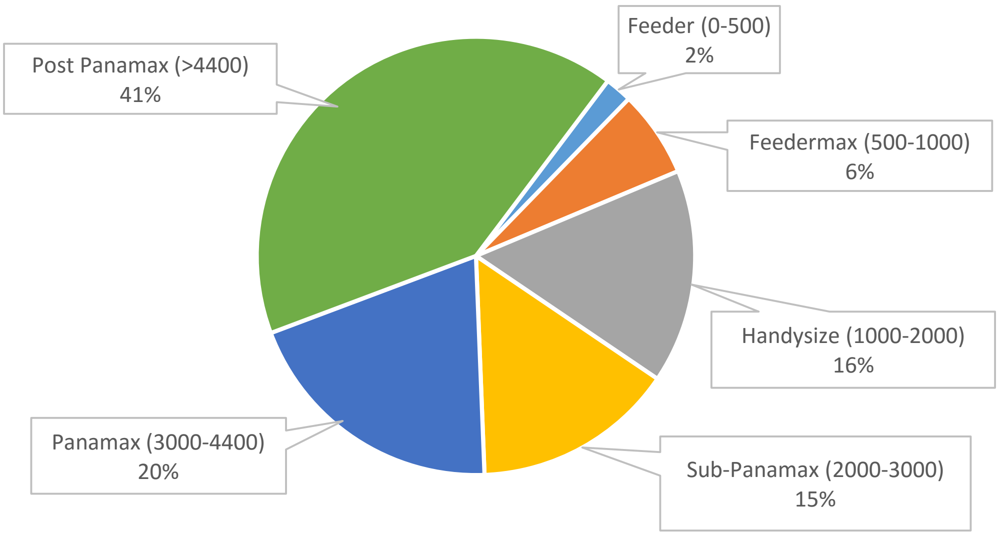


Figure 3.8: CO_2 emissions in container liner shipping for size segment
The values in brackets are the vessels' capacity range in TEU
Adapted from: (Psaraftis and Kontovas, 2009)

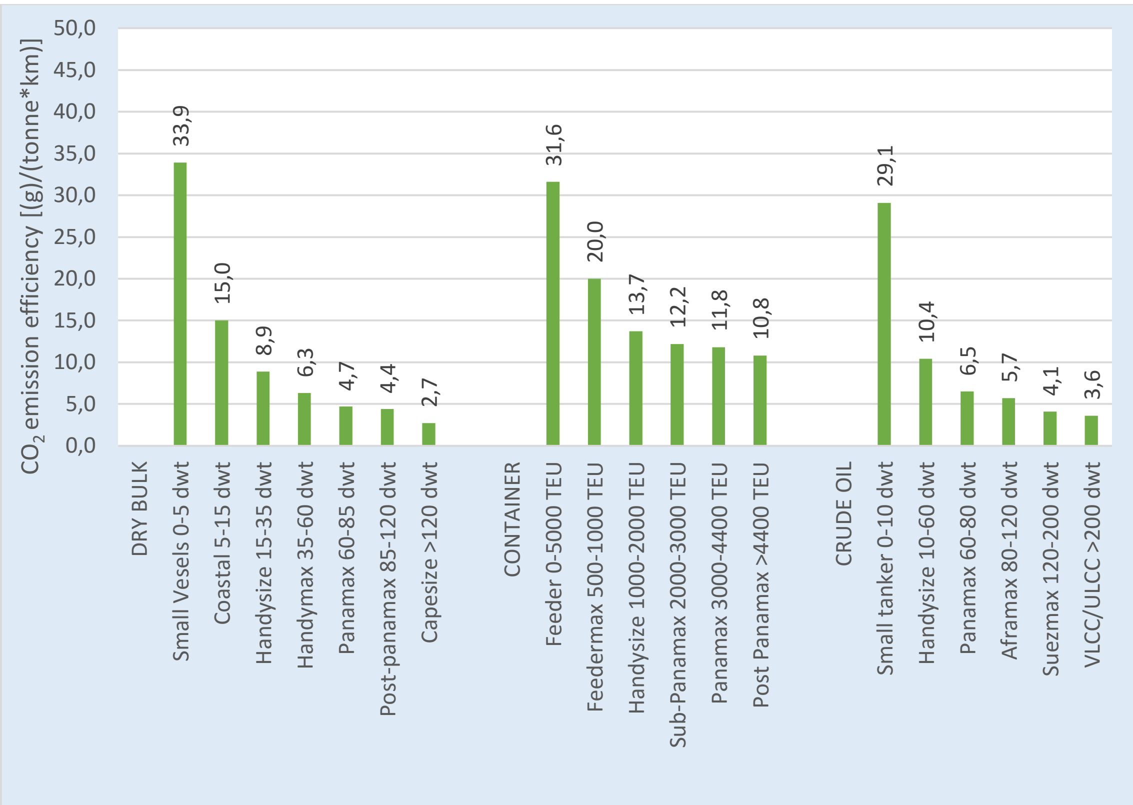


Figure 3.9: CO_2 emissions efficiency for size bracket for containerships, oil tanker and bulk carriers
Adapted from: (Psaraftis and Kontovas, 2009)

3.3 EMISSIONS REDUCTION MEASURES

The significant impact of maritime transport upon the global emissions and the projects, which shows an increasing trend, has forced the international community to work on several measures able to abate the amount of CO_2 produced. The International Maritime Organization (IMO) is currently in charge to develop the most suitable approach, which is able to obtain the emissions reduction required in the shipping market. This challenge is non-trivial since in the shipping market are employed both different type of vessels and operational practices which complicate the evaluation of such measures. Indeed, as said in section 2, the maritime transport is a variegated market whose characteristics vary in respect to the specific branch examined. Moreover, the effectiveness of the proposed solution should involve the interest of both stakeholders concerned, i.e. ship owners and shippers. These solutions frequently allow achieving significant economic benefits since such measures involve fuel savings hence permitting to reduce the bunker expenditure, which is a significant cost source. As reported in (Cariou and Cheaitou, 2014), IMO has established the aim of a 30% GHGs reduction by 2030 (based on the 1990 levels).
According to (Gkonis and Psaraftis, 2012), the reducing measures can be divided in three categories:

→ **Technological measures**: this category includes several measures such as employing more efficient engines, cleaner fuels and other technological improvements. A complete survey concerning the technological measures is provided in (IMO, 2009) and it comprises the information on emission reduction which these solutions allow to achieve;

→ **Logistic-based measures**: also called operational measures, this class includes all the measures related to an improvement in the logistic efficiency such as speed optimization and optimized weather routing;

→ **Market-based measures**: MBMs are policy-makers' instruments that employ economic variables of the market (for example prices or fees) in order to provide incentives for polluter to reduce environmental externalities. This category comprises the adoption of regulatory, such as carbon tax and fuel levy. MBMs can influence the technological and logistic-based measures that are employed by ships owner. For instance, the issuance of a carbon tax would lead ship owners to emit less CO_2 hence it would lead to employ more efficient engines, or other reducing measures. Briefly, a MBM influences economically the market's conditions, making valuable the employment of technological and logistic-based measures.

In table 3.6 are reported several available measures in order to reduce the CO_2 emissions. Additionally, in the same table are reported the CO_2 savings obtainable using such measures. Subsequently, it is provided a review regarding the Energy Efficiency Design Index (EEDI) and the most discussed MBM, that is the employment of a carbon tax.

Measures reducing emissions

Measure	Relative CO_2 savings	Percentage of application (2007-2011)
Speed reduction	17-34%	0-50%
Propeller and rudder upgrade	3-4%	0-0%
Hull coating	2-5%	0-50%
Waste heat recovery	2-6%	0-0%
Optimization of trim and ballast	1-3%	0-50%
Propeller polishing	1-3%	75-75%
Hull cleaning	1-5%	75-75%
Main engine tuning	1-3%	75-75%
Autopilot upgrade	1-1,5%	75-75%
Weather routing	1-4%	75-75%

Table 3.6: Measures reducing emissions and their cost-effectiveness
Adapted from: European Union, Time for international action on CO_2 emissions from shipping, 2013

3.3.1 Energy Efficiency Design Index

In July 2011, IMO adopted the Energy Efficiency Design Index (EEDI), which has defined the end of the unregulated era for shipping regarding CO_2 emissions. Currently, this index is the most important technical solution for reducing GHGs emissions from shipping. The EEDI is a mandatory index for newest ships produced and forces the ship designers to build ships with a minimum efficiency level. Indeed, the EEDI requires a minimum energy efficiency level per capacity mile (for example tonne mile) for different ship type and size segments, such as container ships, tankers and bulk carriers.

The new ships affected have to respect the limits required in the regulation, as follows:

$$Attained\ EEDI \leq Required\ EEDI \tag{3.4}$$[6]

$$Required\ EEDI = \left(1 - \frac{X}{100}\right) * Reference\ line\ value \tag{3.5}$$

Where X is the reduction factor and the reference line value has to be calculated using the coefficients obtained from a regression analysis. These parameters are reported in the regulation[7]. The following equation allows computing the EEDI, which estimates ship CO_2 emissions per tonne-mile:

$$EEDI = \frac{P * SFC * C_f}{DWT * V_{ref}} \tag{3.6}$$[8]

Where P [kW] is 75% of the maximum power of the ship's main engine, SFC [gfuel/kWh] is the specific fuel consumption, C_f is the CO_2 emission factor based on fuel type [gCO_2/gfuel], DWT [tonne] is the ship deadweight and V_{ref} [knots] is the ship's design speed. According to (Gkonis and Psaraftis, 2012), the EEDI imposes a limit on the ship's speed design. In fact, the denominator of the equation is a function of the design speed. Thus, this technological solution entails building more efficient vessels as well as a reduction of the design speed for new ships. However, this influence on the speed must not be confused with the slow steaming practice as slow steaming is a measures employed by ship owners to cut the fuel expenditure in specific market condition, as widely analysed in section 4.1.3.

3.3.2 Carbon Tax

A carbon tax is a form of explicit carbon pricing directly linked to the level of carbon dioxide emissions. This measure allows internalizing the currently external cost of the pollutant emissions. Basically, this means polluters would have to pay the social cost born by society currently, paying for their emissions. One of the most debated aspect with regard to such topic is the proper value that should be paid by polluters. Indeed, as reported in (Bergh and Botzen, 2015), the monetary evaluation of the social cost of CO_2 emissions is a discussed and troublesome challenge. The social cost of carbon (SCC) is

[6] Resolution MEPC.203(62), Annex 19, adopted on 15 July 2011
[7] Resolution MEPC.203(62), Annex 19, adopted on 15 July 2011, Pages 11-12
[8] (ICCT, 2011)

an estimation of the cost over time caused by CO_2 emissions produced [USD/tonne]. Since the SCC is computed through simulations, its value depends on which pollutant effects of CO_2 are considered and depends on which scenarios are taken into account in such simulation. Consequently, the results regarding the evaluation of the SCC are quite dispersive. It is clear that a proper evaluation of the carbon's social cost is the first step for implementing a carbon tax regulation.

Alternatively, the application of a bunker levy may be taken into consideration. Since the fuel consumption are linearly related to the CO_2 emissions, the impact of such solution would be the same of the one entailed by a carbon tax. Several studies deal with the effect of employing both carbon tax or bunker levy. For instance, (Cariou and Cheaitou, 2012) treat which impacts would entail different level of carbon levy within a containership route. As expected, the results show that applying a fuel fee leads ship owners to slow down their fleet employing more vessels in order to reduce the fuel consumption.

3.3.3 Marginal Abatement Cost Curve

The Marginal Abatement Cost Curve is the representation of maximum abatement potential for a set of reducing measures, which do not exclude each other. Then, these measures are subdivided by their cost efficiency, in this way the MACC describes which is the cost born per tonne of CO_2 averted for the set of measures involved. The maximum abatement potential of a measure is the maximum amount (generally in Mtonne) CO_2 that can be avert to emit in a year if all the vessels which can employing such measure make use of it. For example, according to (IMO, 2009) study concerning the projection for 2020, if all vessels apply a speed reduction by 10% the maximum abatement potential will be about 100 Mtonne of CO_2. The cost efficiency of a certain measure is the net costs for reducing a tonne of CO_2 emissions in a year. As explained in (Psaraftis, 2012), where the cost efficiency is called Marginal Abatement Cost (MAC), the cost efficiency *CE* [USD/tonne] for a certain measure can be computed as follow:

$$CE = \frac{NetCosts}{\Delta CO_2} \tag{3.7}$$

Where *NetCosts* is the sum of the costs due to the application of the measures minus the saving concerning the fuel consumption due to the measures, whereas ΔCO_2 is the emissions reduction achievable by implementing such measure. Indeed, the equation below can also be written as:

$$CE = \frac{Implementation\ costs - \Delta Fuel\ P_{bunker}}{\Delta CO_2} \tag{3.8}$$

Where $\Delta Fuel$ is the reduction of the fuel consumption [tonne] and P_{bunker} is the bunker price [USD/tonne]. Therefore, applying a certain measure whose CE is negative, is profitable and it may be applied without any MBM whereas if the CE is positive such measure may not spontaneously because it is economically disadvantageous. Since the CO_2 reduction is related to the fuel reduction through the emission factor EF:

$$\Delta CO_2 = EF\ \Delta Fuel \tag{3.9}$$

Therefore, the 3.8 can be written in order to reveal a significant characteristic of the MACC:

$$CE = \frac{Implementation\ costs}{\Delta CO_2} - \frac{P_{bunker}}{EF} \tag{3.10}$$

Indeed, equation 3.10 shows that the bunker price is a paramount parameter when a MACC is made. Since the emissions factor is constant the bunker price value can shift the curve hence applying a bunker levy has the same effect as his effect is basically increase the bunker price. Furthermore, can be easily demonstrated that the same effect can be produced by implementing a carbon tax. In fact, the equation 3.10 if a carbon tax is present can also be written as:

$$CE = \frac{Implementation\ costs}{\Delta CO_2} - \frac{P_{bunker}}{EF} - Ctax \tag{3.11}$$

Where $Ctax$ is the monetary value of the carbon tax [USD/tonne]. These remarks are reassumed in figure 3.7 where the effects of bunker price, bunker levy or carbon tax alternatively are depicted.

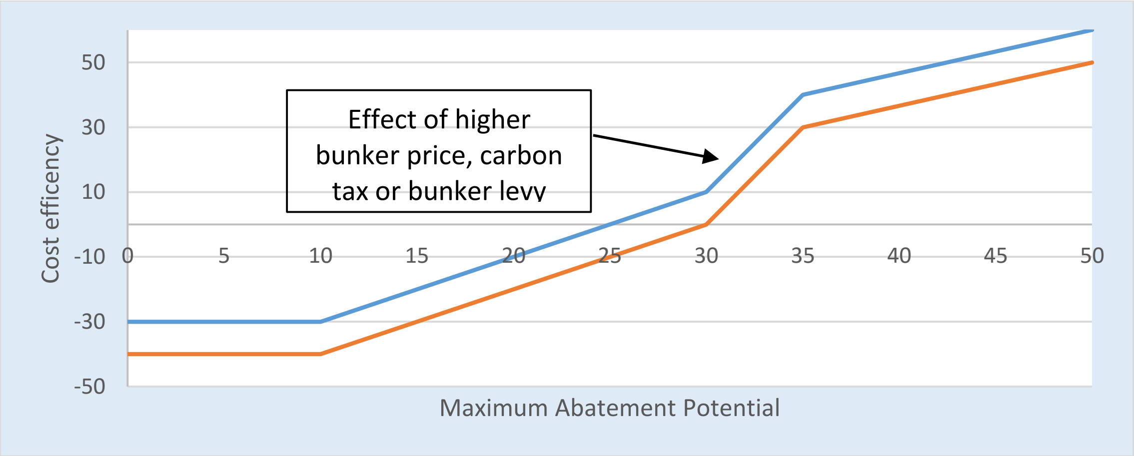


Figure 3.10[9]: Effect of a higher bunker price, a carbon tax and a bunker levy on a MACC

[9] This curve is not based on real data

Figure 3.11 is the MACC provided by (IMO, 2009) for 2020, considering three levels of bunker price. Moreover, in table 3.7 are reported the reducing measures involved in such analysis with their respective values concerning the cost efficiency and maximum abatement potential. As one can see, the cost efficiency for the speed reduction measure is positive. This is because in the IMO's study it is assumed that the decrease in the freight capacity due to the speed reduction is faced by deploying new vessels. As consequence, if these projections are correct, slow steaming will not be applied unless several MBMs will be implemented. Currently, as explained in section 4.1.3, the shipping capacity is higher than the supply demand hence a speed reduction does not involve new vessels but the idle capacity can be used for facing the decrease of freight capacity. Therefore, the current cost efficiency of speed reduction is negative. Such statement means that a speed reduction policy leads to environmental benefits as well as economic benefits. This claim is reported in many study. For several examples see chapter 4.

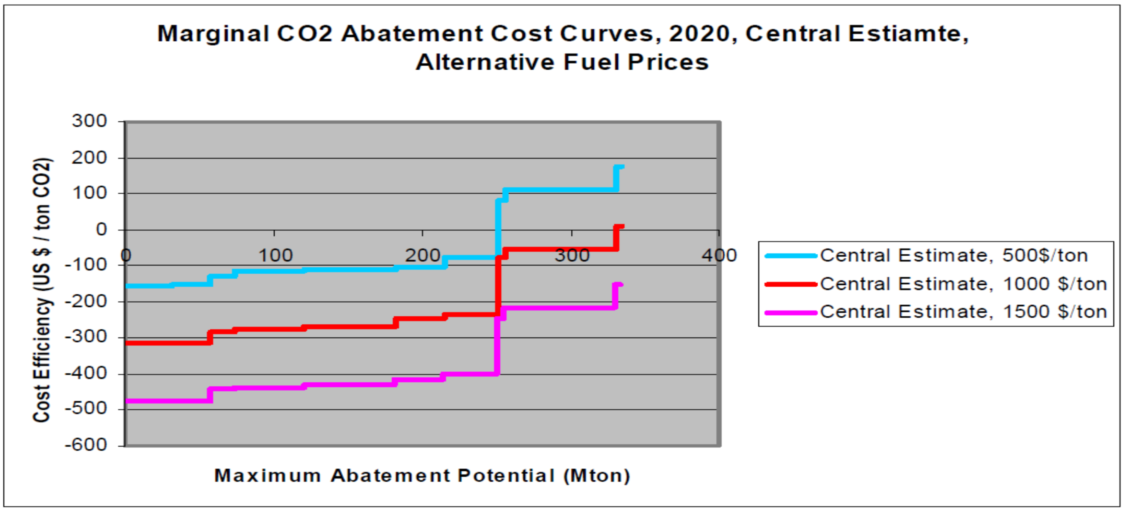


Figure 3.11: MACC in 2020 for three levels of bunker price
Source: (IMO, 2009), Figure A4.2

Reducing Measures

Measure	Cost efficiency [USD/CO_2tonne]	Maximum Abatement Potential [Mtonne]
Retrofit hull	-155	30
Voyage and operational options	-150	25
Air lubrication	-130	20
Propeller upgrades	-115	50
Other retrofit options	-110	70
Hull coating and maintenance	-105	40
Propeller maintenance	-75	45
Auxiliary systems	80	5
Speed reduction	110	100
Main engine improvements	175	5

Table 3.7: Cost efficiency and maximum abatement potential for several reducing measures
The cost efficiency for the speed reduction measure is positive. This is because in the IMO's study they assume that the decrease in the freight capacity due to the speed reduction is faced by deploying new vessels
Adapted from: (IMO, 2009), Table A-4.1

3.4 COMPARISON WITH OTHER TRANSPORT MEANS

The transport sector produces 7 GtCO_2eq in 2010 (including both passenger transport and freight transport) that is approximately 23% of total CO_2 emissions (IPPC, 2014). In spite of more efficient vehicles and policies being adopted, transport emissions are increasing at a faster rate than other sectors. This rise is due to the growth of the transport demand especially regarding the developing economies. Therefore, the environmental impact of the different transport means should be an influential attribute when shippers select how hauling their goods. The main freight transport means are:

→ Seaborne transport

→ Road freight transport

→ Rail freight transport

→ Air freight transport

Airfreight is the fastest transport mode however it is also the most expensive. This characteristic leads to employ airfreight only for types of cargoes wherein speed is an essential factor, such as perishable goods, critical spare part and vaccines. Rail transport and road transport are part of the land-based transport means: the first one, from an ecological point of view, is preferable; nevertheless, road freight is more flexible, allowing hauling goods everywhere all around the world. Electricity is usually an important source of energy for rail freight hence the evaluation of the emission efficiency for this type of shipment mode has to deal with the CO_2, which is emitted from the production of the electricity. The CO_2 emissions efficiency can be used in order to compare the environmental impact of these transport means. Indeed, this coefficient is used in all transport sector as a measure of the emissions produced per transport work made. Nevertheless, the CO_2 emissions efficiency is heavily influenced by several specific conditions characterizing the journey. For instance, the transport efficiency of rails depends by type of cargo, speed as well as transport efficiency of road is affected by traffic, type of road and other factors. Therefore, this analysis should be considered as a comparison between average value of efficiency, keeping in mind that any specific journey has features which could considerably change the proper transport mode. Besides, generally carriers will select for their cargoes the most convenient freight modes as long as the emissions are not regulated or included in their expenditures as internalized cost.

The main result of this comparison is that shipping is the most ecological shipment mode. As shown in figure 3.12, shipping achieves the best results for each ship type and only freight rail can be compared regarding the environmental efficiency. Therefore, shippers should be encouraged to employ shipping such as through market-based measures, allowing to decrease the emissions produced by the freight transport sector. Moreover, the potential saving in CO_2 emissions in shipping sector is by far more interesting whether compared to the saving achievable in the other transport modes or economic sector. Several studies claim that the shipping sector can save by up to 55% of CO_2 emissions (source: European Union, Time for international action on CO_2 emissions from shipping, 2013) by adopting some eco-friendly measures as reported in section 3.3, such as slow steaming and weather routing.

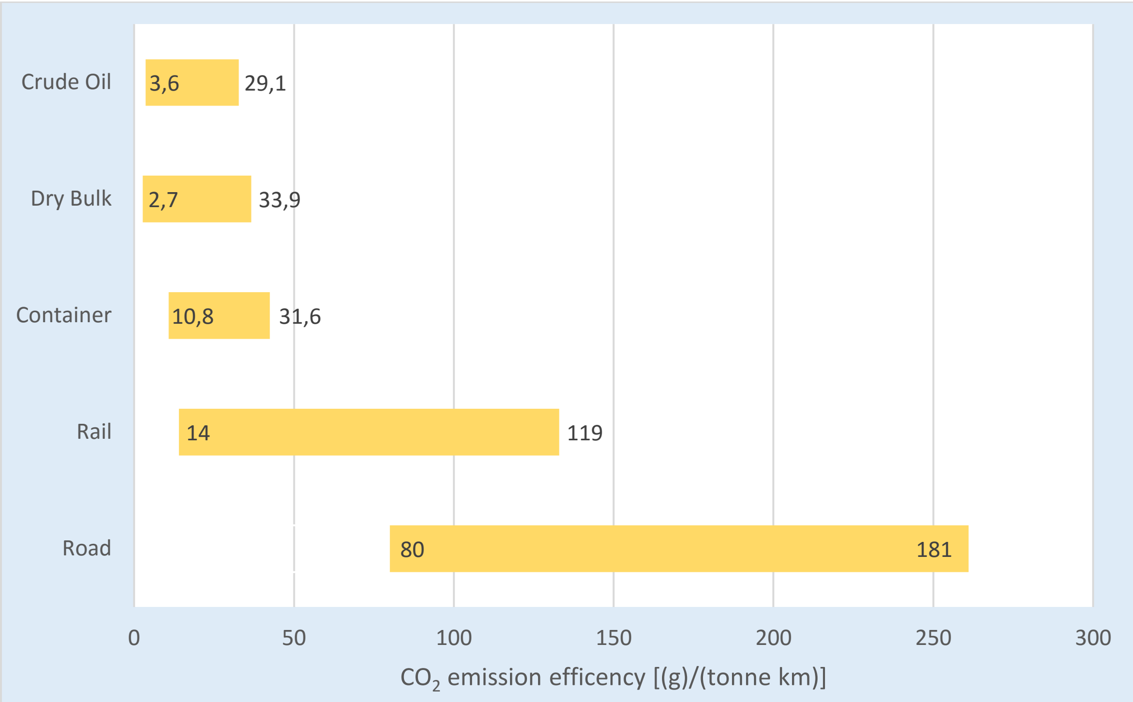


Figure 3.12: CO_2 emission efficiency: comparison of different transport means
The emission efficiency range for shipping are the minimum value and the maximum value present in figure 3.9, for each ship type respectively. Airfreight's range is not present in the graph since its value (435-1800) is too high to be compared with the others.
Adapted from: (Psaraftis and Kontovas, 2009) provide data regarding shipping whereas data regarding the other transport means can be found in (IMO, 2009), Chapter 9

A similar analysis is undertaken in the (IPPC, 2014) paper[10], which deals with the transport of passengers. In such study the CO_2 emission efficiency coefficient is evaluated as grams of carbon dioxide emitted per passengers-kilometres, that is the work-done parameter for the passenger transportation. The result of this study claims waterborne transportation is still a sustainable option as regards transport of passengers. Although, for this transport sector, rail mode and road transport are an efficient alternative.

[10] IPCC (2014), Climate Change 2014: Mitigation of Climate Change, Figure 8.6

3.5 FUTURE SCENARIOS

This section provides a brief summary concerning the development of a simulation model for estimating the emissions future scenarios. In particular, the attention is focused on the parameters and factors, which influence the future emissions of shipping sector. Moreover, the results reported in (IMO, 2009) and (IMO, 2014) are presented at the end of the section. Emissions scenarios are useful tools able to provide information to policymakers and other stakeholders with regard to the future impacts of shipping. This information allows evaluating the effects of policies and measures that aim to curb emissions.
(IMO, 2009) identifies the following categories, which contain the key driving variables:

→ Economy

→ Transport efficiency

→ Energy

The parameters for each category are assessed employing the “open Delphi process”. Fundamentally, the Delphi process relies on expert opinions and analysis and the base-concept of this method is that “judgments derived from multiple experts are generally more accurate than those of individual experts” as stated in (Rowe and Wright, 2001). Subsequently, the parameters’ values are applied to a model of global fleet emissions inventory calibrated using an inventory based on current data. Different scenarios are simulated through this method, principally based on the scenarios provided by the Intergovernmental Panel on Climate Change (IPPC) SRES storylines. These scenarios include various possible future development, for instance regarding future technological improvement or regulatory.

As said at the beginning of this section, there are three main categories, which contains the driving parameters for the evaluation of future emissions scenarios: economy, transport efficiency and energy. The first one, that is economy, deals with the shipping transport demand evaluated in tonne-miles required per year. This parameter is mainly related to economic growth but also to changes in the transport patterns. The economic parameter that can be exploited in order to provide a relationship between economic growth and shipping demand is the Gross Domestic Product (GDP). Indeed, there is a strong historical correlation between GDP and shipping. Moreover, there may be significant future developments regarding trade patterns or changes in transport means such as the commissioning of a new oil pipeline or the modernization of the Siberian railroad, which may partially shift the trade from shipping to land-based transport means.

According to (IMO, 2009), this category is divided in three sub-categories:

→ Ship size (Efficiency of scale)

→ Speed

→ Ship design

The first item is required to simulate the better efficiency of larger vessels. In fact, larger vessels are more efficient than smaller vessels hence it is needed estimating the future size of the fleet. Forecasts concerning the future fleet composition foresee an increase of the vessels size in the future because of the economy of scale in using larger vessels. The second item is the sailing speed of the future fleet. As treated in this thesis, there is a strict link between emissions and speed. Therefore, the future speed must be modelled, taking into account that the speed is driven by the economic condition of the market. Another significant aspect which has to be stated is the ship design. This category includes technological improvement such as a better design of the hull or more efficient engines. In addition, such category also comprises the development of regulatory that may affect the fuel consumption such as air emissions requirements. Lastly, an estimation regarding the future developments in marine fuels must be involved in such analysis as CO_2 emissions from ship depends on the type of fuel used (as seen in section 3.1.3, each type of bunker has a different emission factor value). For instance, it is foreseen that the LNG utilization might increase in the future. Since the LNG's emission factor is lower than the emission factor of MDO and HFO this change of fuel may entail a reduction of CO_2 emissions.

The results provided by (IMO, 2009) and (IMO, 2014) essentially claim the same conclusions. As reported in figure 3.13, according to the scenarios involved the CO_2 emissions produced by the international shipping sector will increase by 2050: (IMO,2015) claims that this increase will be of 50%-250% in the period up to 2050. Moreover, such article states that containership sector will show a larger increase regarding produced emissions. Indeed, while in 2012 the unitized cargo ship sector accounted about for 40% of the CO_2 emissions, this percentage is projected to account up to two thirds in 2050. This projection regarding the CO_2 emissions produced by shipping sector is one of the main reasons for which IMO is in charged to elaborate measures able to curb this trend. Besides, both the studies claim that the most important parameter affecting the growth in future emissions is the increase of the transport demand. As a consequence, if the global economic grows, the CO_2 emissions by the international shipping will likely increase. However, this growth in the demand may be due to balance a decrease of the use of other transport means such as road freight or air freight, which are more pollutant than the maritime freight as seen in section 3.4. Thus, there may be an overall beneficial impact with regard in the total CO_2 emissions by the whole transport sector.

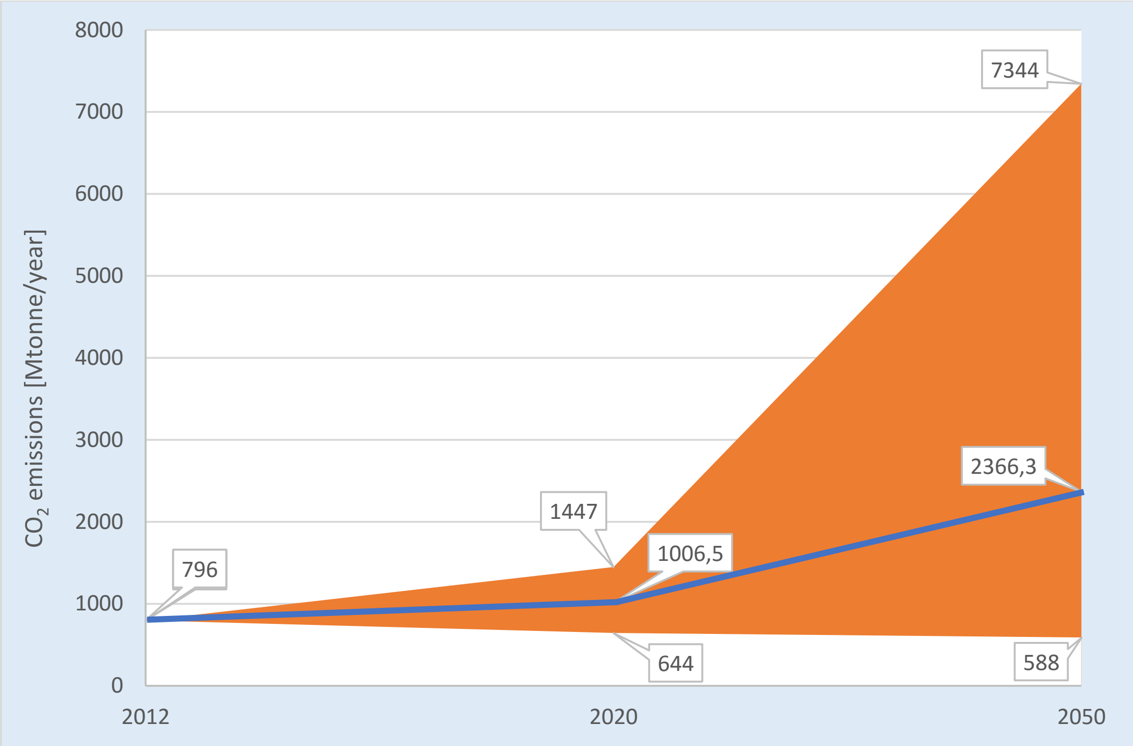


Figure 3.13: Forecast of CO_2 emissions from international shipping
The central blue line represents the future emissions considering the mean of the "base scenarios" involved in the study. The upper and lower borderline represent the maximum value for the "high scenarios" and the minimum value for the "low scenarios" respectively. The emissions in 2012 are the value computed in (IMO, 2015).
Data source: (IMO, 2009), Table 7.23

CHAPTER 4
PROBLEM DESCRIPTION AND MODEL FORMULATION

The optimization of speed is a paramount challenge in sea transportation. The benefits of a high speed are relevant in every transport mode, nevertheless this is especially true in maritime transport. In fact, ships are slower than other delivering method (for example an average container ship can travel at 25 knots (MAN, 2013), which corresponds to 46.3 Km/h). Long voyages can last up to 1 month or more hence significant benefits can be achieved travelling at high speed. The advantages of travelling faster are: firstly, reduced inventory cost, secondly, a larger delivering capacity which increases carrier's revenue. These favourable reasons and growing global trade market entailed to develop faster ships, through technological advances regarding for instance hull design, engine efficiency and hydrodynamic performance. However, travelling at the maximum speed is not always the best decision since both fuel consumption and GHG are related to ship velocity. In fact, increasing bunker price, shipping market crisis and expanding interest in environmental impact lead carriers to give more attention on speed decision. As a consequence, many models have been developed in order to provide tools that can support transportation companies on speed determination (Psaraftis and Kontovas, 2013).

Optimizing ship speed is a wide topic, which has several distinct characteristics determined primarily by market peculiarities. For instance, the speed optimization problem in tanker ship market is quite different compared to container liner shipping. Nowadays, high bunker prices and depressed shipping markets make carriers operators travel at a lower speed than the design speed in order to curb fuel consumption and at the same time decreasing the transport capacity: this strategy is called slow steaming. In fact, this logistic-based strategy allows decreasing fuel costs thanks to the non-linear relationship between speed and fuel. Moreover, slow steaming help operators to deal with low freight rate due to market crisis, balancing the mismatch between supply and demand of transport capacity. Therefore, operators apply slow steaming strategy for economic reasons. However, it also has considerable environmental effects thanks to the fuel consumption reduction which cuts down CO_2 fleet emissions. Slow steaming is practiced in container shipping because of the high design speed; 25 knots, for instance tanker ships have a design speed about 16 knots, as reported in (Gkonis Psaraftis, 2012). Nevertheless, it is reported in every shipping market. Speed optimization obviously includes slow steaming as response to the boundary conditions of the model since speed can be considered as function of scenario attributes which is simulated inside the model. In brief, speed optimization problem arises to help carriers to define the speed within a market where sailing at maximal speed is not always the proper decision.

4.1 SPEED OPTIMIZATION PROBLEM

This section firstly introduces optimization problem as well as speed influences in order to give the necessary acknowledge, allowing a full comprehension of section 4.2. Additionally, the logic behind slow steaming and its effects are examined, reporting actual market situation and bunker price trend. Furthermore, below it is furnished a review of the papers which concern ship speed optimization problem and slow steaming. Regarding this point, the paper (Psaraftis and Kontovas, 2013), which provide an exhaustive taxonomy concerning speed models in maritime transportation is strongly recommended. Such article lists the mainly characteristics of many speed optimization model and it is a useful tool to start dealing with ship speed optimization problem.

(Wang and Meng, 2012) elaborated a model whose aim is minimizing the total operating cost, dealing with a set of routes in container liner business. Mandatory weekly frequency is imposed. The objective function comprises container-handling costs, fuel cost and fixed operating cost, besides the decisional variables are the number of vessels deployed on each route, speed on each leg and transported cargoes on each leg. Since the problem is non-linear it is applied an approximation resolution method which exploit the convex property of the objective function, thus the problem is linearized replacing the fuel consumption function with an approximated function. This article also provides a calibration of fuel consumption for different capacity of container ship. (Vad Karsten et al., 2015) consider a similar situation, however this model contemplates a set of different type of goods. Besides, the available speed on each leg are fixed. The resolution method is based on the decomposition of the problem. (Gkonis and Psaraftis, 2012) determine the optimal speed (laden and ballast) of a tanker and afterwards it estimates the emissions of the global fleet in a specific tanker segment. The fundamental characteristic is that this model encompasses revenue because of non-fixed quantity. Moreover, it takes into account of inventory cost as well.

(Psaraftis and Kontovas, 2014) collect the mainly factors involved in the speed optimization problem. The form of fuel consumption formulation is discussed as well as which parameters should be considered in his estimation, such as pay-load, weather conditions and hull conditions. Furthermore, the influence of market state, fuel price and inventory cost is addressed and a mathematical formulation of these factors is embedded in an optimization equation. Then finally, the paper provides several significant conclusions about the effects on speed of inventory cost and pay-load. (Meyer et al., 2012) furnish an optimization model regarding container shipping and through some simplification assumptions estimates the main economic effects of slow steaming. In this paper the oil consumption is taken into account and, more interesting, it also factors in revenues in the objective function as well. (Cariou, 2011) obtains an estimation of the bunker break-even point price, which is the minimum fuel price that make slow steaming economically advantageous. In this estimation fuel cost, inventory cost and are considered, additionally the number of vessels along the route depends on speed. (Ronen, 2011) basically states the number of vessels deployed and the sailing speed are related whether a constant weekly frequency is required along the loop, that is the usual practice in container liner shipping.

(Notteboom and Vernimmen, 2009) evaluate the effect of high fuel cost on liner service configuration. The paper claims slowing down vessels entails an improvement in liner service, increasing the buffer time, as well as a significant increase in average vessel size. Besides, the effect of bunker price on the number of ports of call is examined. (Yin et al., 2013) furnish a simple model, which shows the relationship between sailing speed and bunker price, providing the optimal speed as a function of fuel consumption savings, operating costs, idle costs and involving also a carbon tax. (Corbett et al., 2009) address the cost-effectiveness of CO_2 in different scenarios. Firstly, they analyse the reduction in CO_2 emission for different fuel price, secondly, they estimate the marginal abetment cost when a speed limit is imposed. (Maloni et al., 2013) mainly deal with the advantages involved in slow steam practice, sorting between carriers and shippers. Thus, it clearly lists which are the trade-off encompassed in slow steaming and the equity of such measure in the shippers-carriers' rapport. (Woo and Moon, 2014) assess the effects of employing slow steaming in a route regarding the operating costs and the environmental effect, through a simulation model. Inside the paper is studied the CO_2 elasticity of voyage speed, which allows to find the speed range where it is more advantageous to reduce the speed in order to achieve higher emission abetment. Eventually, it is provided a sensitive analysis involving the enlargement of vessel size in respect of operating cost and CO_2 emissions. (Eide et al., 2009) evaluate the cost-effectiveness of several CO_2 reducing measures such as slow steaming, optimized hull design and other technological measures. Such analysis furnishes a decisional parameter called CATCH (cost of averting a tonne of CO_2-equivalent heating) which is the ratio between the costs born in order to apply the measure and the expected reduction of CO_2 achieved. Such parameter allows to compare the feasible different measures, from an economical point of view. (Cariou and Cheaitou, 2012) assess the economic consequences both simulating the introduction of a European speed limit and the introduction of a bunker levy. The conclusion is that issuing a European speed limit the GHG emissions may increase; moreover, this limitation entails carriers to bear costs per CO_2 saved which are higher than they would like to pay.

4.1.1 SPEED OPTIMIZATION

The optimization problem concerning the ships speed is analysed employing tools furnished by operations research. Therefore, it is necessary to develop objective function, constraints and ranges of variables involved in the model (for example it must be stated whether a certain variable is integer). The objective function is dependent of optimization variables, which may be one or more. This function is the mathematical description of the interesting features regarding the model, such as profits, costs and others. Constrains are a set of either inequality or equality equation that permit to describe mathematically the domain of the problem. The resolution of optimization problem is a wide argument and it is not an objective of this thesis dealing with it. Generally, elaboration of a speed optimization problem consists in two stage: firstly, the optimization problem is expressed; secondly, the resolution method that may be an exact or a heuristic algorithm is formulated (Psaraftis and Kontovas, 2014). However, it is essential to be aware that the solution method depends on the mathematical properties of both objective function and constrain. In fact, the first differentiation can be made between linear and non-linear problem, subsequently it is legitimate to divide between problems which have only integer variables, problems that have only continuous variable and then finally, problem with integer and continues variable. Since most decision problems in the management sector involve both integer and continuous variables, many optimization problems are likely included in one of these categories:

- → **MILP** (mixed-integer linear programming): both objective function and constraints are linear hence the mathematical formulation of the optimization problem can be expressed as:

  $$max\{c^T\, x\} \tag{4.1}$$

  Where *x* represents the vector of decision variables, which comprises at least one integer variable, and *c* is vector of coefficients;

- → **MINLP** (mixed-integer non-linear programming): either objective function or constrains is non-linear. MINLP includes most optimization problem because of the intrinsic non-linear nature of most model in order to replicate properly the reality. Combining difficulty of optimizing over integer variables with the challenges of handling non-linear function make these models troublesome to be solved (Belotti et al., 2012);

Moreover, it is relevant to be aware that mathematical features of the problem influence which software can be used to find the solution. For instance, CPLEX is a optimization software and handles integer, mixed-integer, linear and quadratic programming (www-01.ibm.com, 12-10-2016). Therefore, not every software may be suited to find the solution of a certain problem and every problem has specific features, which can be exploited in order to find the optimal solution. Additionally, the computing time and the calculation power is related to the complexity of the problem hence to the cost, which has to be borne. As consequence, a proper formulation of the problem should take into account which are the objectives of the analysis hence which simplifying assumption can be made in order to reach a good trade-off between complexity and information collected.

4.1.2 SPEED INFLUENCES

The ship speed optimization problem has an objective function which is either the maximization of profit or the minimization of cost. Both costs and profits are typically evaluated in a period, for instance many model computes daily costs or weekly cost. The first decision in sailing speed optimization problem is to define whoever decides the speed (Gkonis and Psaraftis, 2012). As said in section 2.4, there are distinct types of contract in shipping market, which define who pays for the fuel. In fact, the speed decision is taken by who manages the ship, which depends on the stipulated contract:

- → In spot charter market the cargo owner pays a freight rate [USD/TEU] to the ship owner which delivers the cargo along the ship route, therefore speed decision is made by ship owner. The ship owner purpose is to maximize his profits;

- → In bareboat charter market and time charter market the cargo owner hires a vessel and obtains full control of it. In this case, cargo owner pays for the bunker hence his aim is minimizing costs. Nevertheless, ship can also be rented in order to haul someone else’s cargoes, hence to realize a profit: in this case the objective is maximize the profit as expected;

Regarding the container liner market, operators haul cargoes using both owned ships and chartered ships: about 50% of vessels are chartered in the bareboat market (UNCTAD, 2015). Although there are obviously several economic distinct characteristics in these two situations, these differences do not influence the result since they are independent of speed. In fact, in case carrier hires a ship, the charter rate should be contemplated, however this expenditure is not related to speed. As a result, the speed determination in container liner shipping regards the maximization of the operator´s profits. Nevertheless, in case of problem that allows to rearrangement the number of ships deployed, since this number is a decisional variable, the rent cost is not negligible. Therefore, in this type of optimization issue, the fixed operating cost weights in the final result.
Once the decision respecting whoever sets speed, the objective function must be formulated. The purpose of this step is to establish all the items, which weights upon

profit. The proper identification and formulation of every element involved into the function is fundamental otherwise the model may not actually represent the real characteristics of the market. Since speed is the decisional variable of the problem, it is more significant assessing the items which are dependent of speed. In fact, elements that do not depend of speed are negligible because optimal speed is not affected by them, hence it is straightforward to add these items as they are constant factor. A general objective function, in a speed optimization problem, consequently can be expressed for example as:

$$a\, f(v) + b\, g(v) - c\, f(v)\, h(v) + K \qquad (4.2)$$

Where *a, b* and *c* are constant parameters which do not depend on speed, *K* represents the items which are independent of speed and do not influence the result and then finally *f, g* and *h* are functions of speed and can be either linear or non-linear. For example, one can consider the objective function in figure 4.13, the inventory costs item and the fuel consumption item are two examples of speed function. Several costs and revenues depend on sailing speed. These items determine the result of the optimization, i.e. the optimal speed. In fact, the objective of the problem is to compute the speed that realize the best trade-off between them. Literature furnishes a wide set of models, which usually considers the same aspect even if in different way. However, some models involve cost that are not provided in others. Therefore, this list is a gathering of costs and incomes determined by speed as well as:

→ **Fuel cost**: fuel costs are clearly related to fuel consumption. As well-known fact, the relationships between speed and fuel consumption is non-linear. Usually, the fuel consumption function is stated as:

$$f(v) = A + Bv^n \qquad (4.3)$$

Where *f(v)* [tonne/day] is the daily consumption of bunker at a certain speed *v* [kn] and *A*, *B* and *n* are coefficients that should be calibrated with real consumption data for a proper evaluation. These coefficients depend heavily on the type of the vessel. Although usually a cubic relationship is applied. As stated in (Psaraftis and Kontovas, 2013) and (Meyer et al, 2012) for container ships the exponent should be up to 4-5 or higher, because the cubic function is not suitable for the commonly high speeds of container vessels. However in (Wand and Meng, 2012)[11] is provided a calibration of bunker consumption for container ships of different cargo capacity, based on real data, whose results state that third power relationship is a good approximation. This formula consumption takes into account also auxiliary fuel consumption, indeed when ship is at port the consumption is not equal to zero: the coefficient A involves the fuel consumption when vessel is

[11] The calibration encompasses 20 historical data for each leg hence the statistical basis is restricted.

stationary. Typically, it is assumed that only one type of fuel used on the ship in order to simplify the model. Sailing speed is the main element in fuel consumption nevertheless other conditions affect the daily fuel function at a fixed speed[12] (Psaraftis and Kontovas, 2013):

- Pay-load: another influencing factor on fuel consumption is the carried payload. In order to include his effect can be adopted the following approximation:

$$f(v,w) = (A + Bv^n)(w + L)^{\frac{2}{3}} \qquad (4.4)$$

  Where w is the payload and L is the weight of the vessel empty. Payload impacts on ship resistance hence can be decisive, especially in tanker and bulk shipping where generally ships travel either completely filled or empty. Conversely, in container shipping ships are usually intermediately laden (although, on the Far East to Europe route ships are frequently more full in one direction). Nonetheless, in both cases, pay-load could lead to cause non-trivial, entailing an incorrect estimation of fuel consumption;

- Weather condition: implementing the effect of weather condition is a non-trivial challenge. There are different complexity levels to include weather conditions in fuel consumption: through either a simple coefficient or sophisticated approaches that consider wave height, wind speed and other factors;

- Hull condition: the frictional resistance of a ship is associated to the condition of its hull, more the hull is rough higher is the friction with water, hence the fuel consumption rises;

Therefore, the fuel consumption function may be more or less complex. A complex function obviously can simulate more aspects hence the fuel consumption computed may be a more accurate estimation of the real consumption. Nevertheless, such function has to be calibrated using real data and, as expected, the increasing complexity also entails that the calibration requires more real consumption data and a non-trivial calibration. For example, in order to develop a function which embeds the dependency on the payload, it is necessary to have real data showing, at a fixed speed, the trend of the consumption varying the payload. The factors, which can be embedded into the fuel consumption function are reassumed in figure 4.1.

[12] (Wang and Meng, 2012) claim the daily fuel consumption function is also a function of leg involved. This fact is probably because the calibration is based upon real data. In fact, using real data the consumption is without doubt influenced by weather condition and other factor.

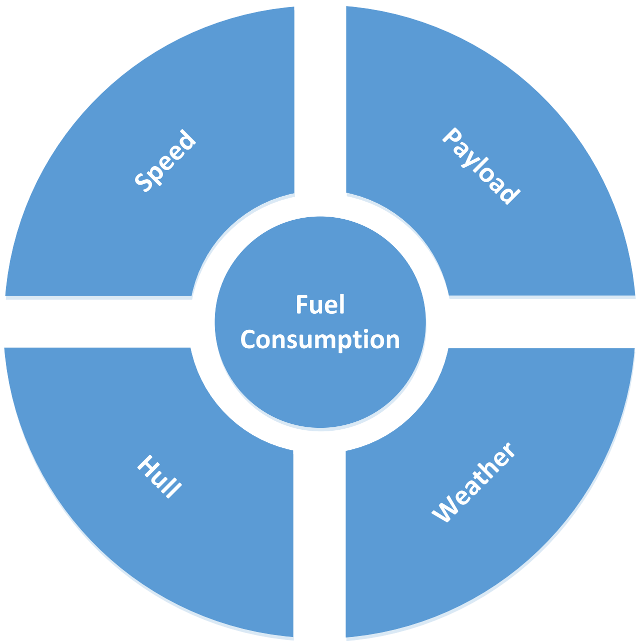


Figure 4.1: Fuel consumption function's influencing factors
Speed, payload, hull condition and weather condition are the influencing factor on the fuel consumption at sea per vessel.

→ **Inventory cost**: this cost is directly borne by the cargoes owner. Inventory costs represent the capital costs of transported cargoes during the travel as goods are cargo owner's capital whose monetary value may be employed in other way (in other words it is the opportunity cost of cargoes). Speed affects this item because inventory cost is related to travel time, which is obviously a function of speed. Moreover, inventory cost depends on goods quantity and also it depends on monetary value of transported goods and may be computed by:

$$\beta = \frac{P\ i}{365} \tag{4.5}$$

Where β is the daily inventory cost per cargo quantity [USD/TEU], P is the monetary value of good [USD/TEU] and i is the cargo owner's yearly capital cost. Therefore, cargo inventory cost may be influential mainly in the liner market where voyage time and ship size are usually high and freights may have high unit value, especially in container liner shipping. Although, charterer bears this cost and it is not included when ship owner negotiates the freight rate with the charterer, owner should take into account inventory cost because of the increasing supply chain cost and the related competitiveness loss (Jasper Meyer, 2012).

Indeed, a shipper may prefer a fast service than a slower if they are proposed one at the same price;

→ **Revenue**: a critical decision regarding the model formulation is to state whether the quantity of cargoes, which have to be transported are either fixed or non-fixed. In fact, there is a remarkable difference between models, which consider fixed quantity and model which does not consider fixed quantity. Most model contemplates, explicitly or implicitly, fixed quantities of cargoes: since the amount of cargo to be transported in a certain period is fixed there is no doubt that revenues are also fixed in the same period therefore earnings may be neglected and the objective function is independent of revenues. Thus, the model does not take into account the carrier may want to increment his income by delivering as much goods as possible when freight rate is higher within a definite period, hence ships must sail at high speed. Instead, when freight rate is lower carrier would like to slow down his vessels, delivering fewer cargoes in order to curb expenditure. Therefore, ships may travel at a lower speed, applying the slow steam strategy. Considering the following objective function, provided in (Psaraftis and Kontovas, 2013), this matter is straightforward to be comprehended:

$$max_v \left\{ \frac{s\ C\ v}{d} - p\ f(v) \right\} \tag{4.6}$$

The purpose of this equation is the maximization of the carrier's daily profits upon a route between two ports; where *C* is the ship's cargo capacity [TEU], *d* is the roundtrip distance [NM], *v* is the sailing speed [NM/day], *p* is the bunker price [USD/tonne], *s* is the freight rate [USD/TEU] and then finally *f(v)* is the daily fuel consumption [tonne/day]. The first part regards daily revenue and assumes non-fixed quantities: in fact, since there are always goods to be transported hypothetically the vessel is allowed to cross countless times the route. However, if goods are fixed, for instance a fixed weekly demand is stated, the voyage number will be fixed as well as revenue. As an example, even if (Vad Karsten et al., 2015) furnish a model which takes into account revenue, this revenue is considered fixed as cargo quantity is fixed and hence is independent of speed;

→ **Vessels deployed**: moreover, in the market of container liner shipping, as said in section 2.5, at least weekly service frequency is needed for each port of call therefore the decision concerned speed must take into consideration the number of vessels as well. Indeed, as reported in (Ronen, 2011) and shown in figure 4.2, in order to provide weekly service on a route the number of vessel deployed must be equal to:

$$N = \frac{S + P}{168^{13}} \tag{4.7}$$

$$S = \frac{D}{24\ v} \tag{4.8}$$

Where *N* is the number of vessel shipping upon the route, *P* is the port time [h], *S* [h] is the sailing time, which is equal to the route length *D* [NM] divided by the sailing speed *v* [kn]. For instance, whether at a certain speed the route is travelled in 28 days then at least 4 vessels must be deployed. Going faster less ships are needed because the time to complete such route is fewer. Therefore, not only the speed must be optimized in order to achieve best profits but the issue also must involve the number of ships deployed as variable, which, as stated in equation 4.7, is a non-proportional constraint function of speed. This peculiarity discriminates the speed issue between liner shipping market and others, which do not have a mandatory schedule.

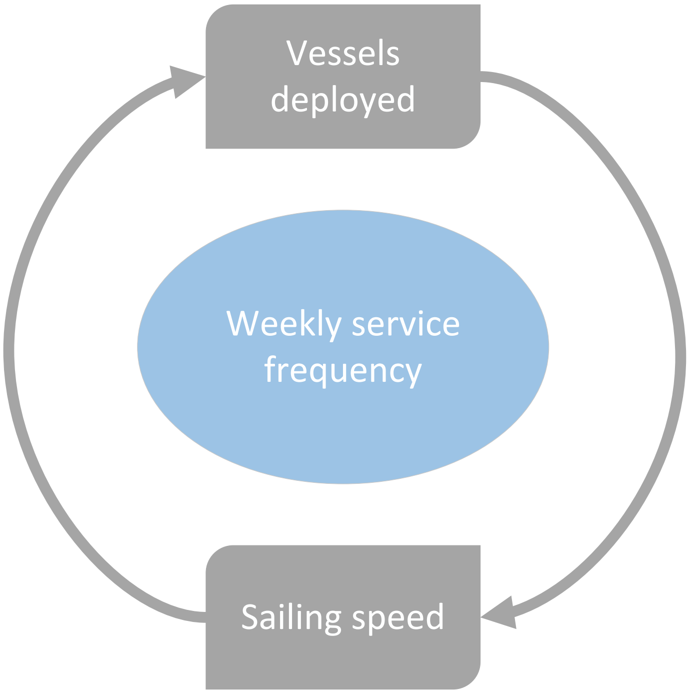


Figure 4.2: Relationship between sailing speed and number of vessels deployed
The peculiarity of container liner shipping market is the bond between sailing speed and number of vessels deployed along the route in order to respect the scheduled frequency.

[13] This value is the result of multiplying 24 by 7, in order to convert *P* and *S* in [week]

Additionally, in order to evaluate properly profit, it is meaningful to take into account costs, which are typically independent from speed:

→ **Operating fixed cost**: several cost items are comprised underneath operating cost such as crew costs, insurance costs, administration cost and others (Počuča, 2006). These costs are not directly function of speed. Nevertheless, as said, in the speed optimization problem regarding the liner container market, the decisional variables are both the speed and the number of ships as the number of vessel is a function of the speed. Therefore, this cost item related to the vessels number, it is not negligible and has to be considered in the objective function;

→ **Others**: there are many other costs which can be encompassed within the profit function. For instance, some papers involve container handling cost (Wang and Meng, 2012), harbour fees or lubricant consumption (Meyer, 2012);

It must be noted that when are considered non-fixed quantity of cargoes transported and when the objective function it is evaluated in a time frame, as it is made in this thesis, each cost items are dependent on speed. Such significant aspect it is analysed in section 4.2.2.

4.1.3 SLOW STEAMING

Slow steaming can be basically defined as operating along a route sailing at certain speed which is lower than the design speed in order to achieve economic improvement. World's shipping community has implemented slow steaming since 2007 (MAN, 2012)[14]. According to (Woo and Moon, 2014) carriers have generally selected speed to 15-18 knots on major routes, achieving significant economic advantages. Although the primary purpose of carriers in implementing slow steaming regarding economic aspects, it has relevant environment effect as well. For this motive, slow steaming can be considered as a win-win proposal in order to curb maritime emissions (Psaraftis and Kontovas, 2013). According to Alphaliner, 45% of container liner capacity has been using slow steaming (Yin et al., 2013).
It is reasonable subdividing the practice of slowing down ships depending on the speed that is set (Maloni et al., 2013)[15]:

→ 24 knots, full steaming;

[14] MAN, Slow Steaming practices in the Global Shipping Industry, 2012
[15] These speed values are general; indeed, a more proper classification should be made dealing with the vessel type

→ 24-21 knots, slow steaming;

→ 21-18 knots, extra slow steaming;

→ 18-15 knots, super slow steaming;

The ship's engines are designed to operate constantly at maximum power, however there are two feasible approaches to implement slow steaming. The first one is the simplest, that is basically slowing down vessels, the second one involves some engine retrofit. Engine retrofit means derating engine such as implementing slide fuel valve and turbocharger cut-out: applying these technological measure allows to improve engine efficiency hence to cut more fuel costs (MAN, 2012)[16]. It is well-know that the relationship between daily fuel consumption *FC* [tonne/day] and main engine power is (Cariou, 2011):

$$FC = 24\, BSFC\, E_{load}\, P_{engine} \qquad (4.9)$$[17]

Where *BSFC* is the brake specific fuel consumption (also called SFOC, specific fuel oil consumption) [g/kWh], E_{load} is the engine load and P_{engine} [kW] is the main engine power. In fact, as fig. 4.3 shows, BSFC varies with speed. Besides, being ships designed to sail at about 25 knots, around this value of speed BSFC reaches the lowest value. Employing one of the kit available, specifically developed to adopt slow steaming, the BSFC curve can be shifted to lower speed values in order to obtain a better efficiency.

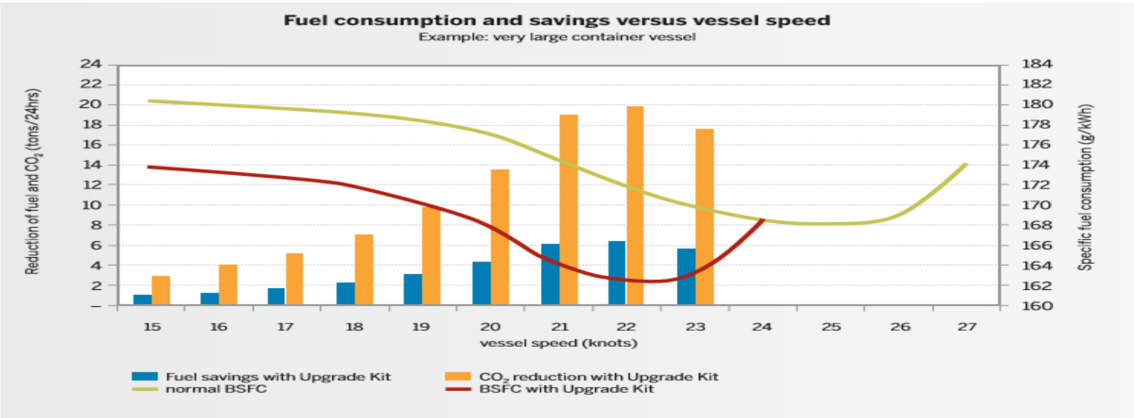


Figure 4.3: BSFC trend
This graph shows the BSFC trend. Container ships are designed to travel at a certain speed, around 25 knots, indeed the BSFC value is lowest around this speed value. Employing a slow steaming kit, it is possible obtaining a considerable improvement of engine efficiency also at lower speed. In this way the fuel consumption savings are greater
Source: (Wiesmann, 2010)

[16] MAN, Slow Steaming practices in the Global Shipping Industry, 2012
[17] Being engine power commonly a cubic function of speed, this equation is fundamentally the starting point for obtaining the cubic relationship between speed and daily fuel consumption

The reasons that lead ship operators to practice slow steaming are:

→ Fuel price

→ Market condition

→ Environmental issues

Principally, slow steaming strategy arose when bunker price increased. As shown in fig. 4.4, bunker price sharply increased since early 2000s, making fuel cost by the far the main cost item for carriers. Although, since 2015 bunker price has been decreasing, recently the MDO value is decreasing, attaining about 500 USD/tonne. Nevertheless, fuel expenditure is still crucial for shipping companies. Prices that are more recent are reported in figure 4.5, additionally are presented prices regarding IFO 180 and IFO 380. Slow steaming represents the most effective measure to reduce fuel expenditure (MAN, 2012)[18].

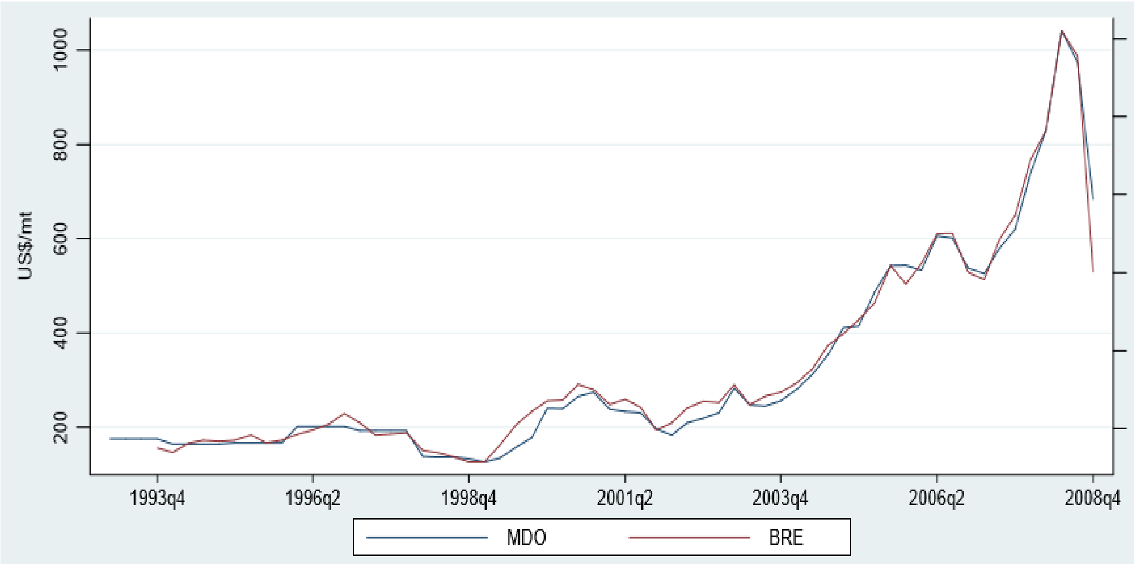


Figure 4.4: BRE and MDO price trend
Brent crude oil (BRE) is a sweet light type of crude oil. Notice the correlation between BRE price and MDO price.
Source: (UNCTAD, 2010)

[18] MAN, Turbocharger Cut-Out, 2012

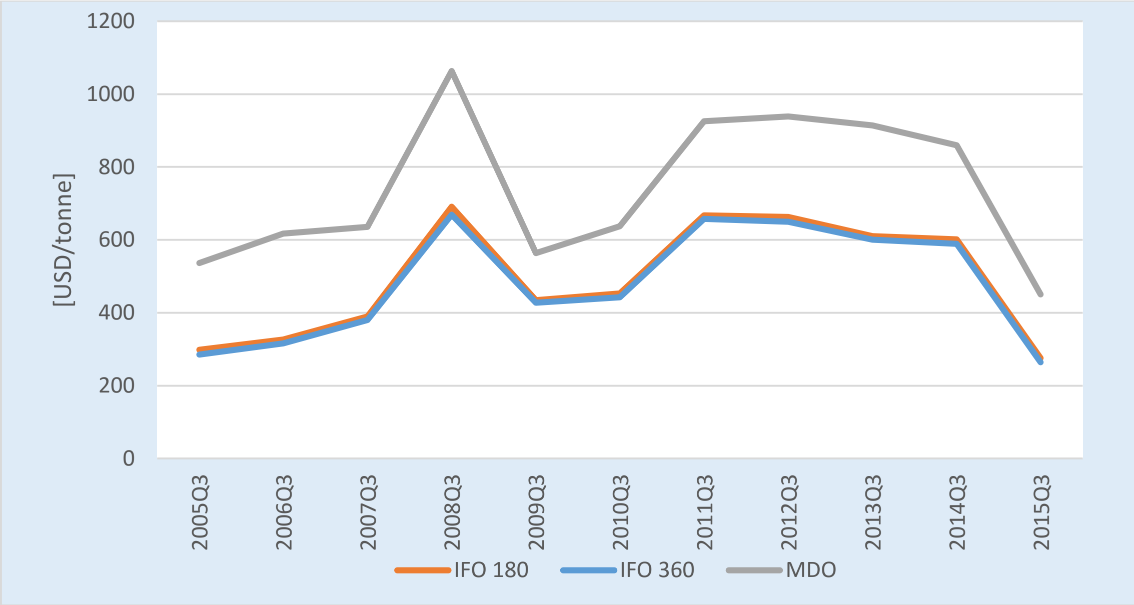


Figure 4.5: Singapore bunker price trend
Adapted from: www.transport.govt.nz, New Zealand Ministry of Transport, 19-10-2016

Since fuel cost is a substantial expense in liner shipping, the bunker price rise led carriers to cut fuel consumption for economic purpose. Indeed, slow steaming represents the most effective measure to reduce fuel expenditure (MAN, 2012)[19]. As reported in (Ronen, 2012), if the fuel price per bunker tonne is 500 USD, about 75% of the operating cost for a large containership are attributable to the fuel consumption. The objective of reducing fuel consumption can be achieved following three different strategies (Notteboom and Vernimmen, 2009):

→ **Changing fuel grades**: using cheaper bunker fuels, such as IFO 420, 500, 600 and 700, considerable cost savings can be obtained (up to 16 USD per tonne). These fuels are more viscous than usual bunker fuels IFO 380 and IFO 180. Indeed, vessels should be able to deal with these high-viscosity combustible and especially old vessels are not capable to work with them. As a consequence, despite the increasing interest in high-viscosity grades, conventional fuels still remain the most popular choice;

→ **Technological advances**: this strategy regards the improvement of the ship efficiency. This can be made through a better design of vessels, for instance improving aerodynamic characteristics, main and auxiliary engine efficiency. Moreover, the new generation of container vessels are designed to sail at lower speed, avoiding all the problems related to the engine efficiency (Psaraftis and Kontovas, 2013). Nevertheless, these technological measures are not applicable in short term;

[19] MAN, Turbocharger Cut-Out, 2012

→ **Vessel speed**: the most valuable method to reduce ship fuel consumptions is certainly speed reduction. As said in section 4.1.2, the relationship between speed and fuel consumption is non-linear and typically it is considered as cubic. Thus, a 20% reduction in speed allows a 50% reduction in daily fuel consumption (Ronen, 1982). Although the cubic relationship between speed and daily fuel consumption, fuel savings per travel are not a cubic function of speed. Indeed, the increasing transit time entails more fuel burning days. As reported in (Wiesemann, 2010), a speed reduction from 27 to 22 knots allows to save approximately 58% of hourly main engine consumption. However, considering the increasing voyage time, the fuel savings are reduced by 45%. This remark can easily be demonstrated as the fuel consumption along a leg FC is roughly related to the square of the vessel's speed. Indeed, replacing the voyage time T the result is:

$$T = \frac{D}{v} \tag{4.10}$$

$$FC = f(v)\, T = k\, v^3\, \frac{D}{v} = k\, D\, v^2 \tag{4.11}$$

Where *f(v)* is the daily fuel consumption function [tonne/day] approximated as a cubic function of speed, v is the speed [mile/day] and *D* is the leg length [mile];
In addition, one should observe that changing the vessel speed is a short-term measure as it can be practically applied in any moment;

In table 4.1 data concerning the employment of slow steaming in 2007 and 2012 for container ships sorted by TEU capacity are provided. The data shows clearly the increasing utilization of slow steaming from 2007 to 2012, moreover one can see that the speed is decidedly lower for larger vessels. Lastly, the average data regarding bulk carrier and oil tanker are provided. The comparison of these data shows clearly that the container ship sector is the most affected shipping sector because of their higher design speed, as it will explain below.
In addition to the bunker price rise, world economic crisis and increasing transport capacity have curbed freight rate as reported in figure 4.6, whose value depends on global container demand and supply capacity. Indeed, if supply capacity is bigger than the actual transport demand, freight rate value will consequently decrease. As shown in figure 4.7, demand and supply in container shipping growth rate follow an analogous trend, except in 2009 as global crisis brought down required global demand.

Slow Steaming for 2007 and 2012

Ship Type	Size [TEU]	Average at sea speed/design speed in 2007	Average at sea speed/design speed in 2012	Percentage change of daily fuel consumption
Container	0-999	0.82	0.77	-19%
	1000-1999	0.80	0.73	-26%
	2000-2999	0.80	0.70	-37%
	3000-4999	0.80	0.68	-42%
	5000-7999	0.82	0.65	-63%
	8000-11999	0.85	0.65	-71%
	12000-14500	0.84	0.66	-73%
	>14500	/	0.60	/
Bulk Carrier	/	0.88	0.83	-19%
Oil Tanker	/	0.89	0.78	-25.3%

Table 4.1: Slow steaming data for 2007 and 2012
Data Source: (IMO, 2014), Table 17

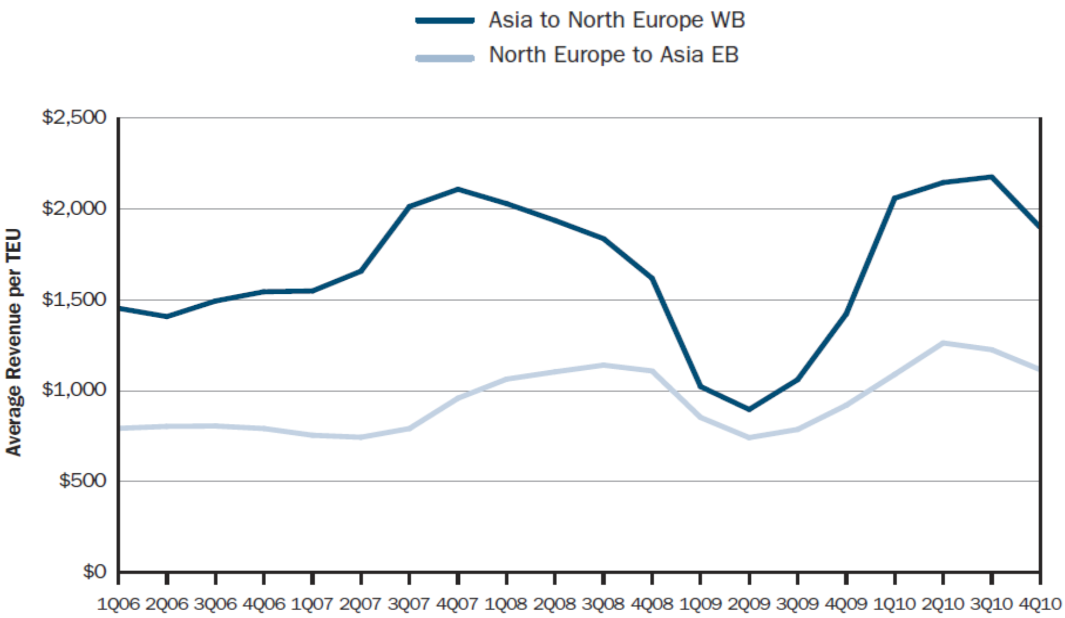


Figure 4.6: Average freight rate trend along the Asia-Europe route
The economic crisis and the overcapacity curbed the freight rates.
Source: (FMC, 2012), Figure AE-19

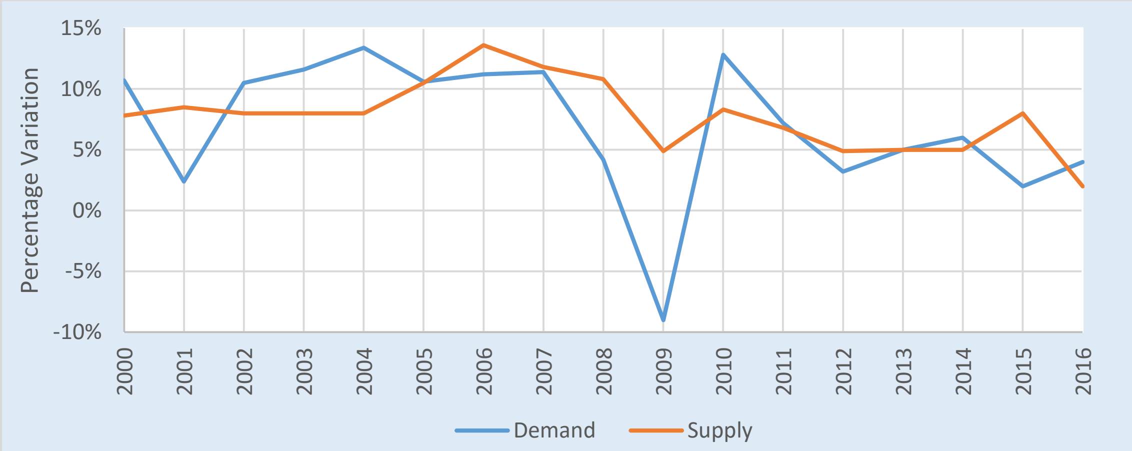


Figure 4.7: Demand and supply, the percentage variation trend
This graph shows both demand trend and supply capacity trend. Freight rate is determined by these factors because of the well-known law of supply and demand. Notice the demand collapse in 2009 due to the global economic crisis.
Adapted from: (UNCTAD, 2015), Figure 3.7 for 2000 data and (UNCTAD, 2016), Figure 3.1 (percentages for 2016 are projected figures)

However, it should be noticed that freight rate is decidedly volatile, changing considerably in respect to time and ship route involved, as shown in table 4.2 and figure 4.8. Moreover, one can notice that the container freight rates have sharply declined in 2015, reaching record low prices as reported in (UNCTAD, 2016).

Container freight rate

Market	2009	2010	2011	2012	2013	2014	2015
Trans-Pacific			USD per FEU[20]				
Shanghai-United States West Coast	1372	2308	1667	2287	2033	1970	1506
Percentage change	-	68.21	-27.77	37.19	-11.11	-3.10	-23.55
Shanghai-United States East Coast	2637	3499	3008	3416	3290	3720	3182
Percentage change	-	47.84	-14.03	13.56	-3.7	13.07	-14.45
Far East-Europe			USD per TEU				
Shanghai-Northern Europe	1395	1789	881	1353	1084	1161	629
Percentage change	-	28.24	-50.75	53.58	-19.88	7.10	-45.82
Shanghai-Mediterranean	1397	1739	973	1336	1151	1253	739
Percentage change	-	24.49	-44.05	37.31	-13.85	8.86	-41.02

Table 4.2: Freight rate trend for different routes
Adapted from: (UNCTAD, 2016), Table 3.1

[20] FEU is a container 40-foot-long, i.e. it is equal to 2 TEU

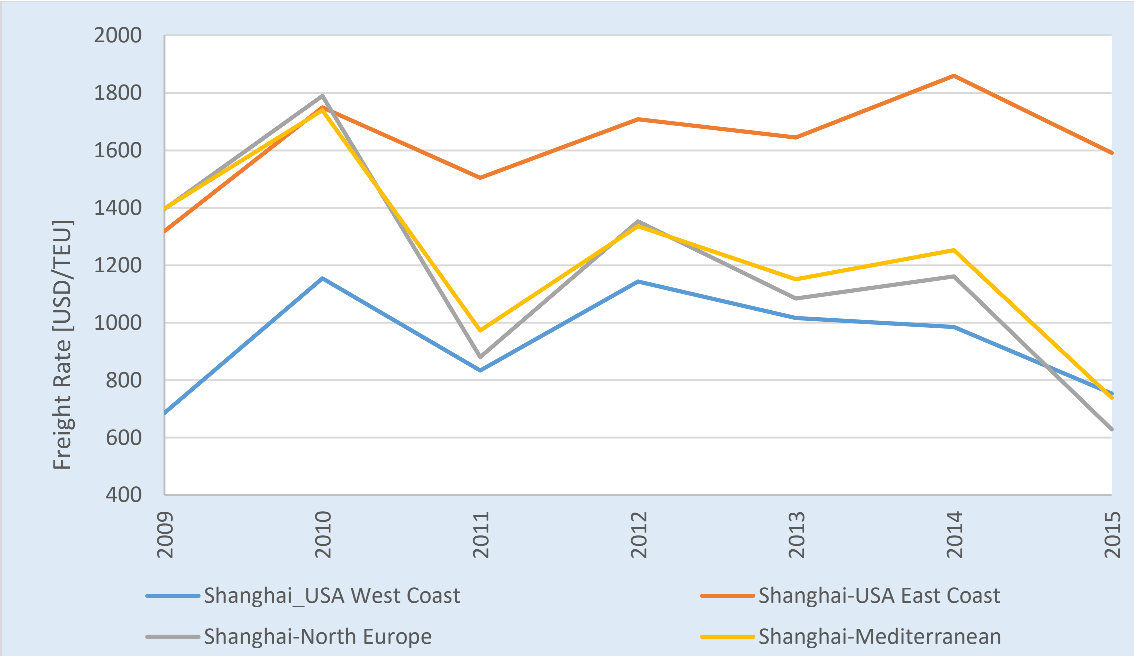


Figure 4.8: Freight rate trend on different routes
Freight rate trends and values are strictly related to the route examined and are highly volatile in time. Notice the steep decrease in 2015.
Adapted from: (UNCTAD, 2016), Table 3.1

This discrepancy between capacity and demand is a direct consequence of world economic crisis. Due to the generally long vessel's building time, in high market periods ship operators ordered new vessels. However, these orders cannot be deleted when low market time approaches. Indeed, in the time previous such crisis, ship building request was considerably high: according to (UNCTAD ,2010), during 2009 the striking number of 3,658 new ships were built, which was a new historical record. As stated in section 3.3.3, the idle capacity is a paramount characteristic that allows slow steaming to be a profitable solution. Indeed, the economic benefits, which are currently provided by slow steaming could disappear if in order to maintain the freight capacity, the manufacturing of new ships is required. As stated above, slow steaming is determined by freight rate and bunker price trend in the market: this aspect is fully present in (Gkonis and Psaraftis, 2012) and (Psaraftis and Kontovas, 2013), providing the following simple equation regarding a single leg (notice, this model considers non-fixed cargo):

$$max_v \left\{ \frac{C\,v}{d} - \rho\, f(v) \right\} \tag{4.12}$$

$$\rho = \frac{P}{s} \tag{4.13}$$

With *C* as ship cargo capacity, *v* as ship speed, *d* as voyage distance, *f(v)* as daily fuel consumption, *P* as bunker price and then finally *s* as freight rate. Equation (4.10) clearly explains how the non-dimensional ratio ρ determines the optimal speed.
Another decisive impulse towards slow steaming strategy is the increasing interest in environmental aspects, especially regarding GHGs. The increasing focus on environmental aspect is evidently connected to rising concern on global warming and climate change. Indeed, IMO is searching a measure which is able to curb CO_2 emissions produced by maritime transport with a high sense of urgency. This topic is addressed in section 4.1.3.1 in order to distinguish between economic and environmental effects.
Since speed has a crucial effect in each aspect regarding maritime logistics, it is very significant to analyse which effects leads slow steaming strategy:

→ The first clear consequence of reducing sailing speed is a reduction of fuel consumed by the vessel. Therefore, this entails shrinking fuel cost borne by carrier and as we will see it involves a reduction of emission produced by the vessel as well. Since, as said in section 4.1.2, the relationship between speed and daily fuel consumption is non-linear this effect is stronger for high speed. Moreover, as container ships travel at a higher speed than other ships and the exponent for a container vessel is higher as well, this aspect it is especially true in liner container market. This statement is effortless demonstrated analysing the general equation of fuel consumption fuel and the first derivative of speed and exponent:

$$FC = A\, v^{n} \tag{4.14}$$

$$\frac{dFC}{dv} = n\, A\, v^{n-1} \tag{4.15}$$

$$\frac{dFC}{dn} = A\, v^{n} \log(v) \tag{4.16}$$

In fact, the fuel consumption variation is a function of speed to the power of n-1. Therefore, it is clear-cut that such variation is higher for higher speed value and for higher value of exponent n, considering a changing speed. Besides, considering equation 4.16, for a fixed speed value, fuel consumption decreases more for a higher exponent value.

→ The mismatch between supply and demand has drawn to increase the number of vessel in lay-up, especially during the economic crisis (Meyer et al., 2012). Idle vessels are a cost for carriers because these ships have to be stored. Furthermore, this discrepancy entailed a decrease of the freight rate value hence of the carrier's revenue. It is estimated that adoption of slow steaming in 2014 have absorbed 2.5 million TEUs of global nominal capacity, which is around 19 million TEUs (13%)

(UNCTAD, 2015). Nevertheless, in a high market state, i.e. when freight rate is high, carrier would like to transport as many cargoes as possible. Hence, traveling at lower speed, in order to cut fuel cost, may be economically disadvantageous and a proper trade-off must be sought;

→ Slower speed also implies longer transit time. Hence, another effect of slow steaming is the possibility of improving the customer's service level. In fact, according to (Vernimmen et al., 2007) and as reported in fig 4.9, over 40% of container vessels deployed in liner shipping have delays of one or more day. Specifically, 52% of vessel, involved in the survey, were on time. Approximately 43% of ships were late, of these: 21% were one day late, 8% were 2 days late and 14% arrived 3 or more days behind the schedule. The remaining 4% arrived before the scheduled time. Commonly, the reasons that lead a vessel to be late are: weather condition, port congestion, labour strikes and other unpredictable events. Slow steaming allows taking a higher buffer time and allows dealing with delays by increasing sailing speed. Therefore, achieving better service levels. In brief, whether ship is late, ship operator can speed up in order to recover the loss time. Schedule unreliability impact the level of safety stocks that should be kept by a manufacture or someone else into supply chain hence the supply chain economic competitiveness. Indeed, the required level of safety stock SS is calculated by this equation:

$$SS = K\,\sigma \tag{4.17}$$

Where K is the safety factor and σ is the standard deviation of the demand's statistical distribution within the lead time. The value of σ is given by the following equation:

$$\sigma = \sqrt{L\,\sigma_D^2 + D^2\sigma_L^2} \tag{4.18}$$

Where L is the average lead-time, D is the average demand, σ_D is the standard deviation of the demand and σ_L is the standard deviation of lead time. It is clear that an unreliable service entails a rise of the safety stock, with the obvious consequences regarding warehouse costs. Moreover, whether the supply chain becomes economically non-competitive, when it is feasible, cargo owner may prefer a land-based transport. However, shippers bear higher inventory cost, linked to the opportunity cost of goods, whether transit time is higher although this cost is not borne by carrier it should be taken into account because of, as said before, the economic competitiveness of the supply chain;

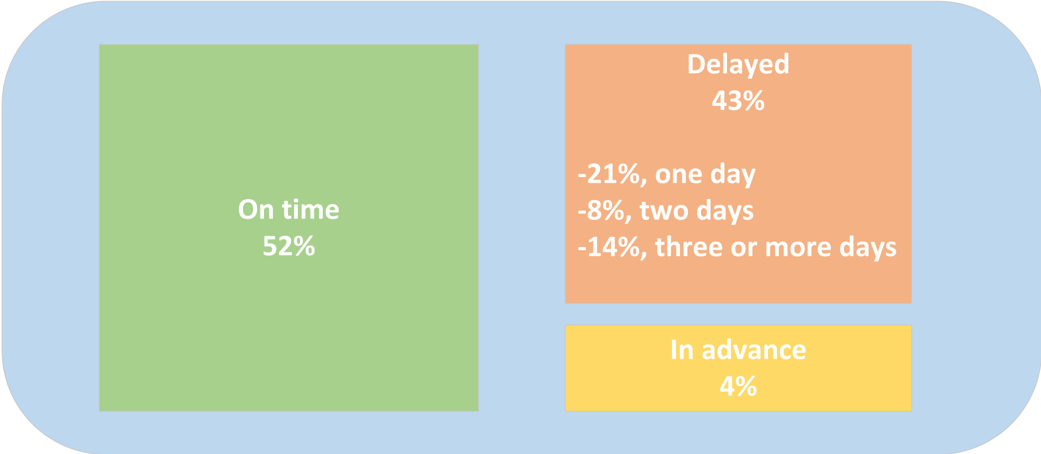


Figure 4.9: Delays in container liner shipping
Adapted from: (Vernimmen et al, 2007)

→ At the end, in order to maintain weekly service in each port call for the route, the number of vessel deployed rise. More vessel means increasing fixed operating cost. However, there is a beneficial effect in deploying more vessel. (Maloni et al, 2013) estimate approximately 5% of overall container ships is idle because of demand lack. Slow steaming allows to resolve these problems as it is a tools in the carriers' hand enabling to reduce the supply capacity. Thus, carriers are able to influence the market without laying-up.

An overall overview is provided in fig. 4.10. Notice that this list gathers each effect which may be involved by slow steaming. However, depending on the case examined, not each item may be present and the effects can be considerably distinct in various scenarios. For instance, considering a depressed market, there is no revenue loss in slowing down since the supply demand is low.

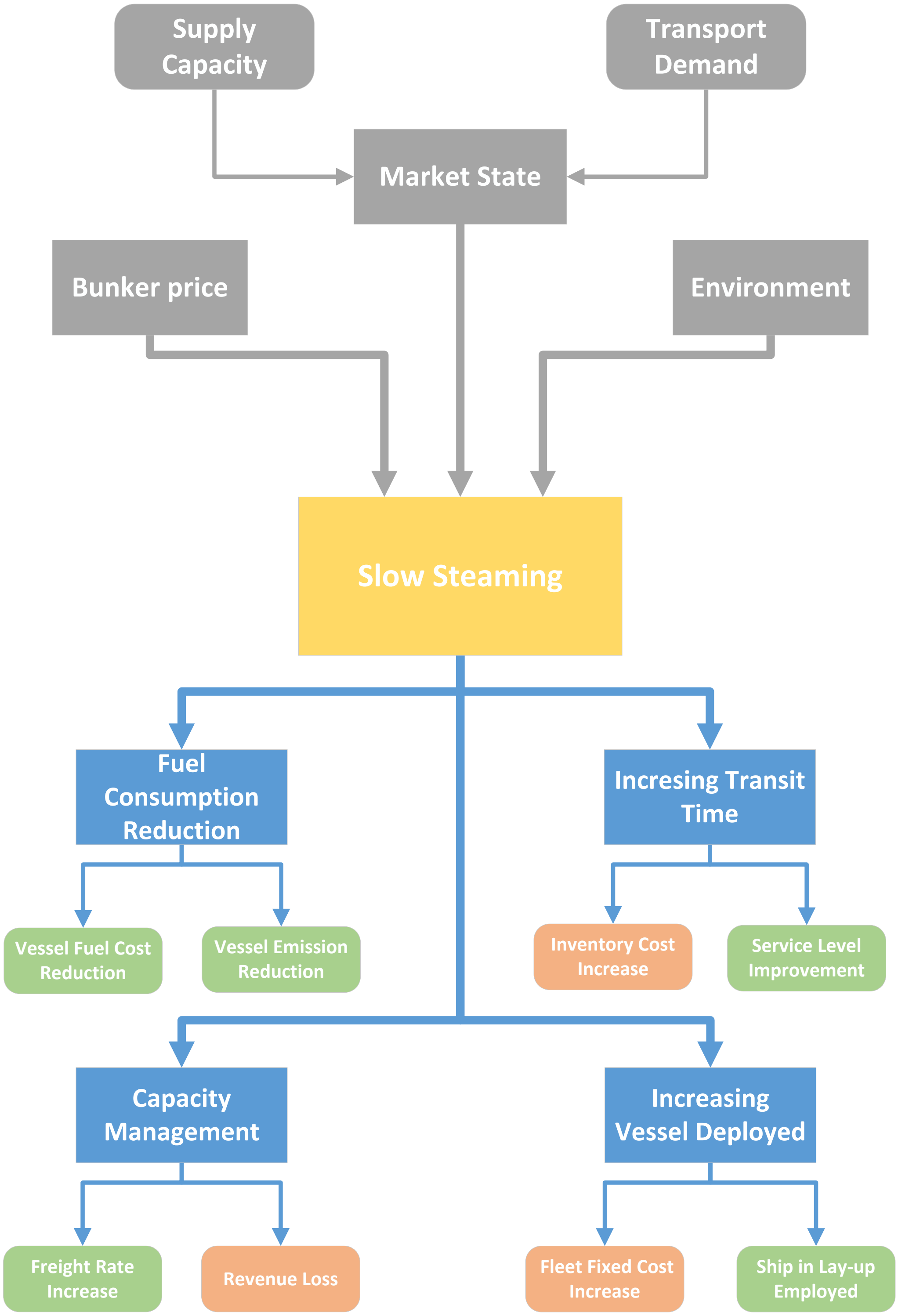


Figure 4.10: Slow steaming's causes and effects diagram
This diagram reassumes the causes and the conceivable effects involved in the practice of slow steaming. Such effects are related and they depend on the actual conditions considered. A complete model regarding the speed optimization problem should encompass all these factors.

4.1.3.1 ENVIRONMENTAL IMPACTS

Slow steaming has indisputable economic consequences, as stated in the previous section. Besides, as obviously expected, slowing down also entails beneficial environmental effects. As deeply analysed in section 3.1, international liner shipping heavily contributes to the global GHG emissions. This contribution is estimated to be around 3% of global emissions (Eide et al., 2009). Therefore, the liner sector as well as each maritime transport area are under pressure to diminish their emissions. Since ship fuel consumption is related to CO_2 emissions, it is manifest that a reduction of the first factor leads to reduce the latter as well. As reported in (Woo and Moon, 2014), a deceleration by 20% entails a reduction of fuel consumption by more than 40% and a reduction in CO_2 emissions by 20%. However, reducing the speed also implies that the number of vessels deployed along the route increases because of voyage transit time's increase. More vessels deployed signifies more pollutant sources. Therefore, there is a dual effect when the sail speed is reduced. Nevertheless, according to (Kontovas and Psaraftis, 2011) and (Woo and Moon, 2014), it is certified that slow steaming has beneficial effects on environment. The effectiveness of slow steaming in reducing emission is also estimated in (Cariou, 2011) and reassumed in table 4.3:

Impact of slow steaming on CO_2 emissions

Route	Slow steaming vessels	CO_2 emissions 2010 [tonne]	Emissions variation 2008-2010
Europe-Far East	78,6%	12,900,000	-16.4%
Asia-North America	42,3%	29,400,000	-9.7%
North Atlantic	22,7%	5,778	-6.7%

Table 4.3: Slow steaming impact on CO_2 emissions
Adapted from: (Cariou, 2011)

This claim can theoretically be validated through a simple example, which is defined as scenario 1^{st}. Such scenario does not consider neither port times nor emissions at ports and it deals with a route which involves only two ports of call:

→ The time between two consecutive arrivals t_0 [days] is:

$$t_0 = \frac{L}{24\, N\, (v_1 + v_2)} = \frac{T_0}{N} \qquad (4.19)$$

Where N is the number of ships, L is the round-trip length, T_0 is the roundtrip time [day] and v_1 and v_2 are the speeds along the two legs [knots].
Taking for simplicity the same speed along the outward leg and the back way leg, the equation becomes:

$$t_0 = \frac{L}{48\,N\,v} \tag{4.20}$$

The service frequency is considered constant hence also the throughput *Q* [TEU/day] along the route is constant:

$$Q = \frac{c\,48\,N\,v}{L} = \frac{c}{t_0} \tag{4.21}$$

Where *c* is the amount of cargoes [TEU] transported by each ship.
Assuming a cubic fuel consumption function *f(v)* [tonne/day] such as:

$$f(v) = kv^3 \tag{4.22}$$

The total emission produced per roundtrip *E* [tonne/day] during the roundtrip time is:

$$E = \frac{EM_{CO_2}\,k\,v^3\,\frac{L}{48\,N\,v}}{t_0} = \frac{EM_{CO_2}\,k\,L\,v^2}{48\,N\,t_0} \tag{4.23}$$

Where EM_{CO_2} is the emission factor. Replacing v in the equation 4.23 with the equation 4.20, which states the link between *N* and *v*, the result is:

$$E = \frac{EM_{CO_2}\,k\,L^3}{48^3\,{t_0}^3 N^3} = A\,\frac{1}{N^3} \tag{4.24}$$

$$A = \frac{EM_{CO_2}\,k\,L^3}{48^3\,{t_0}^3} \tag{4.25}$$

Therefore, this equation claims that adding more ships, which sail at a lower speed, is an effectively measure to reduce the CO_2 emissions if the service frequency is constant. This aspect is reassumed in fig. 4.11.

Despite this ecological implication, shipping companies are more interested in making profits. Therefore, as long as the slow steaming practice is economically advantageous they will adopt it but if, for any reasons, sailing at lower speed becomes a burden on the operators' account balance they will not employ such practice. Indeed, at the moment there is no regulation regarding the speed that liner companies should adopt. According to (Cariou, 2011), a bunker break-even price (BEP) can be estimated: in case the bunker price reaches a value higher than BEP, employing slow steaming carriers can achieve better economic results. The results of this study is reported in table 4.4:

Bunker BEP price[21]	
Route	**[USD/tonne]**
Europe-Far East	394
Asia-North America	345
North Atlantic	440

Table 4.4: Bunker break-even point price
Adapted from: (Cariou, 2011)

This factor is extremely significant as it shows that without any market-based measure, slow steaming may not be a long-term strategy to curb liner-shipping emissions because it remains economically sustainable only for high bunker price level. In case of the bunker price is higher than BEP, slow steaming is a win-win strategy because it allows both curbing CO_2 emissions and increasing operators' profits. These aspects are treated in section 3.3.

[21] These values refer to the IFO price

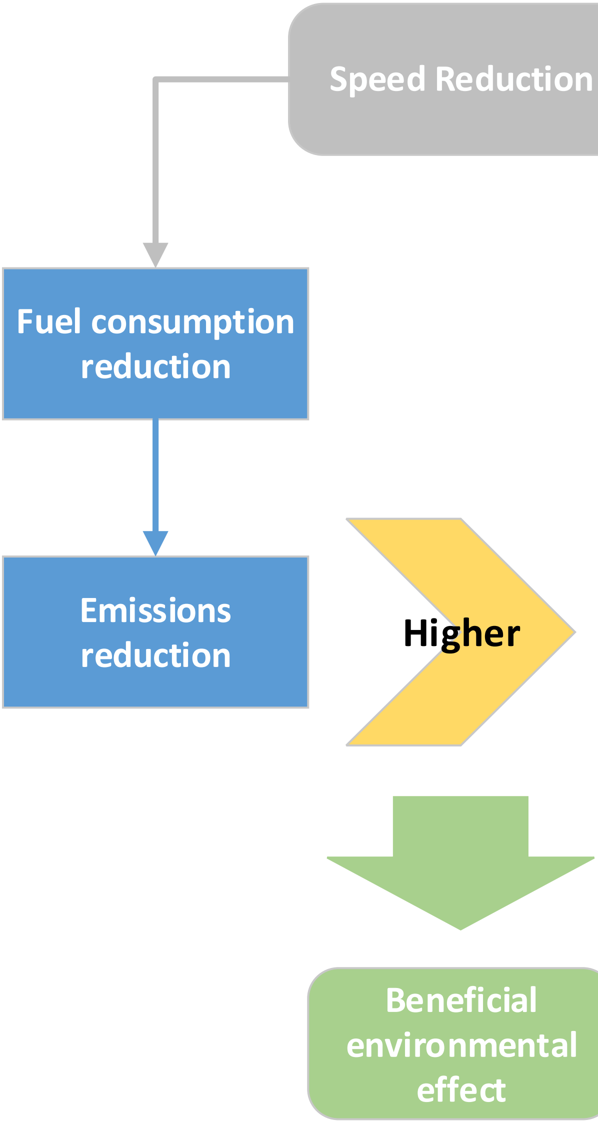


Figure 4.11: Slow steaming's environmental effects
Reducing the speed entails both the fuel consumption reduction of the single vessel and the increase of the vessel deployed in order to maintain the same throughput. These consequences might lead to increase the overall emissions; however, it is demonstrated that putting into action slow steaming is an ecological measure

4.2 MATHEMATICAL MODEL

The main aim of this thesis is providing a model, which allows computing the effect of freight rate on the speed in the container liner industry. The route as well as the legs are considered fixed, therefore the optimization problem's objective is to maximize the economic performance of such fixed route. The model present in this thesis considers carrier as the speed decision maker, hence the objective function's purpose must be the maximization of the carrier's revenue. As said in section 4.1.2 and stated in (Psaraftis and Kontovas, 2013), in order to evaluate the influence of freight rate on speed it is necessary to consider a non-fixed transport demand, otherwise the revenue would be constant and as a consequence the optimization problem would not take freight rate into account. The freight rate is certainly not the unique parameters that influence the optimal speed, indeed, there are other influential factors which have to be considered inside the objective function, such as bunker price, operating costs and inventory costs. Besides, the required service frequency constrains the problem and binds the number of vessels to the sailing speeds. The next sections introduce the model function as well as its inputs and constraints; moreover, they explain the main characteristics regarding the resolution method adopted.

4.2.1 LIST OF PARAMETERS AND VARIABLES

The parameters and variables involved in the model are:

→ **N**: number of ships deployed on the route;

→ **F_{xz}**: freight rate for transporting a TEU from the port x to the port z [USD/TEU]. Notice, the freight rate value depends on the direction therefore:

$$F_{xz} \neq F_{zx}$$

For example, the freight rate from Vancouver to Shanghai is about 305 USD whereas the freight rate from Shanghai to Vancouver is about 900 USD (source: www.worldfreightrates.com, 08-12-2016);

→ **C_{xz}**: transport demand between the port x and the port z [TEU]. As for the freight rate, the transport demand depends on the direction hence:

$$C_{xz} \neq C_{zx}$$

→ **P**: bunker price [USD/tonne];

→ **E**: operating costs per vessel per day [USD/day];

→ **v_i**: speed along the ith leg [knots]. The speed is bound above by v_{max} and bounded below by v_{min};

→ **$f(v_i)$**: daily fuel consumption at sea [tonne/day]. As explained in section 4.1.2, the fuel consumption for a ship depends on his speed. The daily fuel consumption function includes both the main engine fuel consumption and the auxiliary engine fuel consumption at sea;

→ **Fp**: auxiliary fuel consumption at port [tonne/;

→ **L_i**: length of ith leg [NM];

→ **T_i**: required time to complete the leg ith [days]. The value of T_i is given by the following equation:

$$T_i = \frac{L_i}{24\, v_i} \tag{4.26}$$

→ **C_i**: goods quantity transported along the leg ith [TEU];

→ **W_i**: average monetary value of cargoes on the leg ith [USD/TEU]. The cargo's value depends on the leg involved for example because the average value may be substantially different from eastbound and westbound;

→ **$i_{\%}$**: annual capital cost;

→ **α_i**: daily inventory costs on the leg ith per TEU [USD/(TEU*day)], which is equal to:

$$\alpha_i = \frac{W_i\, i\%}{365} \tag{4.27}$$

→ **t_j**: time spent at port jth [hours];

→ **C_j**: cargoes loaded and unloaded at the port jth [TEU];

→ **H**: handling cost per TEU [USD/TEU];

→ **T_0**: time for one ship to complete the route [days]. The value of T_0 is equal to:

$$T_0 = \sum_i \frac{L_i}{24\, v_i} + \sum_j t_j \qquad (4.28)$$

Which is basically the sum of the time spent at sea and the time spent at ports along the route by one vessel;

→ **t_0**: service period [days]. For example, if the service period is equals to 7, each ports is visited by a vessel every 7 days; The service period is the inverse of the service frequency. For example, if the service period is equal to 7, then the service frequency is one time a week;

→ **C_{ap}**: transport capacity of one vessel [TEU];

→ **E_d**: daily CO_2 emissions produced by the fleet [tonnes/day];

4.2.2 OBJECTIVE FUNCTION

The first step in order to develop the objective function of the optimization problem is to define the total carrier's profit for the considered route. For instance, one can consider a general route such as the route shown in figure 4.12:

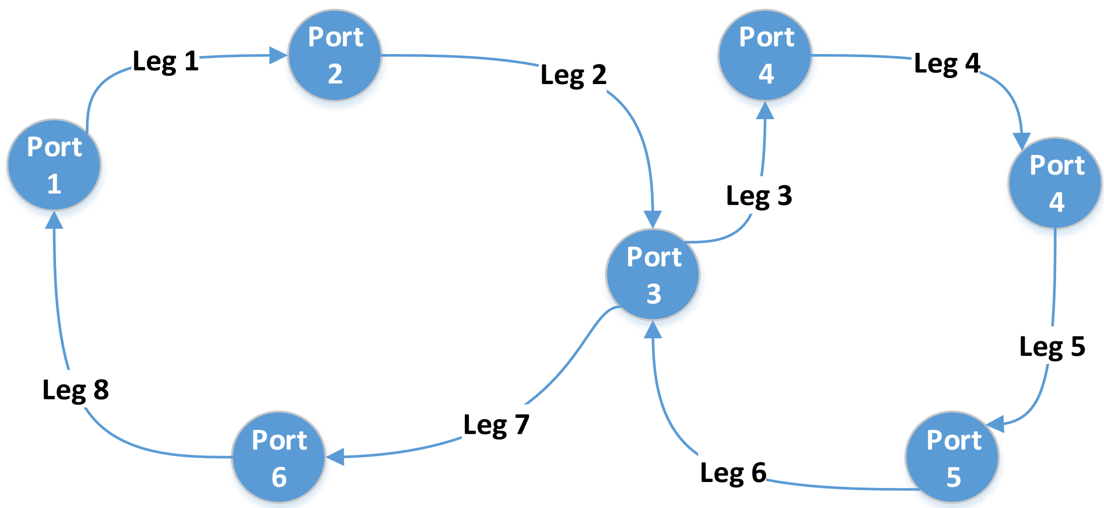


Figure 4.12: Representation of a general service lane

The total profit π [USD] that the carrier earns for the considered route is:

$$\pi = N \sum_x \sum_z F_{zx}\, c_{zx} \; - \; N \sum_i P\, f(v_i)\, T_i - N \sum_j P\, Fp\, t_j - N \sum_i \alpha_i\, C_i\, T_i - NE\, T_0 - N \sum_j H\, C_j \tag{4.29}$$

Where the first term regards the revenue, the second and the third terms regard the expenditures for fuel at sea and at ports respectively, the third item concerns the inventory costs, the fourth term concerns the operating costs and the last item is the sum of the handling costs. Subsequently, in order to compute the daily carrier's profit $\dot{\pi}$ for the route, the total profit must be divided by the time to complete the route T_0:

$$\dot{\pi} = \frac{\pi}{T_0} = \frac{N\, \sum_x \sum_z F_{zx}\, c_{zx} \; - \; N \sum_i P\, f(v_i)\, \frac{L_i}{24\, v_i} - N \sum_j P\, Fp\, t_j - N \sum_i \alpha_i\, C_i\, \frac{L_i}{24\, v_i} - NE\, T_0 - N \sum_j H\, C_j}{T_0} \tag{4.30}$$

The daily profit function can be rewritten employing the equation that establishes the relationship between T_0 and t_0:

$$t_0 = \frac{\sum_i \frac{L_i}{24\, v_i} + \sum_j t_j}{N} = \frac{T_0}{N} \tag{4.31}$$

This equation is the most significant constraint for the model and his meaning is explained in section 4.2.3. Employing such formula, the equation 4.30 becomes:

$$\dot{\pi} = \frac{1}{t_0} \left(\sum_x \sum_z F_{zx}\, c_{zx} \; - \sum_i P\, f(v_i)\, \frac{L_i}{24\, v_i} - \sum_j P\, Fp\, t_j - \sum_i \alpha_i\, C_i\, \frac{L_i}{24\, v_i} - \sum_j H\, C_j \right) - N\, E \tag{4.32}$$

Therefore, the objective function is:

$$\dot{\pi} = Max_{v_i, t_0, N} \left\{ \frac{1}{t_0} \left(\sum_x \sum_z F_{zx}\, c_{zx} \; - \sum_i P\, f(v_i)\, \frac{L_i}{24\, v_i} - \sum_j P\, Fp\, t_j - \sum_i \alpha_i\, C_i\, \frac{L_i}{24\, v_i} - \sum_j H\, C_j \right) - N\, E \right\} \tag{4.33}$$

Figure 4.13 reassume the total profit equation and his factors, besides it contains the objective function. As said, the main purpose of this thesis is to assess the freight rate influence on the containership's speed optimization problem. In order to achieve such aim, the revenue must be variable, which means that the model must consider the service frequency (similarly the service period) as a variable of the problem.

Total profit on the route

$$\pi = N\sum_{x}\sum_{z} F_{zx}\, c_{zx} - N\sum_{i} P\, f(v_i)\, T_i - N\sum_{j} P\, Fp\, t_j - N\sum_{i} \alpha_i\, C_i\, T_i - NE\, T_0 - N\sum_{j} H\, C_j$$

$N\sum_{x}\sum_{z} F_{zx}\, c_{zx}$	Revenue	$N\sum_{i} \alpha_i\, C_i\, T_i$	Inventory Costs
$N\sum_{i} P\, f(v_i)\, T_i$	Fuel expenditures at sea	$N\sum_{i} E\, T_i$	Daily Fixed Operating Costs
$N\sum_{j} P\, Fp\, t_j$	Fuel expenditures at ports	$N\sum_{j} H\, C_j$	Handling Costs

Objective Function

$$\dot{\pi} = Max_{v_i, t_0, N}\left\{\frac{1}{t_0}\left(\sum_{x}\sum_{z} F_{zx}\, c_{zx} - \sum_{i} P\, f(v_i)\, \frac{L_i}{24\, v_i} - \sum_{j} P\, Fp\, t_j - \sum_{i} \alpha_i\, C_i\, \frac{L_i}{24\, v_i} - \sum_{j} H\, C_j\right) - N\, E\right\}$$

Figure 4.13: Total profit equation and objective function

4.2.3 CONSTRAINTS

The problem is subject to three constraints, which are:

→ **Speed bounds**: the sailing speed of the ships along each leg is bounded above by v_{max} and bounded below by v_{min}. Both such bounds are due to technological limits, indeed the upper speed limit is imposed by the max power that the main engine can provide, whereas the lower limit is caused by the minimum operating condition of the main engine. Therefore, the speed of each vessel on each leg has to respect the following constraints:

$$v_i \le v_{max} \qquad \forall\, i \tag{4.34}$$

$$v_i \ge v_{min} \qquad \forall\, i \tag{4.35}$$

→ **N integer**: The number of ships obviously has to be integer and positive, therefore:

$$N \in \mathbb{N}^{+} \tag{4.36}$$

→ **Service period**: as said in section 4.1.2, in the containership liner market the number of ships deployed and the sailing speeds on each leg are linked by the service period. Basically, such constraint assures that the number of ships is sufficient to provide the specific required period and can be expressed as:

$$t_0 = \frac{\sum_i \frac{L_i}{24\, v_i} + \sum_j t_j}{N} = \frac{T_0}{N} \tag{4.37}$$

Since the speeds v_i as said above are bounded, one can clearly observe that given a certain period t_{0*}, the possible values for N are restricted. In fact, supposing that ships sail at the maximum allowable speed and at the minimum allowable speed, one can find the minimum and the maximum required number of ships, rounding up and down the following equations:

$$N_{min} = \left\lceil \frac{\sum_i \frac{L_i}{24\, v_{max}} + \sum_j t_j}{t_0^*} \right\rceil \tag{4.38}$$

$$N_{max} = \left\lfloor \frac{\sum_i \frac{L_i}{24\, v_{min}} + \sum_j t_j}{t_0^*} \right\rfloor \qquad (4.39)$$

Subsequently, the number of ships can be bounded between N_{max} and N_{min}:

$$N_{max} \geq N \geq N_{min} \qquad (4.40)$$

One can exploit this fact in order to shrink the set of value analysed by the resolution software hence the computing time. This fact is especially significant when the problem is non-linear;

4.2.4 LINEARIZATION

The objective function of the model is clearly non-linear. In fact, the variables v_i and t_0 are in the denominator and the daily fuel consumption function is a nonlinear function. Moreover, the constraint in equation 4.37 is also non-linear, being the speeds in the denominator. A non-linear problem is not trivial to be analysed and there is no certainty with regard to the optimality of the solution, besides the computing time required could be very long Nevertheless, in order to simplify the resolution of the problem, both the objective function and the constrain can be linearized. Doing that, any linear resolution software such as CPLEX can find the optimal solution quickly and properly. The stages in order to linearize the problem are:

→ The service period can reasonably assume a prescribed set of values. For example, a value t_0 equals to $\sqrt{2}$ is absurd because of obvious reasons. In addition, such value cannot practically be equal to 1000 or 0,01. Therefore, one can fix a set of possible values for t_0 (such as 3,4,5 etc.) and make the simulation for each value in the set. Thereby, being a fixed value t_0 is not a problem's variable and the optimal solution can be manually find from the optimal solution obtained for each value of t_0. As a consequence, the objective function can be written as:

$$\dot{\pi} = Max_{v_i,N} \left\{ \frac{1}{t_0} \left(\sum_x \sum_z F_{zx}\, c_{zx} - \sum_i P\, f(v_i)\, \frac{L_i}{24\, v_i} - \sum_j P\, Fp\, t_j - \sum_i \alpha_i\, C_i\, \frac{L_i}{24\, v_i} - \sum_j H\, C_j \right) - N\, E \right\} \quad \forall t_0 \qquad (4.41)$$

→ The variable v_i must be replaced by the variable u_i which is his reciprocal:

$$u_i = \frac{1}{v_i} \tag{4.42}$$

Replacing the variable u_i into the objective function, the equation (4.33) can be expressed as:

$$\dot{\pi} = Max_{u_i,N}\left\{\frac{1}{t_0}\left(\sum_x\sum_z F_{zx}\,c_{zx} - \sum_i P\,f(u_i)\,\frac{L_i\,u_i}{24} - \sum_j P\,Fp\,t_j - \sum_i \alpha_i\,C_i\,\frac{L_i\,u_i}{24} - \sum_j H\,C_j\right) - N\,E\right\} \quad \forall t_0 \tag{4.43}$$

After the substitution, the objective function is linear in the new variable u_i, excepted for the daily fuel consumption function. Moreover, the constraint (4.37) also becomes linear:

$$\text{N}\,t_0 = \sum_i \frac{L_i\,u_i}{24} + \sum_j t_j = T_0 \tag{4.44}$$

Finally, the constraints 4.34 and 4.35 can be rewritten as:

$$u_i \le u_{max} \qquad \forall\, i \tag{4.45}$$

$$u_i \ge u_{min} \qquad \forall\, i \tag{4.46}$$

Where u_{max} and u_{min} definitions are:

$$u_{max} = \frac{1}{v_{min}} \tag{4.47}$$

$$u_{min} = \frac{1}{v_{max}} \tag{4.48}$$

4.2.4.1 LINEARIZATION OF THE FUEL CONSUMPTION FUNCTION

Given a general daily fuel consumption function at sea, expressed as a power function of speed:

$$f(v) = a\, v^{b} \tag{4.49}$$

One can substitute, as previously made, the variable *v* with his reciprocal *u*:

$$f(u) = a\, u^{-b} \tag{4.50}$$

The function $Q(u)$ is a convex function. Therefore, as explained in (Wang and Meng, 2012), it is possible to use a piecewise linear function to approximate such function, making the objective function of the model a linear function. The linearization regards the fuel consumption per nautical mile function, that is:

$$Q(u) = \frac{a\, u^{1-b}}{24} \tag{4.51}$$

The linear approximation entails to make an error one the fuel consumption function, which is called $\bar{e}$ [tonne/NM]. Such error entails to make an error e on the evaluation of the optimal solution which is proportional to $\bar{e}$:

$$e = P\, \bar{e} \sum_{i} L_i \tag{4.52}$$

Therefore, the optimization error can be managed by setting a proper value of the error regarding the approximation of the fuel consumption function. The following algorithm, reported in (Wang and Meng, 2012), whose aim is the linearization of the fuel consumption function is coded in MATLAB and the program is attached in the appendix C. The first step is to define the first derivative of the function Q:

$$Q'(u) = \frac{a\,(1-b)\, u^{-b}}{24} \tag{4.53}$$

The piecewise linear function which approximates the fuel consumption function is defined by the points on the y-axis and the points on the x-axis for each approximant segment, which are Q^{k+1}, Q^{k}, u^{k+1} and u^{k} respectively. Moreover, each segment is characterized by the slope m_k which is equal to:

$$m_k = \frac{Q_{k+1} - Q_k}{u_{k+1} - u_k} \tag{4.54}$$

Consequently, the final approximation is a set of k segments. Figure 4.14 depicts a general piecewise function.

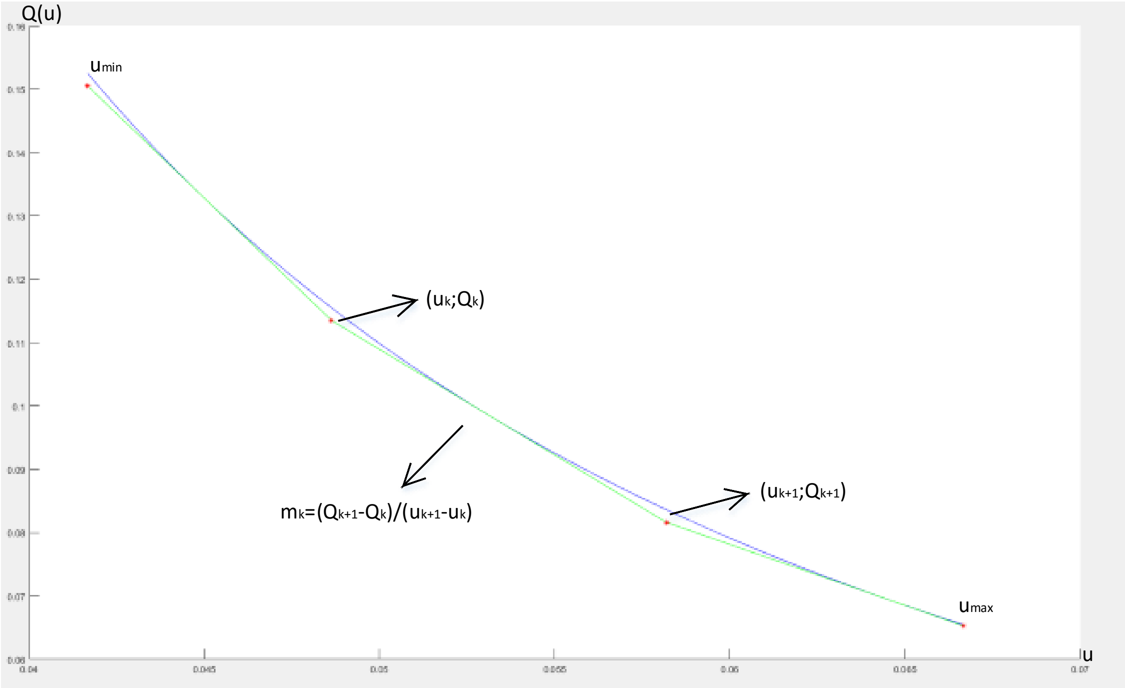


Figure 4.14: Example of the piecewise linear function in MATLAB

Therefore, the algorithm task is to calculate every segment of the piecewise function, assuring that the approximation error is lower than $\bar{e}(u_i)$. The algorithm is subdivided in several steps which are:

→ **Step 1**
The first point, for k=0, is defined as:

$$u_1 = u_{min} \quad and \quad Q_1 = Q(u_1) - \bar{e}(u) \tag{4.55}$$

→ **Step 2**
For k=k+1, if the inequality in 4.56, that means the point *(u_k, $Q(u_k)$)* is on or below the tangent line in u_{max}, holds:

$$\frac{Q(u_{max}) - Q_k}{u_{max} - u_k} = Q'(u_{max}) \tag{4.56}$$

Add the line k, defined as:

$$Q(u) = Q(u_{max}) - Q'(u_{max})\,(u_{max} - u) \tag{4.57}$$

to the set of line Ψ and go to the step 4. Else, add to Ψ the line that passes to the point (u_k, Q_k) and is tangent to the graph of $Q(u)$. Such line can be obtained as follows. Supposing that the tangent point of such line is $(\hat{u}_k, \hat{Q}_k)$ hence the following equations are valid:

$$\hat{Q}_k = \frac{a\,\hat{u}_k^{\,1-b}}{24} \tag{4.58}$$

$$\frac{\hat{Q}_k - Q_k}{\hat{u}_k - u_k} = Q'(\hat{u}_k) = \frac{a\,(1-b)\,\hat{u}_k^{\,-b}}{24} \tag{4.59}$$

Combining equation (4.58) and equation (4.59), one can estimate $\hat{u}_k$ by the bisection method and subsequently $\hat{Q}_k$ from equation (5.58). The equation of such line is:

$$Q(u) = \frac{\hat{Q}_k - Q_k}{\hat{u}_k - u_k}\,(u - u_k) - Q_k \tag{4.60}$$

→ **Step 3**

For the line found in equation (4.60), if the following inequality is valid:

$$Q_k + \frac{\hat{Q}_k - Q_k}{\hat{u}_k - u_k}\,(u_{max} - u_k) \geq Q(u_{max}) - \bar{e} \tag{4.61}$$

Go to step 4.

This statement means that the difference between the approximation line and the function $Q(u)$ is lower than $\bar{e}$ even u is equal to u_{max} hence the gap does not exceed the error for any value within u_k and u_{max}. Otherwise, it exactly exists one point (u_{k+1}, Q_{k+1}) along the line within $u_k < u_{k+1} < u_{max}$ such that:

$$Q_{k+1} = Q(u_{k+1}) - \bar{e} \tag{4.62}$$

The value of u_{k+1} can be obtained by the bisection method as previously made, combining the following equations:

$$Q_{k+1} = \frac{a\,u_{k+1}^{1-b}}{24} - \bar{e} \tag{4.63}$$

$$\frac{\hat{Q}_k - Q_{k+1}}{\hat{u}_k - u_{k+1}} = Q'(\hat{u}_k) = \frac{a\,(1-b)\,{u_{k+1}}^{-b}}{24} \qquad (4.64)$$

Go to step 1;

→ **Step 4**

The algorithm computes a set *Ψ* of lines. The generic form of such lines is:

$$Q = u\,m_k + Q_k \qquad (4.65)$$

Where m_k is the slope and Q_k is the intercept. Supposing the number of line is *n*, one can replace the fuel consumption function Q(u) with the approximated function $\bar{Q}(u)$, defined as follows:

$$\bar{Q}(u) = max\{u\,m_k + Q_k;\ \forall k = 1, 2 \ldots n\ \} \qquad (4.65)$$

Subsequently, the objective function of the model can be linearized introducing the new variable Q_i, which basically is the linearized fuel consumption per nautical mile:

$$\dot{\pi} = Max_{u_i,N}\left\{\frac{1}{t_0}\left(\sum_x\sum_z F_{zx}\,c_{zx} - \sum_i P\,Q_i\,L_i - \sum_j P\,Fp\,t_j - \sum_i \alpha_i\,C_i\,\frac{L_i\,u_i}{24} - \sum_j H\,C_j\right) - N\,E\right\} \quad \forall t_0 \qquad (4.66)$$

In addition, introducing a new set of constraints:

$$Q_i \geq u_i\,m_k + Q_k \quad \forall k = 1, 2 \ldots n \quad \forall i \qquad (4.67)$$

As explained in figure 4.15, since the problem is the maximization of the objective function, given a generic value of u_i, the resolver will take the feasible lowest value of *Qi*, respecting the constraints (6.67), that is the piecewise linear function.

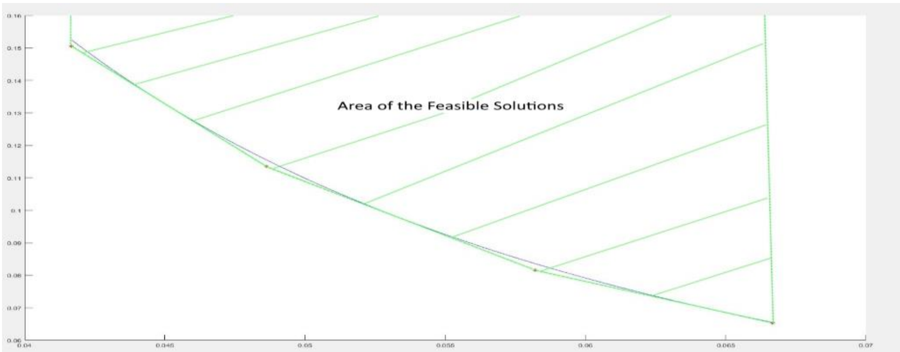


Figure 4.15: Area of feasible value for Q_i
The optimal value inside the area of the feasible solution is surely the lowest value of Qi, namely, the piecewise linear function used to linearize the fuel consumption function

4.2.5 LINEARIZED PROBLEM

The optimization problem employed in this study is:

$$\dot{\pi} = Max_{u_i,N}\left\{\frac{1}{t_0}\left(\sum_x \sum_z F_{zx}\, c_{zx} - \sum_i P\, Q_i\, L_i - \sum_j P\, Fp\, t_j - \sum_i \alpha_i\, C_i\, \frac{L_i\, u_i}{24} - \sum_j H\, C_j\right) - N\, E\right\} \quad \forall t_0 \tag{4.68}$$

Subjected to the following constraints:

$$Q_i \geq u_i\, m_k + Q_k \quad \forall k = 1, 2 \ldots n \quad \forall i \tag{4.69}$$

$$\mathrm{N}\, t_0 = \sum_i \frac{L_i\, u_i}{24} + \sum_j t_j \quad \forall i \quad \forall j \tag{4.70}$$

$$u_i \leq u_{max} \quad \forall\, i \tag{4.71}$$

$$u_i \geq u_{min} \quad \forall\, i \tag{4.72}$$

$$N \in \mathbb{N}^{+} \tag{4.73}$$

The thesis employs an Excel spreadsheet in order to implement the model.

4.2.6 EMISSIONS

The daily emissions of the deployed fleet can be computed as made for the calculation of the profits. The total CO_2 emissions E [tonnes] produced by the fleet for one route are:

$$E = N\, EF_{CO_2}\,(FC_{Sea} + FC_{Port}) \tag{4.74}$$

Where N is the number of vessels, EF_{CO_2} is the CO_2 emissions factor [tonnes of CO_2/tonnes of fuel], FC_{Sea} is the fuel consumption of both main engine and auxiliary at sea for one ship [tons of fuel] and FC_{port} is the fuel consumption of the auxiliary at port for one ship [tons of fuel].

The fuel consumption at sea, as previously said, is equal to:

$$FC_{Sea} = \sum_i Q_i\, L_i \tag{4.75}$$

Whereas the fuel consumption at ports is equal to:

$$FC_{Port} = \sum_j F_p\, t_j \tag{4.76}$$

Therefore, the total CO_2 can be expressed as:

$$E = N\, EF_{CO_2}\,(\sum_i Q_i\, L_i + \sum_j F_p\, t_j) \tag{4.77}$$

In order to evaluate the daily CO_2 emissions produced by the fleet E_d [tonnes of CO_2/day], the equation (4.77) must be divide by the route time T_0 and considering the equation (4.31), such value is equal to:

$$E_d = \frac{EF_{CO_2}\,(\sum_i Q_i\, L_i + \sum_j F_p\, t_j)}{t_0} \tag{4.78}$$

CHAPTER 5
NUMERICAL STUDIES

The chapter 5 deals with the application of the model on three real container liner routes which link:

→ North Europe and Asia

→ North America (West Coast) and Asia

→ North Europe and North America (East Coast)

Such lanes are characterized by many parameters, such as ports distances, freight rates, transport capacity utilization along the legs and many others. Therefore, the chapter reports the sources of such parameters and the estimations made.
As said in chapter 4, the model comprises three variables, correlated to each other, which are: the service period t_0, the number of ships N and the speed on each ith leg v_i. Consequently, the thesis analyses three different cases:

→ First case: the frequency is constant and the number of ships is variable. Therefore, the variables in such case are the speed and the number of deployed vessels;

→ Second case: the number of ships is constant and the frequency is variable hence the variables are the speeds and the service frequency;

→ Third case: both the frequency and the number of ships are variable however the number of ships is bounded above. This bound is implemented because otherwise the optimal number of ships may reach unrealistic values. Nevertheless, in order to prove this statement, an example in which the number of ships is unbounded is provided;

For each case, the effect of the following parameters on the decisional variables of the problem is addressed:

→ Bunker price

→ Freight rate

→ Operating costs

→ Inventory costs

At the end of the chapter, it is present a study regarding the impact on the fleet CO_2 emissions of implementing either a carbon tax or a speed limit.

5.1 Analysis of Simple Cases

The first and the second cases in which one of the variables is considered as constant can also be addressed analytically. Considering the simple case in which only two ports are present, as depicted in figure 5.1:

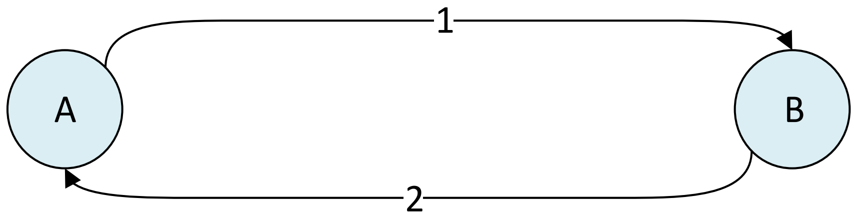


Figure 5.1: Example of a route in which only two ports are present

Considering only the freight rate *F*, the bunker price *P* and the operating costs *E*, the daily profit can be computed by the following equation:

$$\dot{\pi} = \frac{N\left[F_1\,C_1 + F_2\,C_2 - P\left(f(v_1)\frac{L}{24\,v_1} + f(v_2)\,\frac{L}{24\,v_2}\right) - E\,T_0\right]}{T_0} \tag{5.1}$$

Where *C* is the transported cargoes quantity, *L* is the leg's length and *f(v)* is the daily fuel consumption function. One can establish the daily fuel consumption function as a third power function of speed:

$$f(v) = k\,v^3 \tag{5.2}$$

As a consequence, the equation 5.1 becomes:

$$\dot{\pi} = \frac{[\, F_1 C_1 + \; F_2 C_2 - L\; P\; k \left(\frac{v_1^2}{24} + \frac{v_2^2}{24} \right)]}{t_0} - N\; E \qquad (5.3)$$

In addition, the service frequency entails that the number of ships and the speeds are linked by the following constrain:

$$T_0 = 2\; L \left(\frac{1}{24\; v_1} + \frac{1}{24\; v_2} \right) = N\; t_0 \qquad (5.4)$$

In order to further simplify the analysis one can first assume that:

→ $v = v_1 = v_2$

→ $F = F_1 = F_2$

→ $C = C_1 = C_2$

Assuming such equalities, one can rewrite the daily profit equation and the constraint as:

$$\dot{\pi} = N \; \left(\frac{12\; C\; F\; v}{L} - \frac{Pk\; v^3}{2} - E \right) \qquad (5.5)$$

$$T_0 = \frac{L}{6\; v} = \; N\; t_0 \qquad (5.6)$$

Moreover, the daily CO_2 emissions are:

$$E_d = \frac{EF_{CO_2} L\; k\; \frac{v^2}{12}}{t_0} = \; N\; EF_{CO_2} k\; \frac{v^3}{2} \qquad (5.7)$$

This simple model can explain which are the influencing parameters with regard to the optimization problem; moreover, the results provided by such model can be extended to realistic cases in which the number of variables, such as different speed along each leg, is much higher. The analytical results from these simple examples are subsequently validated through the simulation results.

5.1.1 FIXED FREQUENCY

If the service frequency is constant, then the profit optimization problem can be written as:

$$\max_{v,N}\{\dot{\pi}\} = \max_{v,N}\left\{\frac{2\,C\,F - P\,l\,k\,\frac{v^2}{12}}{t_0} - N\,E\right\} \tag{5.8}$$

And being t_0 fixed only the speed is a variable and the optimal speed value can be obtained from the following equation:

$$\min_v\left\{\;P\,k\,\frac{v^2}{2} + \frac{E}{v}\right\} \tag{5.9}$$

Therefore, it is clear that the speed's optimal value depends on the operating costs and the bunker price:

$$v_{optimal} \longrightarrow \left(\frac{E}{P}\right) \tag{5.10}$$

The arrow means that the optimal speed is connected to the ratio between *E* and *P*. Namely, the optimal speed depends on such ratio through a specific function. In order not to define e specific function for each decisional variable, the arrow is employed to define a dependency, which may be a different function depending on the specific case involved. Such convention is used throughout the paper.

Because of the equation 5.4, the optimal number of ships is proportional to the reciprocal of speed, hence the number of ships depend on:

$$N_{optimal} \longrightarrow \left(\frac{1}{v}\right) \quad therefore \quad N_{optimal} \longrightarrow \left(\frac{P}{E}\right) \tag{5.11}$$

As one can see, if the service frequency is fixed, the revenue does not influence neither the optimal speeds nor the optimal number of vessels. Such result is predictable, indeed if the service frequency is constant then the revenues are also constant. As regards the CO_2 emissions, considering the equation 5.7 the emissions depend on the speed hence are related to the same parameters of speed:

$$E_d \longrightarrow f(v) \quad therefore \quad E_d \longrightarrow f\left(\frac{E}{P}\right) \tag{5.12}$$

5.1.2 Fixed Number of Ships

The optimization problem in such case can be written as:

$$\max_{v,N}\{\dot{\pi}\} = \max_{v,N}\left\{N \left(\frac{12\ C\ F\ v}{L} - Pk\frac{v^3}{2} - E\right)\right\} \tag{5.13}$$

And being N fixed the only variable of the problem is the speed:

$$\max_{v}\{\dot{\pi}\} = \max_{v}\left\{\frac{12\ C\ F\ v}{L} - Pk\frac{v^3}{2}\right\} \tag{5.14}$$

From this equation, it is clear that the optimal speed depends on the freight rate and the bunker price:

$$v_{optimal} \longrightarrow \left(\frac{F}{P}\right) \tag{5.15}$$

Then, considering the equation 5.4, the optimal service period is proportional to the reciprocal of speed, hence the optimal period depends on:

$$t_{0,optimal} \longrightarrow \left(\frac{1}{v}\right) \quad therefore \quad t_{0,optimal} \longrightarrow \left(\frac{P}{F}\right) \tag{5.16}$$

Basically, such case is similar to the case addressed in (Psaraftis and Kontovas, 2012) with regard to the container liner market, that is considering the required service frequency. In fact, the optimization function is exactly the same. The daily CO_2 emissions, as stated before, are proportional to the speed hence are proportional to the freight rate and to the reciprocal of the bunker price:

$$E_d \longrightarrow (v) \quad therefore \quad E_d \longrightarrow \left(\frac{F}{P}\right) \tag{5.17}$$

5.2 Parameters Determination

The section deals with the definition of the parameters involved in the model. Collecting actual data regarding actual services is an exhausting challenge. For instance, there are no data available in literature and in the specialized magazines regarding specific routes or specific vessels. Since in order to simulate a real market case the model needs actual data with regard to several model's parameters, such as freight rates on each leg and the transport demand between ports, these data has to be estimated properly. Indeed, using average and general data provided in some specialized studies and magazines, it is possible to make some estimation whereby the model can fit the actual conditions. For example, even finding the vessels employed in a specific service and their characteristics such as the transport capacity in TEU or the max sailing speed is a non-trivial challenge. Therefore, the following sections explain how all the data employed in the model are estimated and the data sources employed for the estimations. Although the data are only appraisals, the main objective of the thesis, that is to assess how the market condition influences the sailing speeds in the liner market, can be achieved.

5.2.1.1 Transport Demand

The data regarding the transport demand between ports are not freely spread by shipping companies. Therefore, in order to assess the transport demand, it is necessary to follow another way. In (FMC, 2012) are reported several data with regard to the average capacity utilization of containerships in 2010. Such data are available for each service analysed by the thesis, which are shown in section 5.3. The transport capacity utilization percentages usually refer to either the westbound direction or the eastbound direction. Therefore, it is essential to define properly the legs to which the percentages refer. Indeed, it is not completely clear which legs have to be considered as "westbound" or as "eastbound". Typically, an international liner service is composed by two sets of ports: one in the first continent and one in the second one, as depicted in figure 5.2.

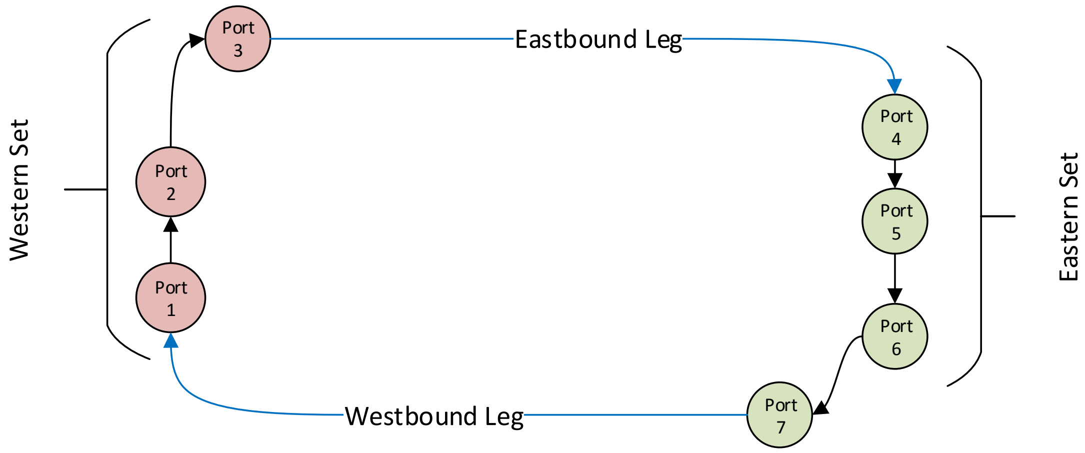


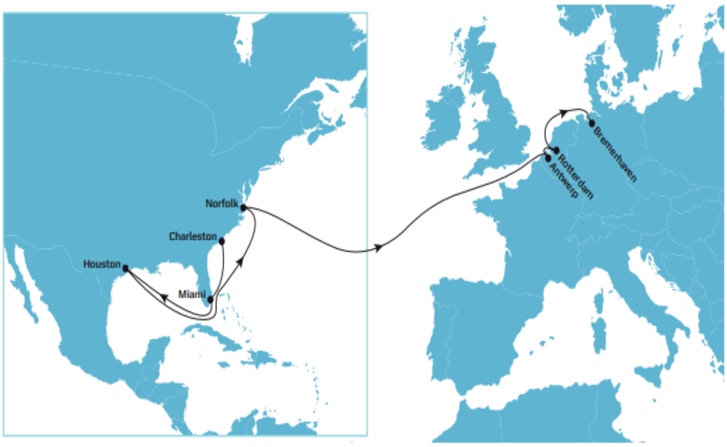
Figure 5.2: A typical arrangement of harbours in an international liner service
The legs, which link the two sets are usually the longest in the route

As a consequence, it seems to be logical to consider the legs which link these two sets as the eastbound leg and the westbound leg. Once defining the westbound leg and the eastbound leg, the demand between ports can be estimated. Basically, the transport demand between ports is hypothesized, ensuring that the capacity utilization on the westbound leg and the eastbound leg are approximately equal to the benchmark values. The schedule published on internet by shipping companies for the same service are always two: one schedule for the "eastbound transport demand" and one for the "westbound transport demand", as shown in figure 5.3. Equally, the model supposes that the cargoes travel only from eastern ports to western ports and vice versa. Moreover, it supposes that the demand is approximately the same for each port. The transport demand tables, the capacity utilization tables and the data provided in (FMC, 2012) are reported in the appendix D. Figure 5.4 reports an example of transport demand table, explaining better the framework of such tables.

TA1 EASTBOUND

SERVICE HIGHLIGHTS

- Coverage and flexibility from key points along the US East Coast
- Connecting to an extensive inland network for hinterland markets
- Provides US East Coast exporters flexibility into north Europe

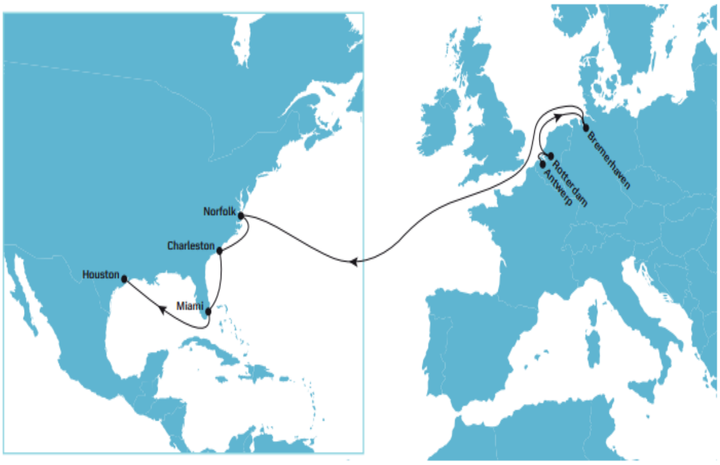


From	Dept\Arr	ANTWERP, Belgium SUN	ROTTERDAM, Netherlands MON	BREMERHAVEN, Germany WED
CHARLESTON, United States	MON	19	20	22
MIAMI, United States	WED	17	18	20
HOUSTON, United States	SUN	13	14	16
NORFOLK, United States	FRI	8	10	11

TA1 WESTBOUND

SERVICE HIGHLIGHTS

- Operating US flagged vessels
- Direct access to key locations on the east coast United States
- Comprehensive northern European coverage



From	Dept\Arr	NORFOLK, United States SAT	CHARLESTON, United States MON	MIAMI, United States WED	HOUSTON, United States SAT
ANTWERP,Belgium	MON	12	14	16	19
ROTTERDAM, Netherlands	TUE	10	12	14	17
BREMERHAVEN, Germany	THU	9	11	13	16

Figure 5.3: Example of the westbound and the eastbound schedule for the same route
Source: www.maerskline.com/lt-lt/shipping-services/routenet/maersk-line-network, 20-10-2016

Transport demand table				
Demand Table Westbound				
FROM/TO [TEU]	4	5	6	7
1	350	350	350	350
2	350	350	350	350
3	350	350	350	350

Demand Table Eastbound			
FROM/TO [TEU]	1	2	3
5	340	340	340
6	340	340	340
7	340	340	340
8	340	340	340

Table 5.1: Example of transport demand table
The numbers in the tables refer to a specific port, the western ports set comprise the ports 1, 2 and 3 whereas the eastern ports set comprises the ports 4, 5, 6 and 7. One can notice that the demand is the same for each western port or for each eastern port. Besides, the tables show that the demand is only among eastern ports and western ports

5.2.1.2 Inventory Costs

In order to evaluate the inventory costs along each leg, it is needed to know the average monetary value of a TEU on each routes, regarding both westbound and eastbound direction. The (FMC, 2012) reports two significant figures with regard to the assessment of the inventory costs:

→ The annual monetary value of cargoes transported westbound and eastbound: MV_{West} and MV_{East} respectively;

→ The annual quantity of TEU transported westbound and eastbound: Q_{West} and Q_{East} respectively;

Using such values, the average monetary value of a TEU transported westbound AV_{West} and eastbound AV_{East} [USD/TEU] can easily be computed as:

$$AV_{West} = \frac{Q_{West}}{MV_{West}} \quad (5.18)$$

$$AV_{East} = \frac{Q_{East}}{MV_{East}} \tag{5.19}$$

Subsequently, one can calculate the numbers of TEU heading to West and to East on each leg by the demand tables. Finally, considering the monetary value of TEU as AV_{West} for TEU heading to western ports and as AV_{East} for TEU heading to eastern ports, the monetary value of payloads on each leg can be computed as well as the related daily inventory costs by the equation 4.27. The average monetary values on each leg for the three routes and the benchmark values are reported in the appendix D. The annual capital costs *i%* is considered equal to 5% for each route.

5.2.1.3 Freight Rate

In order to calculate the carrier's revenue for transporting goods along the route it is necessary to know the freight rate per transported TEU between each couple of ports. Such information is not freely available besides it depends on many factors, such as the monetary value of the cargo and his dangerousness. Therefore, as done for the transport demand, the freight rates among ports must be estimated. Taking a couple of ports as the benchmarks, one can obtain the freight rate for such ports on the following website: http://www.worldfreightrates.com. The benchmark freight rate should be taken for both eastbound and westbound with regard to the same couple of ports. Indeed, as discussed in section 4.1.3, freight rates are significantly influenced by the voyage direction and the difference might be substantial. Moreover, one should select one port from the eastern set and the other one from the western set. For example, as regards the AE2 lane, one can take the Felixstowe's port and the Shanghai's port as benchmarks, finding the eastbound as well as the westbound freight rate between such ports in the worldfreightrates's site. Subsequently, the freight rate values are divided by the distances of the involved ports, thus the result can be considered as the average income per TEU transported per nautical mile, eastbound and westbound respectively. Finally, one can calculate the freight rates table multiplying the previous values to the distances among ports. The freight rates table contains the freight rate for each couple of ports. The benchmark values and the freight rates tables for each route are reported in appendix D.

5.2.1.4 Fuel Consumption Calibration

Along each route are disposed different type of ships with different characteristics such as the transport capacity and the construction year. As a consequence, the fuel consumption for such vessels is different. Nevertheless, the model formulation considers only one possible fuel consumption function hence only a vessel type for the route because considering different type of vessels would require longer computing time and the complexity of the model would sharply increase. Therefore, the model needs an average fuel consumption function which must approximate the average characteristics of the ships. Shipping companies do not freely furnish actual data concerning the fuel consumption of ships therefore the fuel consumption data are estimated using an Excel spreadsheet provided in https://www.shipowners.dk/en/services/beregningsvaerktoejer (the spreadsheet is specifically designed for containerships). The spreadsheet requires some data regarding the ship, such as the dimensions, the deadweight and the capacity in TEU. The ship features employed in the spreadsheet are the average values concerning the vessels deployed on the route. Fundamentally, the spreadsheet computes the consumption per hour at sea of the main engine and the auxiliary and the consumption per hour at port of the auxiliary for a specific speed. Since the model requires the daily consumption function which is a function of the speed, the results obtained for a set of speeds must be represented in a graph, then the best interpolating function can be assessed, as shown in figure 5.4:

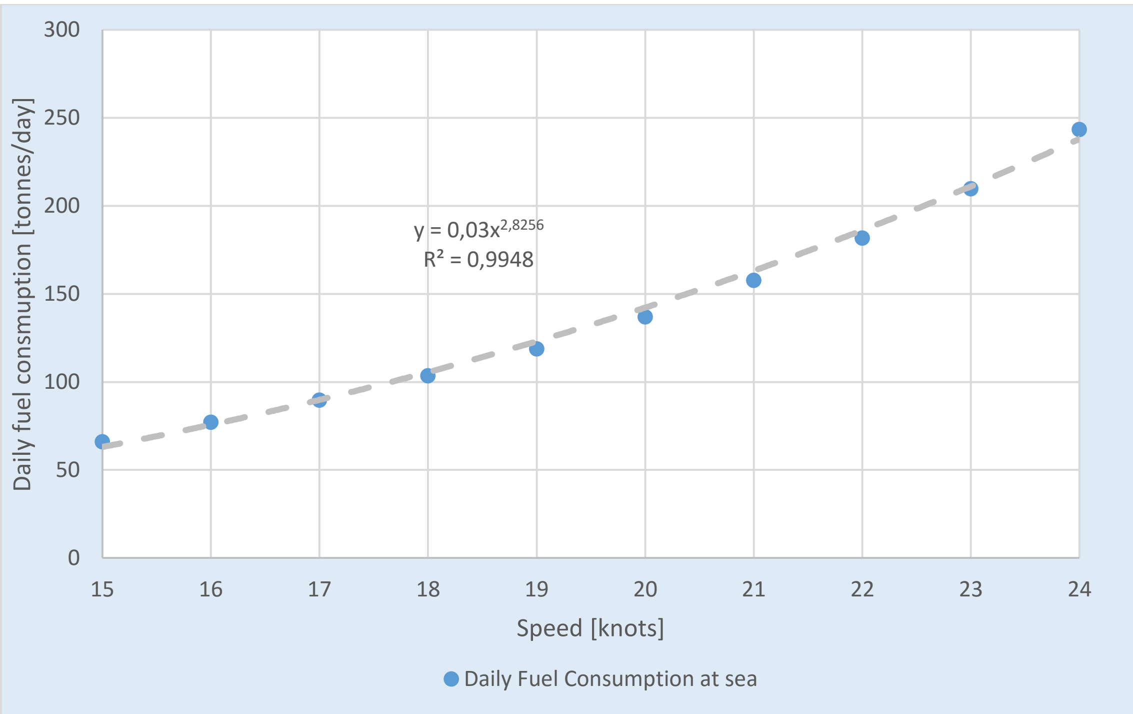


Figure 5.4: Interpolating curve for the AE2 lane
The grey line is the interpolating function

The interpolating function must have the following form:

$$f(v) = k\, v^n \tag{5.20}$$

Subsequently, employing the linearization MATLAB program the function is linearized. The appendix D reports the values of *k* and *n* for each route and the interpolating graphs. The bunker prices are taken from the website: www. http://shipandbunker.com/prices. In the website are reported the prices for three type of fuel: IFO 380, IFO 180 and MGO, moreover the prices are provided for several harbours in different locations, such as Rotterdam, New York and Hong Kong. The table 5.2 reports the bunker price employed as base scenario in the thesis, such value is the average of the value for the ports involved moreover the model considers that the fuel employed by the fleet is IFO 180.

Base Bunker Price [USD/tonne]	
Singapore	362
Rotterdam	348
Houston	387
Fujairah	363,5
LA-Long Beach	373
Hong Kong	371
Istanbul	361,5
New York	360,5
Rio de Janeiro	378
Piraeus	356
Gibraltar	350,5
Average	364,6

Table 5.2: Base bunker price considered in the model
Adapted from: www. http://shipandbunker.com/prices, 6-01-2017

Finally, the model considers the maximum speed equal to 24 knots while the minimum speed equal to 15 knots.

5.2.1.5 Operating Costs

(Drewry, 2015) reports the following operating costs for vessel size in figure 5.5:

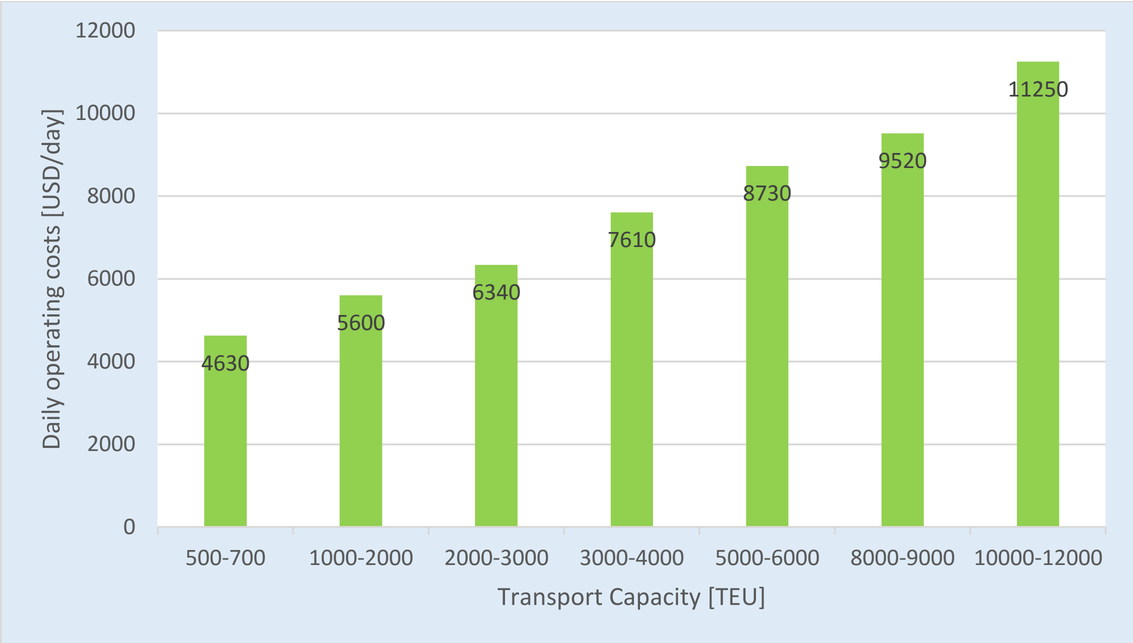


Figure 5.5: Daily operating costs for vessel size in 2014
Adapted from: Drewry Maritime Research, Ship Operating Costs Annual Review and Forecast, Table 3.2.1.

Since the AE2 comprises ships with a transport capacity higher than 12000 TEU, the operating costs for such lane must be estimated. Assuming a linear interpolating function, one can obtain the following equation:

$$OP_d = 0{,}5962\, TEU + 4849{,}9 \tag{5.21}$$

Where OP_d [USD/TEU] are the daily operating costs and *TEU* is the capacity [TEU]
Such equation can be employed to assess the daily operating costs for the vessels deployed along the route AE2 whereas the operating costs with regard to the TP1 lane and NEUATL1 lane are directly obtained from the table 2.7., moreover the results are reported in table 5.5.

Operating Costs	
Route	**Daily operating costs [USD/day]**
AE2	15357
TP1	9125[22]
NEUATL1	8730

Table 5.3: Daily operating costs for each route

As discussed in section 2.3, the operating costs should also contain the depreciation cost which is the cost related to the ship purchase. The depreciation cost can be assessed using the equation 2.3 and assuming a depreciation period of 20 years. However, the value of the ship at scrapheap is not considered in this thesis. The assumed prices of a new ship for the three routes and the associated daily depreciation costs are reported in table 5.3; such prices obviously are different, mainly because they depend on the transport capacity of the vessels.

Depreciation Cost		
Route	**Purchase price [millions of USD]**	**Daily depreciation cost [USD/day]**
AE2	140[23]	19200
TP1	98,4[24]	13500
NEUATL1	69,5[25]	9500

Table 5.4: Daily depreciation costs for each route

Therefore, the values for the operating costs *E* employed in the model, whose results are reported in table 5.4, is the sum of the daily operating costs and the daily depreciation cost.

E values used in the model	
Route	**Daily operating costs [USD/day]**
AE2	34557
TP1	22625
NEUATL1	18230

Table 5.5: Operating costs used in the model

One can consider daily fixed operating costs *E* as the daily payment for the rent of the ship. In such case, the value of *E* should refer to the current condition concerning the ship renting market. However, the optimization function has the same formulation.

[22] The value is the average of the range 8000-9000 and the range 5000-6000 of figure 5.5
[23] Source: https://en.wikipedia.org/wiki/MSC_Zoe
[24] [47] (Murray, 2016)

5.2.1.6 Time at Ports

The time at ports are derived from the ship schedules provided on the Maersk site. As shown in figure 5.5, such schedules contain the time of arrival and the departure time for each port. The difference between these two values is the time at port considered in the model.

Schedules for **MSC ZOE**

Port	Terminal	Arrival	Voyage	Departure
Felixstowe	Felixstowe Trinity Terminal	18 Feb 2017, 19:00	702W | 708E	20 Feb 2017, 16:00
Antwerp	Deurganck Terminal Quays 1732-1742	21 Feb 2017, 22:00	702W | 708E	23 Feb 2017, 14:00
Wilhelmshaven	Eurogate Container Terminal GmbH	24 Feb 2017, 14:00	702W | 708E	25 Feb 2017, 06:00
Bremerhaven	NTB North Sea Terminal Bremerhaven	25 Feb 2017, 18:00	702W | 708E	26 Feb 2017, 12:00
Rotterdam	APM 2 Terminal Maasvlakte II	27 Feb 2017, 11:00	702W | 708E	28 Feb 2017, 23:00
Suez Canal	Canal Zone Terminal	08 Mar 2017, 23:00	708E | 708E	08 Mar 2017, 23:01
Suez Canal	Canal Zone Terminal	09 Mar 2017, 14:59	708E | 708E	09 Mar 2017, 15:00
Colombo	Colombo Intl Contr Tml	17 Mar 2017, 16:00	708E | 708E	18 Mar 2017, 08:00
Singapore	Singapore PSA Terminal	21 Mar 2017, 23:00	708E | 708E	23 Mar 2017, 00:01
Hong Kong	Hong Kong Modern Terminals Ltd	26 Mar 2017, 09:00	708E | 708E	27 Mar 2017, 02:00
Yantian	YanTian Intl. Container Terminal	27 Mar 2017, 08:00	708E | 708E	28 Mar 2017, 02:30
Xingang	Tianjin PAC Int'l Cntr Terminal	31 Mar 2017, 11:00	708E | 713W	02 Apr 2017, 03:00
Qingdao	Qingdao Qianwan Container Co Ltd	03 Apr 2017, 03:00	708E | 713W	04 Apr 2017, 02:00
Busan	Busan new port terminal Co.ltd	05 Apr 2017, 05:00	708E | 713W	05 Apr 2017, 23:00
Ulsan	Busan International Transhipment	06 Apr 2017, 01:00	708E | 713W	06 Apr 2017, 02:00
Shanghai	Yangshan, SGH Shengdong Terminal	07 Apr 2017, 00:01	708E | 713W	08 Apr 2017, 00:01
Ningbo	Beilun Container Terminal Phase 4	08 Apr 2017, 09:00	708E | 713W	09 Apr 2017, 16:00
Yantian	YanTian Intl. Container Terminal	11 Apr 2017, 18:00	713W | 713W	12 Apr 2017, 09:00
Tanjung Pelepas	Pelabuhan Tanjung Pelepas Terminal	15 Apr 2017, 12:00	713W | 713W	16 Apr 2017, 22:00
Suez Canal	Canal Zone Terminal	27 Apr 2017, 23:00	713W | 713W	27 Apr 2017, 23:01
Suez Canal	Canal Zone Terminal	28 Apr 2017, 14:59	713W | 713W	28 Apr 2017, 15:00
Algeciras	Algeciras - ML Terminal	02 May 2017, 20:00	713W | 713W	03 May 2017, 20:00
Felixstowe	Felixstowe Trinity Terminal	06 May 2017, 19:00	713W | 719E	08 May 2017, 16:00

Figure 5.6: Example of a vessel schedule containing the arrival and departure times
Source: www.my.maerskline.com/schedules, 20-10-2016

5.3 SERVICES

The thesis deals with three routes on the mainlane East-West, which are:

→ **AE2**: such service links Asia to North Europe and is provided by Maersk. Nevertheless, the same service is also provided by MSC under the name SWAN. Indeed, both Maersk's ships and MSC's ships are deployed along the route;

→ **TP1**: the route connects Asia to the West Coast of North America. Maersk offers the service however, the same service is also provided by MSC and it is called EAGLE. As for the AE2 service, along the TP1 route are deployed Maersk's vessels as well as MSC's vessels;

→ **NEUATL1**: the NEUATL1 lane links North Europe to the US East Coast. The service is furnished by MSC or similarly by Maersk under the name TA1;

The section contains the main features of such services. Fundamentally, the next three sections report the route maps and the legs' length. The route maps allow to distinguish eastern ports and western ports as well as the eastbound leg and the westbound leg. Besides, the section contains the average characteristics of the fleet for each route, such as the average transport capacity and the average deadweight. The average vessel characteristics are the mean of the fleet's value. The complete information regarding the characteristics for each vessel are reported in the appendix D.

5.3.1 North Europe-Asia Lane (AE2)

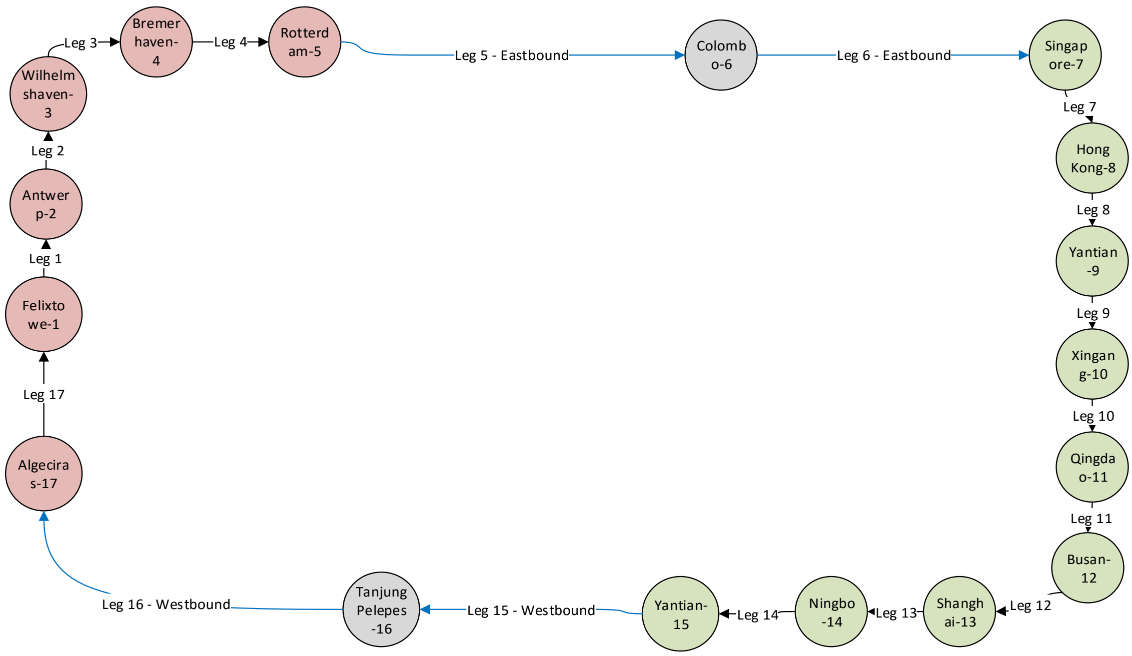


Figure 5.7: AE2 route maps
The legs in blue are the westbound and the eastbound legs. The eastern ports set comprises the green ports whereas the western ports set comprises the red ports. The ports in grey are the intermediate ports.

Distances [NM]	
1 to 2	141
2 to 3	346
3 to 4	63
4 to 5	255
5 to 6	6755
6 to 7	1567
7 to 8	1460
8 to 9	41
9 to 10	1406
10 to 11	412
11 to 12	502
12 to 13	492
13 to 14	127
14 to 15	721
15 to 16	1512
16 to 17	6946
17 to 1	1296

Average vessel characteristics	
TEU Capacity [TEU]	18459,1
Deadweight [tonnes]	192447,8
Length Overall [m]	398,326
Breadth Extreme [m]	58,487
Power [kW]	57414

Table 5.6: Distances between ports and average vessel characteristics for the AE2 route
Data sources (the complete characteristics of the fleet is present in the appendix D):

- *The distances among ports are furnished in www.sea-distances.org, 10-12-2016*
- *The transport capacity is reported in my.maerskline.com, 10-12-2016*
- *The deadweight, the length overall and the breadth extreme are provided in www.marinetraffic.com, 10-12-2016*
- *The power is reported in www.scheepvaartwest.be, 10-12-2016*

5.3.2 Asia-North America Lane (TP1)

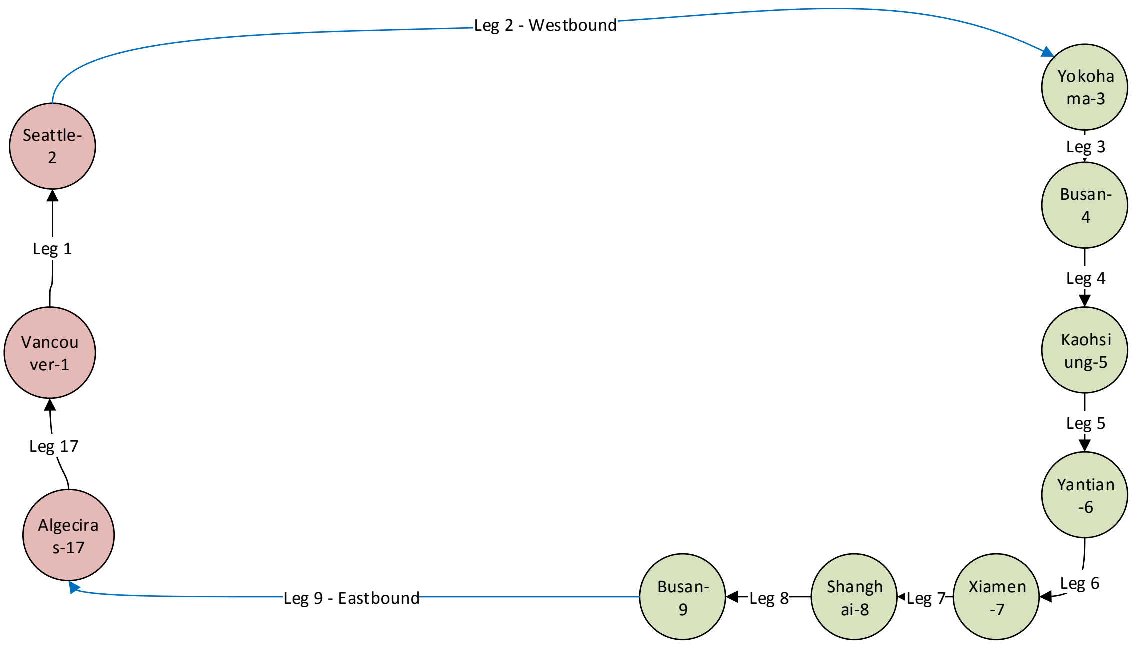


Figure 5.8: TP1 route maps
The legs in blue are the westbound and the eastbound legs. The eastern ports set comprises the red ports whereas the western ports set comprises the green ports.

Distances [NM]	
1 to 2	136
2 to 3	4244
3 to 4	687
4 to 5	930
5 to 6	339
6 to 7	274
7 to 8	545
8 to 9	460
9 to 1	4554

Average vessel characteristics	
TEU Capacity [TEU]	7073
Deadweight [tonnes]	77637
Length Overall [m]	292,83
Breadth Extreme [m]	36,52
Power [kW]	48511,4

Table 5.7: Distances between ports and average vessel characteristics for the TP1 route
Data sources (the complete characteristics of the fleet is present in the appendix D):

- *The distances among ports are furnished in www.searates.com, 12-12-2016*
- *The transport capacity is reported in my.maerskline.com and www.containership-info.com, 12-12-2016*
- *The deadweight, the length overall and the breadth extreme are provided in www.marinetraffic.com, 12-12-2016*
- *The power is reported in www.containership-info.com, 12-12-2016*

5.3.3 North Europe-North America Lane (NEUATL1)

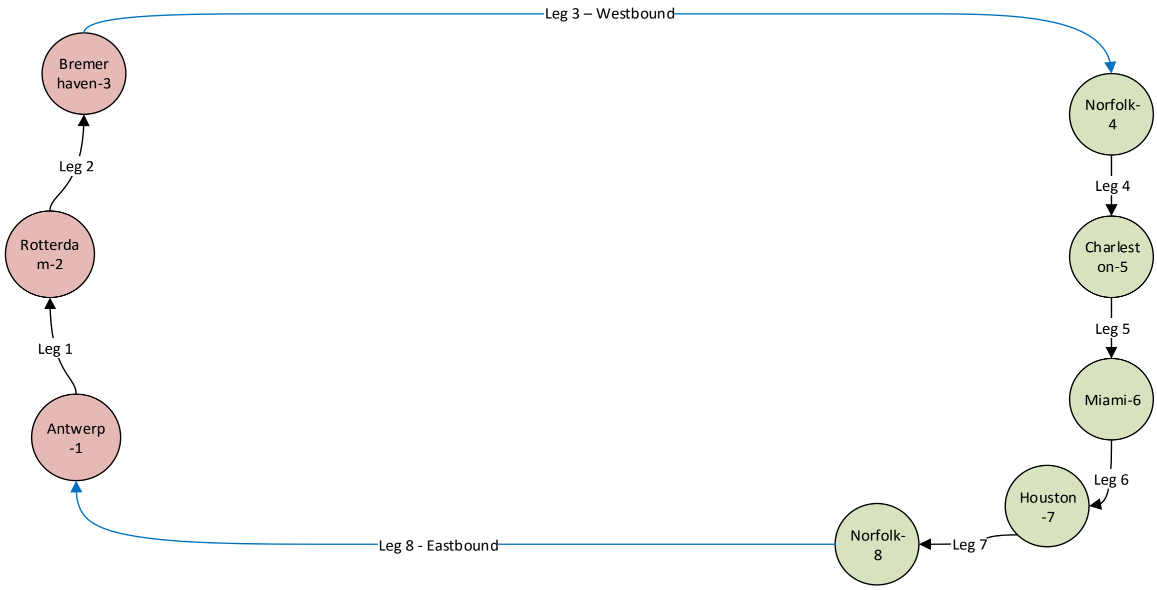


Figure 5.9: NEUATL1 route maps
The legs in blue are the westbound and the eastbound legs. The eastern ports set comprises the red ports whereas the western ports set comprises the green ports.

Distances [NM]	
1 to 2	108
2 to 3	245
3 to 4	3623
4 to 5	413
5 to 6	433
6 to 7	952
7 to 8	1700
8 to 1	3474

Average vessel characteristics	
TEU Capacity [TEU]	4739
Deadweight [tonnes]	61880
Length Overall [m]	292,1
Breadth Extreme [m]	32,33
Power [kW]	44147,6

Table 5.8: Distances between ports and average vessel characteristics for the NEUATL1 route
Data sources (the complete characteristics of the fleet is present in the appendix D):

- *The distances among ports are furnished in www.searates.com, 13-12-2016*
- *The transport capacity is reported in my.maerskline.com and www.containership-info.com, 13-12-2016*
- *The deadweight, the length overall and the breadth extreme are provided in www.marinetraffic.com, 13-12-2016*
- *The power is reported in www.containership-info.com, 13-12-2016*

CHAPTER 6
RESULTS

Chapter 6 reports the results obtained by the model. The section splits in three main subsections:

→ Section 6.1, named "Sensitivity analysis", contains the main results regarding the effects in the three analysed scenarios of a variation of the bunker price, the freight rate and the operating fixed costs. Indeed, such parameters influences the decisional variables of the problem which are the service frequency, the number of ships and the speed on each leg, hence influencing also the CO_2 emissions;

→ Section 6.3 analyses the influence of the inventory costs with regard to the speed on each leg of the route;

→ Finally, section 6.2 deals with the impacts upon the CO_2 emissions of applying two market based measures; namely a bunker levy (or likewise a carbon tax) and a speed limit;

In order to facilitate the reading, the section does not contain all the results from the simulations but it reports only the most significant outcomes.

6.1 SENSITIVITY ANALYSIS

In order to assess the influence of freight rate, bunker price and the operating fixed costs it is necessary to vary such parameters. Fundamentally, for each of the three scenarios involved, such three parameters are changed, afterwards it is possible to evaluate the influence upon the model variables of such fluctuations. The thesis considers the parameters' variation as a percentage fluctuation from the "base value". The "base values" are the values of bunker price, freight rate and operating costs considered as basis for the study. From such benchmark values, the study considers different scenarios in which the variations are expressed as a percentage change of the "base values". For example, considering the base bunker price as 300 USD/tonne, the impact of the bunker price is assessed by simulating some scenarios in which the bunker price is a percentage variation of such value, such as considering a bunker price of 360 USD/tonne which is a percentage change of +20% from the base value. The “base values” are reported in the appendix D and in the chapter 5.2 e; anyway, the table 6.1 reassumes such parameters for the three routes involved. A scenario in which the parameters are “base values” is consequently the “base scenario”. Each scenario employs the base values of each parameter except for the parameters for which a table providing the new parameters’ values is furnished.

Base parameters values				
Route	Bunker price, P [USD/tonne]	Freight rate-westbound, F-WB [USD/TEU]	Freight rate eastbound, F-EB [USD/TEU]	Daily operating fixed costs for a ship, E [USD/day]
AE2	364,6	690	675	34557
TP1	364,6	360	1070	22625
NEUATL1	364,6	1260	1150	18230

Table 6.1: Base parameters values for the three routes involved
For the sources of these data refers to section 5.2 and appendix D

The sensitivity analysis employs the parameter called average speed $v_{average}$. As reported in the equation 6.1, the average speed is equal to:

$$v_{average} = \frac{Route\ Lenght}{24\ T_0'} \tag{6.1}$$

Where *Route Length* is the overall length of the route [NM] and T_0' is the travel time [days] for the route without considering the time spend at ports. Namely, the value of T_0' is given by the following relationship, which derives from the equation 4.28:

$$T_o' = \sum_i \frac{L_i}{24\ v_i} = T_0 - \sum_j t_j \tag{6.2}$$

The average speed is the sailing speed of a vessel if the vessel would travel at a constant speed. Such speed is useful to assess easily how the speed changes in different scenarios. Otherwise, it would be necessary to analyse the speeds on each leg, which would be difficult, moreover a clear representation would be unachievable. The service periods employed for the simulations are: 3.5 (a twice a week frequency), 4, 5, 6, 7 (a weekly frequency), 8, 9, 10, 14 (a frequency of one time in two weeks). Finally, as defined in section 5.1.1, in order not to define a specific function for each decisional variable, which defines the link between the variable and the parameters of the problem, the paper employs an arrow in order to specify that there is a dependency. Such dependency depends on the specific case involved.

6.1.1 Fixed Frequency Scenario

The fixed frequency scenario's service period employed in the simulations is equal to 7 for each route as such value is the most common in the containership market.

6.1.1.1 Operating Costs Effect

The daily fixed operating *E* costs influence the average speed of the vessels, the number of ships employed and hence the CO_2 emissions. Increasing the value of *E* diminishes the number of ships deployed as the total daily expenditure is given by multiplying *E* to the number of ships N. Since the service frequency is constant, such effect also leads to increase the average sailing speed hence the daily CO_2 emissions produced by the fleet. Therefore, one can state the following proportional relationships:

$$N \longrightarrow \left(\frac{1}{E}\right) \quad (6.3)$$

$$v_{average} \longrightarrow f(E) \quad (6.4)$$

$$E_d \longrightarrow f(E) \quad (6.5)$$

Figures 6.1, 6.2, 6.3 depict the effect of *E* in the AE2 route on the average speed, the number of ships and the CO_2 emissions respectively. Table 6.2 reports the daily operating costs' values for the different scenarios.

Daily operating costs		
Scenario	**E [USD/day]**	**Variation**
1	6911,4	-80%
2	20734,2	-40%
3	31101,3	-10%
4-base	34557	/
5	38012,7	+10%
6	48379,8	+40%
7	62202,6	+80%

Table 6.2: Fixed frequency scenario, daily operating costs (route AE2)

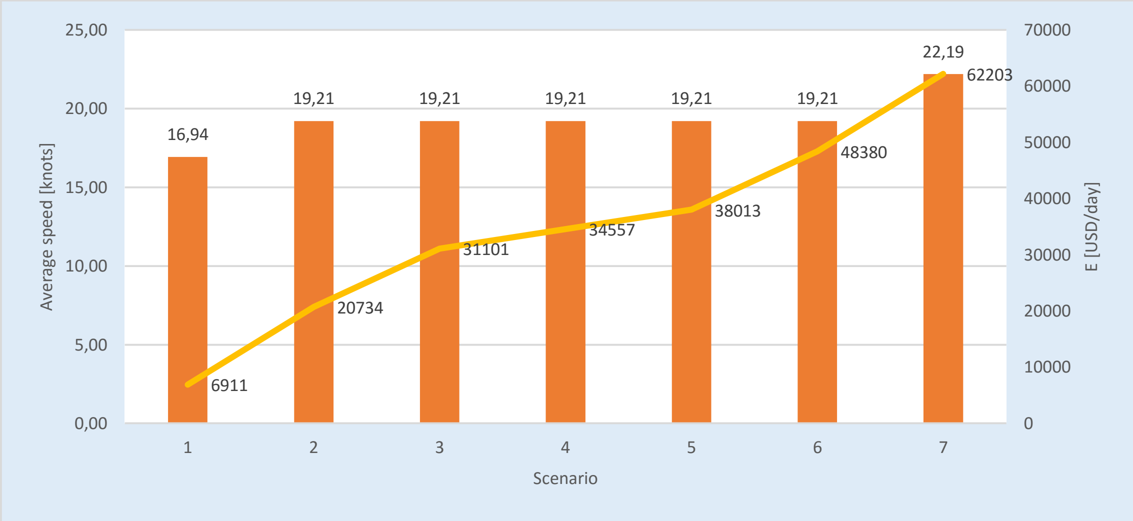


Figure 6.1: Fixed frequency scenario, effect of E on the average speed (route AE2)

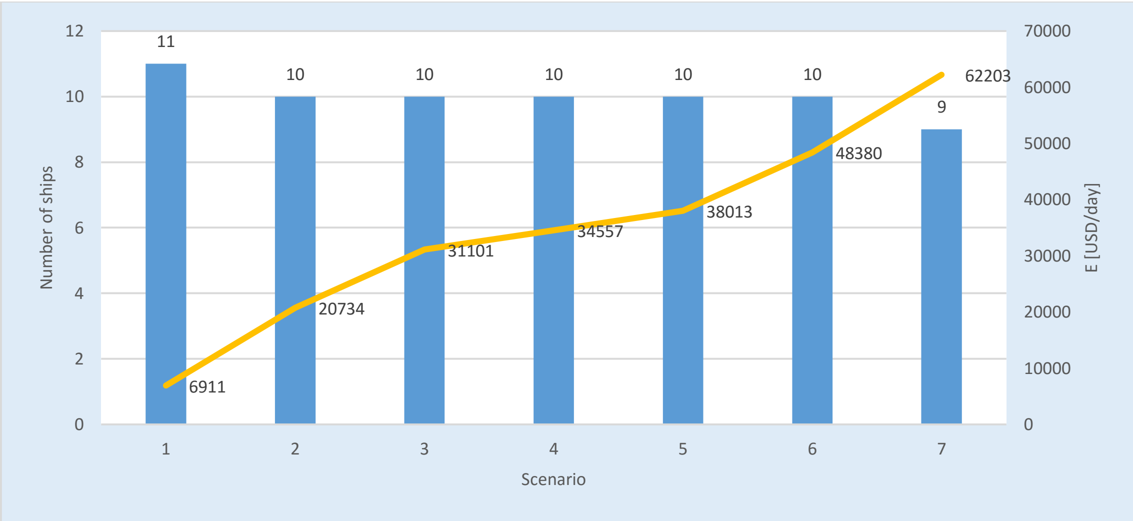


Figure 6.2: Fixed frequency scenario, effect of E on the number of ships (route AE2)

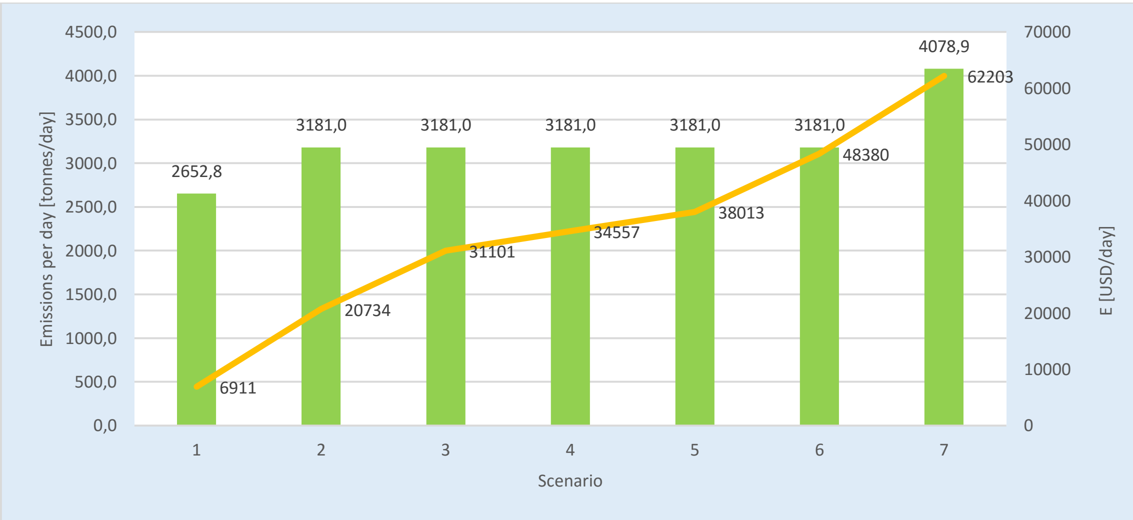


Figure 6.3: Fixed frequency scenario, effect of E on the daily CO_2 emissions (route AE2)

6.1.1.2 BUNKER PRICE EFFECT

The bunker price variation has the opposite effect of the operating costs. Increasing the punker price decreases the average speed of the vessels hence their emissions whereas it increases the number of ships deployed. Since the fuel expenditure are related to the average sailing speed, if the bunker price increases the optimal decisions is to diminish the speed, increasing the number of ships in order to maintain the service frequency constant. As stated in section 4.1.3.1, increasing the number of ships deployed also reduces the CO_2 emissions despite of the increasing number of vessels. Therefore, one can state the following proportional relationships:

$$N \longrightarrow (P) \tag{6.6}$$

$$v_{average} \longrightarrow \left(\frac{1}{P}\right) \tag{6.7}$$

$$E_d \longrightarrow \left(\frac{1}{P}\right) \tag{6.8}$$

The previous statements are shown in figures 6.4, 6.5 and 6.6. Moreover, the table 6.3 reports the bunker price used in the different scenarios.

Scenario	Bunker price P [USD/tonne]	Variation
1	146	-60%
2	292	-40%
3	328	-10%
4-base	365	/
5	401	+10%
6	438	+40%
7	583	+60%

Table 6.3: Fixed frequency scenario, bunker price (route AE2)

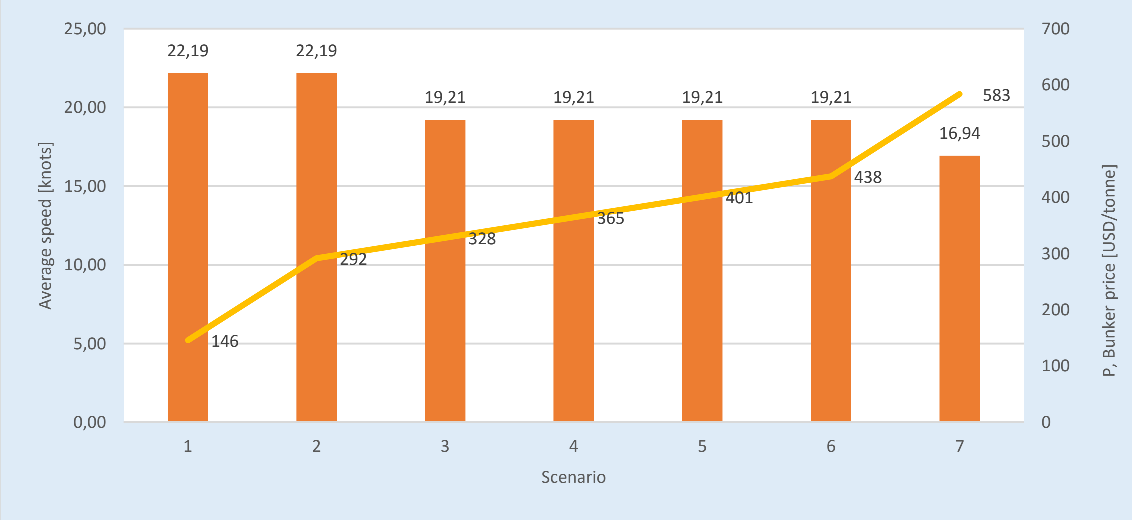


Figure 6.4: Fixed frequency scenario, effect of P on the average speed (route AE2)

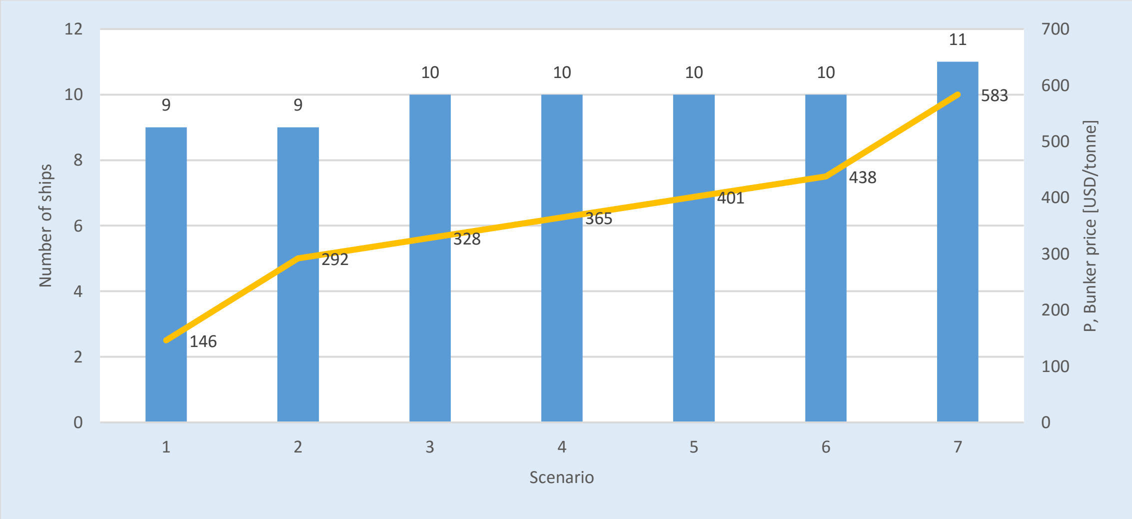


Figure 6.5: Fixed frequency scenario, effect of P on the number of ships (route AE2)

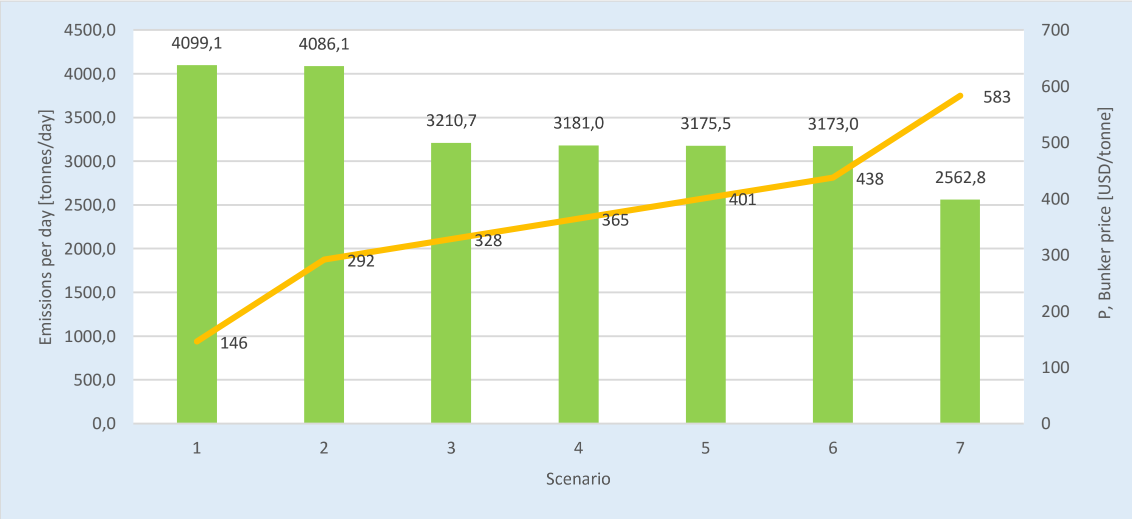


Figure 6.6: Fixed frequency scenario, effect of P on the daily CO_2 emissions (route AE2)

Besides, as stated in the section 5.1.1, the number of ships and the average speed should be proportional to the ratio between the daily operating fixed costs and the bunker price. Such statement is true as long as the inventory costs and the handling costs are not considered in the model. Figure 6.5 depicts how the number of ships (one can see the same effect on the average speed as well as on the daily emissions) changes even if the ratio is constant. On the contrary, figure 6.6 shows that in the case in which the inventory costs and the handling costs are neglected, if the ratio is constant then the number of ships does not vary. Therefore, when the model considers the handling costs and the inventory costs, the problem's variables depend on *E* and *P* but they are not a function of the ratio between *E* and *P*. The following equations describe such behaviour when the model takes into account the inventory and the handling costs:

$$N \longrightarrow \left(\frac{1}{E}, P\right) \tag{6.9}$$

$$v_{average} \longrightarrow \left(E, \frac{1}{P}\right) \tag{6.10}$$

$$E_d \longrightarrow \left(E, \frac{1}{P}\right) \tag{6.11}$$

The table 6.4 reports the scenarios' parameters concerning the scenarios in figure 6.7 and figure 6.8.

		Ratio E/P		
Scenario	**E [USD/day]**	**P [USD/tonne]**	**Variation**	**Ratio E/P**
1	17278,5	182,3	-50%	50
2-base	34557	364,6	/	50
3	69114	729,2	+100%	50

Table 6.4: Fixed frequency scenario, daily operating costs and bunker prices (route AE2)

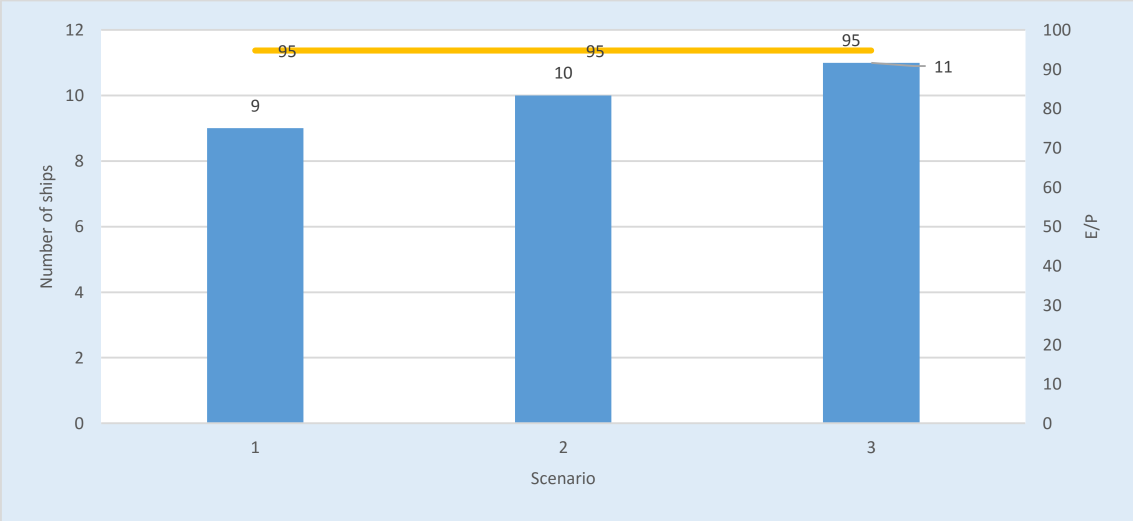


Figure 6.7: Fixed frequency scenario considering inventory and handling costs (route AE2)

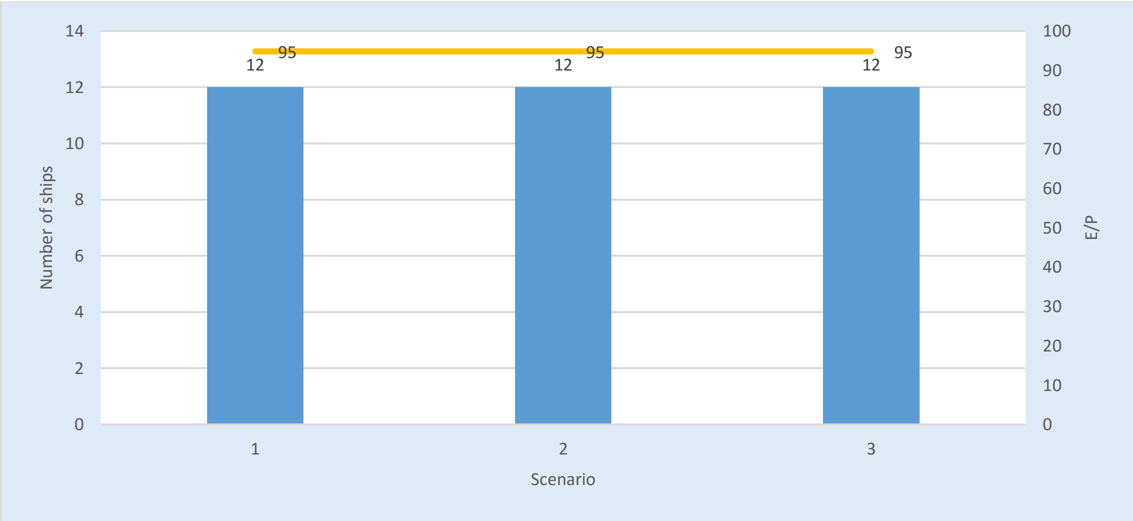


Figure 6.8: Fixed frequency scenario not considering inventory and handling costs (route AE2)

When the model neglects the inventory costs and the handling costs, as previously said, the problem's variables are directly related to the ratio E/P. The section 5.1.1 contains the analytical demonstration of such statement. Therefore, the links between the parameters *E* and *P* and the variables can be described by the following equations:

$$N \longrightarrow \left(\frac{P}{E}\right) \tag{6.12}$$

$$v_{average} \longrightarrow \left(\frac{E}{P}\right) \tag{6.13}$$

$$E_d \longrightarrow \left(\frac{E}{P}\right) \tag{6.14}$$

Figuress 6.9, 6.10 and 6.11 show the influence of the ratio on the average speed, the number of ships and the daily CO_2 emissions when both the inventory costs and the handling costs are neglected. Table 6.5 contains the values of *E* and *P* employed in the simulations.

Ratio E/P					
Scenario	**E [USD/day]**	**Variation**	**P [USD/tonne]**	**Variation**	**Ratio E/P**
1	20734,2	-40%	510,44	+40%	41
2	27645,6	-20%	437,52	+20%	63
3	31101,3	-10%	401,06	+10%	78
4-base	34557	/	364,6	/	95
5	38012,7	+10%	328,14	-10%	116
6	41468,4	+20%	291,68	-20%	142
7	48379,8	+40%	218,76	-40%	221

Table 6.5: Fixed frequency scenario, ratio between E and P (route AE2)

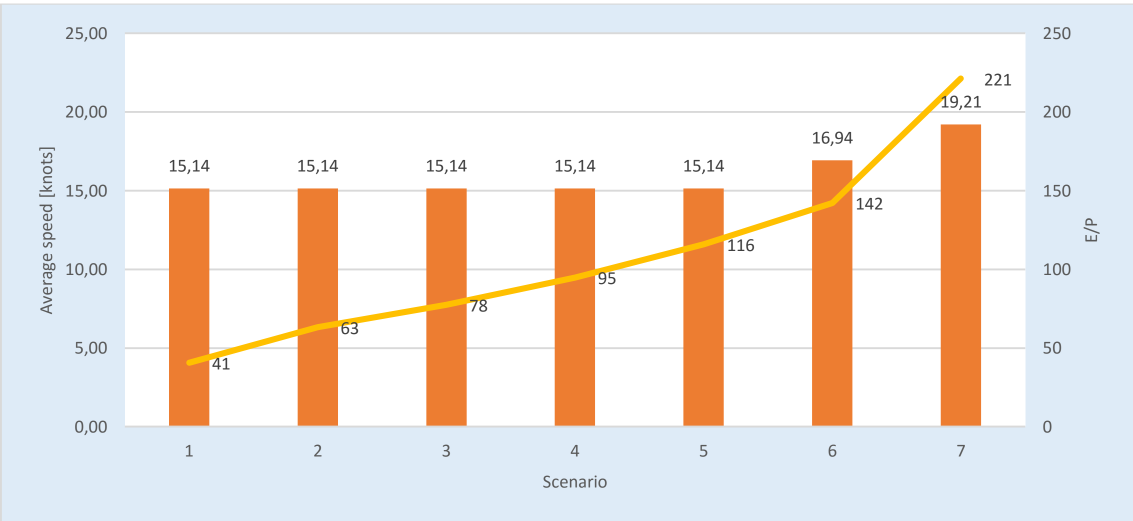


Figure 6.9: Fixed frequency scenario not considering inventory and handling costs, effect of the ratio E/P on the average speed (route AE2)

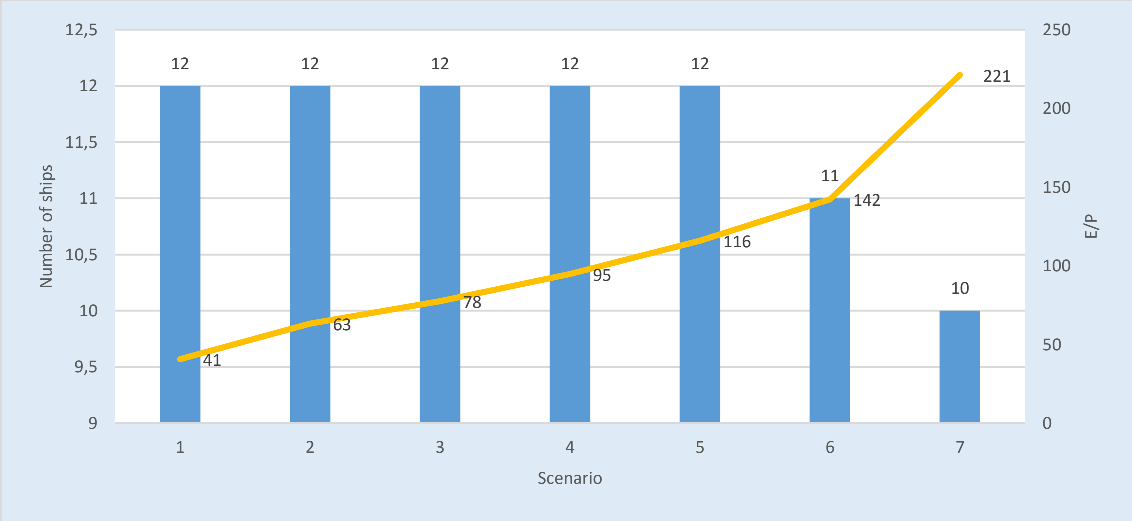


Figure 6.10: Fixed frequency scenario not considering inventory and handling costs, effect of the ratio E/P on the number of ships (route AE2)

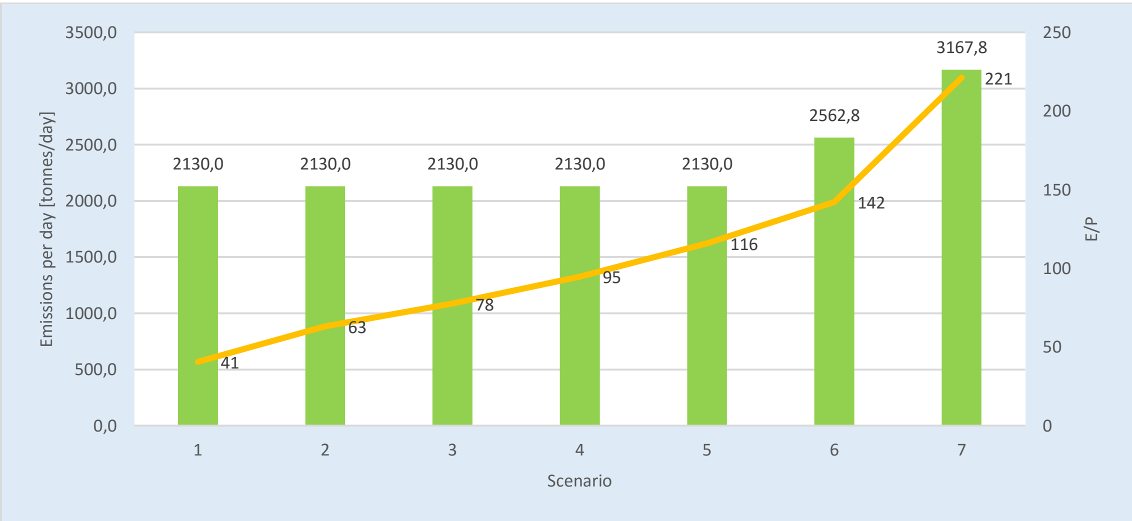


Figure 6.11: Fixed frequency scenario not considering inventory and handling costs, effect of the ratio E/P on the daily CO_2 emissions (route AE2)

6.1.1.3 Freight rate effect

Since the frequency service is constant, the revenue is also constant because the quantity of delivered goods is fixed. Therefore, as analytically demonstrated in section 5.1.1, the freight rate value does not influence any of the problem's decision variables. For example, figure 6.12 depicts the influence of the ratio on the average speed whereas figure 6.13 shows the influence on the number of ships. As one can see, the freight rates' values does not affect the results of the simulations. Table 6.6 reports the data employed in the simulations.

		Freight rate		
Scenario	**F-EB [USD/TEU]**	**F-WB [USD/TEU]**	**Variation**	**$F_{average}$**
1	405	414	-40%	410
2	540	552	-20%	546
3	607,5	621	-10%	614
4-base	675	690	/	683
5	742,5	759	+10%	751
6	810	828	+20%	819
7	945	966	+40%	956

Table 6.6: Fixed frequency scenario, freight rate values (route AE2)

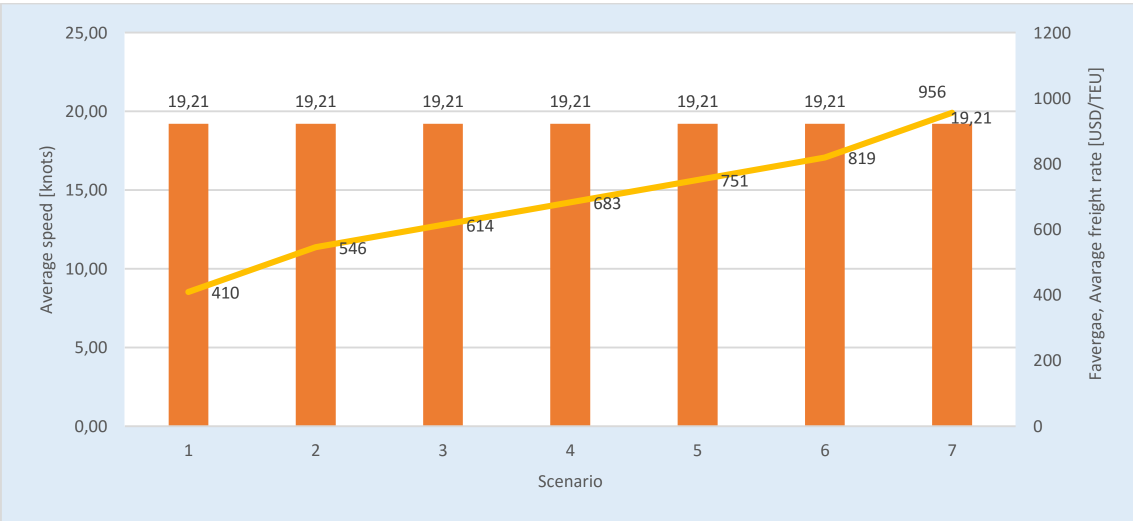


Figure 6.12: Fixed frequency scenario, effect of the freight rate on the average speed (route AE2)

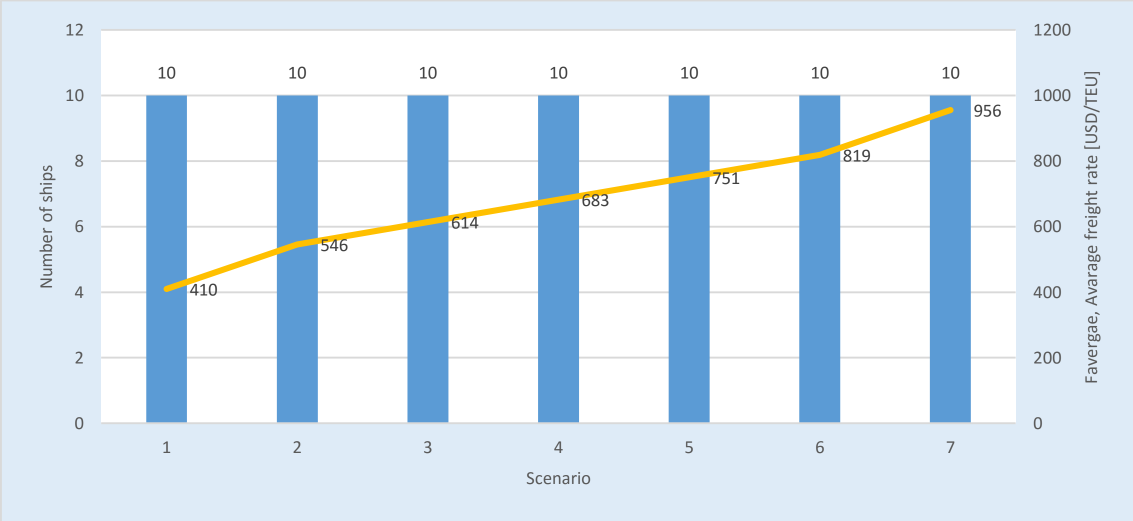


Figure 6.13: Fixed frequency scenario, effect of the freight rate on the number of ships (route AE2)

6.1.2 Fixed Number of Ships Scenario

The number of ships concerning the "base scenarios" is the actual number of ships employed on the route involved; the values are reported in the table 6.7.

Number of ships	
Scenario	**Number of ships**
AE2	10
TP1	5
NEUATL1	5

Table 6.7: Number of ships employed in the fixed number of ships scenario for each routes

6.1.2.1 Operating Costs Effect

Since the scenario considers that the number of ships is constant, the daily fixed operating costs does not influence the results obtained by the model. As explained in section 5.1.2, the optimal solution neglect the daily operating expenditure, namely *N* multiplied to *E*, being constant. Figures 6.14, 6.15 and 6.16, referred to the route TP1, prove this statement. Indeed, varying the value of *E* does not change the results with regard to the service frequency, the average speed and the daily CO_2 emissions. Table 6.8 contains the operating costs' values employed in the scenarios.

Daily operating costs		
Scenario	**E [USD/day]**	**Variation**
1	4525	-80%
2	13575	-40%
3	20363	-10%
4-base	22625	/
5	24888	+10%
6	31675	+40%
7	40725	+80%

Table 6.8: Fixed number of ships scenario, daily operating costs (route TP1)

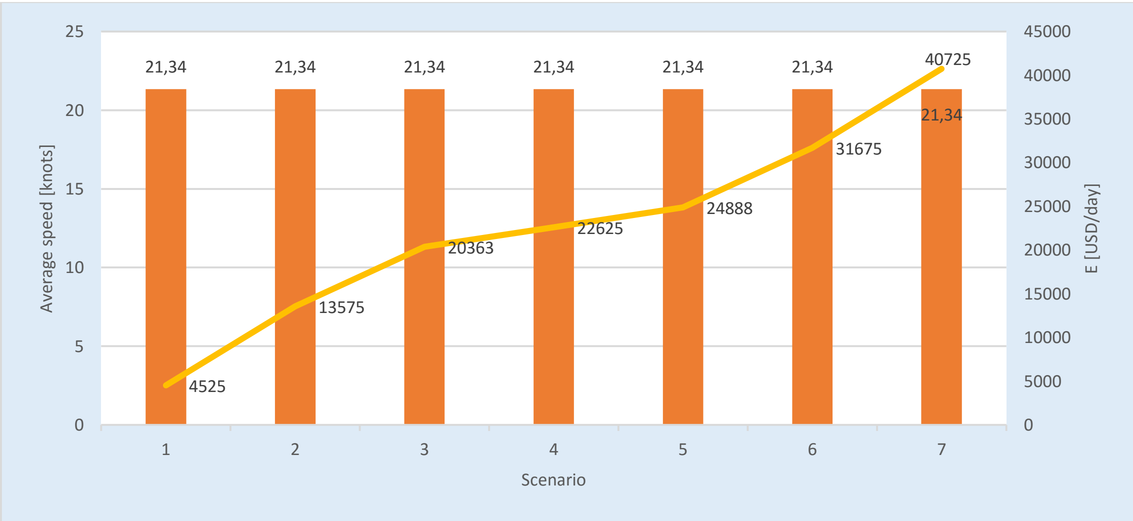


Figure 6.14: Fixed number of ships scenario, effect of E on the average speed (route TP1)

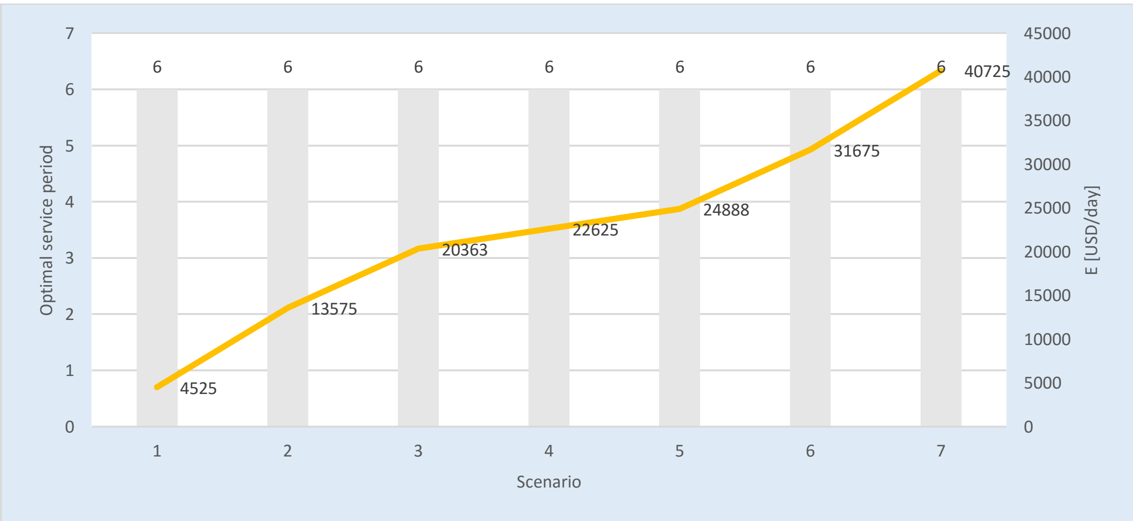


Figure 6.15: Fixed number of ships scenario, effect of E on the optimal service period (route TP1)

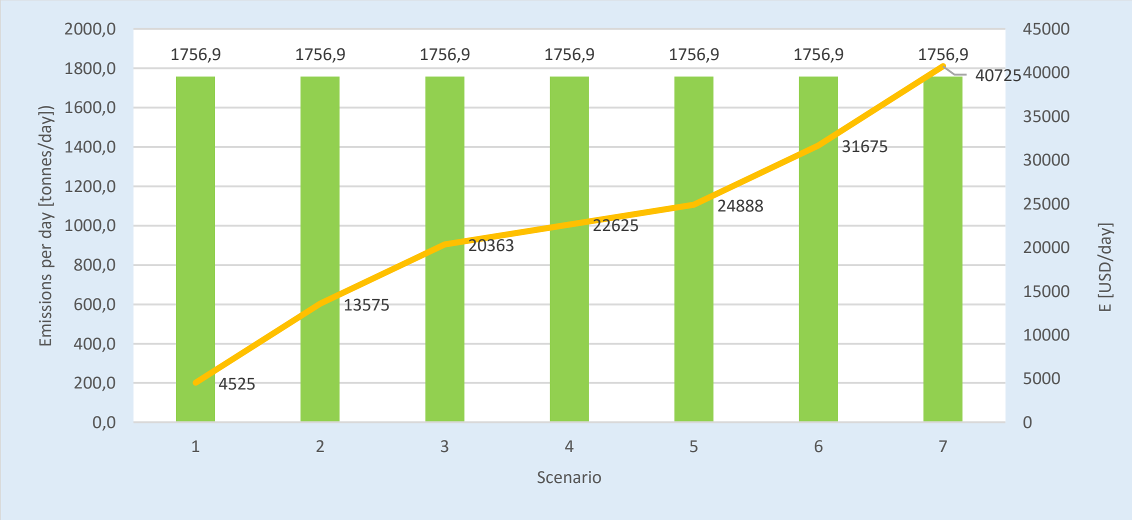


Figure 6.16: Fixed number of ships scenario, effect of E on the daily CO_2 emissions (route TP1)

6.1.2.2 Bunker price effect

As in the fixed frequency scenario, if the bunker price rises the average speed decreases because the fuel consumption is strictly related to the average speed. The CO_2 emissions, being related to the average speed, also decrease when the bunker price rises. If the number of ships is constant, the only way to reduce the speed is to decrease the service frequency hence increasing the service period. Mathematically, one can state the following proportional relationships:

$$t_0 \longrightarrow (P) \tag{6.15}$$

$$v_{average} \longrightarrow \left(\frac{1}{P}\right) \tag{6.16}$$

$$E_d \longrightarrow \left(\frac{1}{P}\right) \tag{6.17}$$

Figures 6.17, 6.18 and 6.19 depict the result for the AE2 route. The table 6.9 contains parameters' values for each scenario.

Scenario	Bunker price P [USD/tonne]	Variation
1	146	-60%
2	292	-40%
3	328	-10%
4-base	365	/
5	401	+10%
6	438	+40%
7	583	+60%

Table 6.9: Fixed number of ships scenario, bunker price (route AE2)

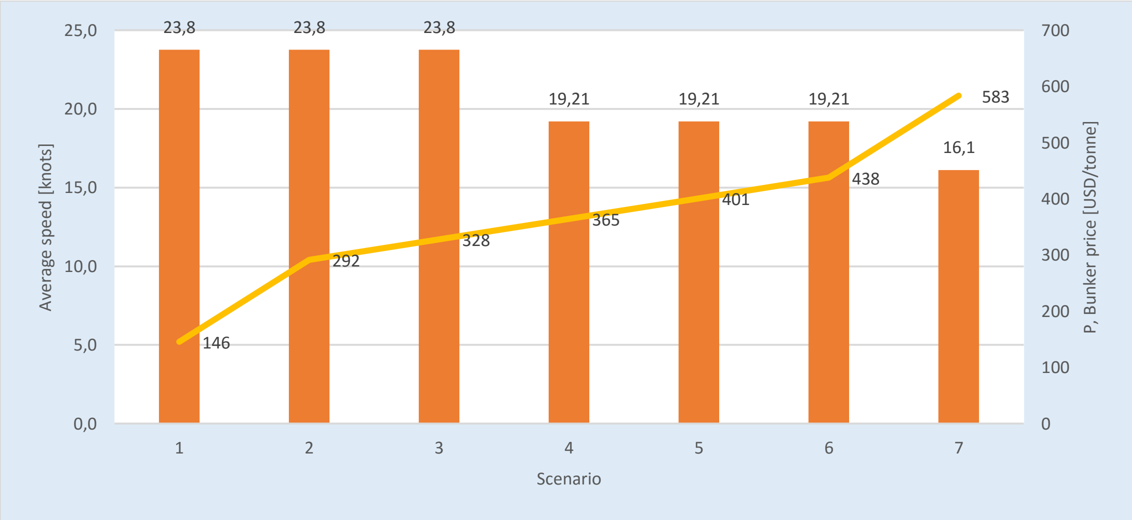


Figure 6.17: Fixed number of ships scenario, effect of P on the average speed (route AE2)

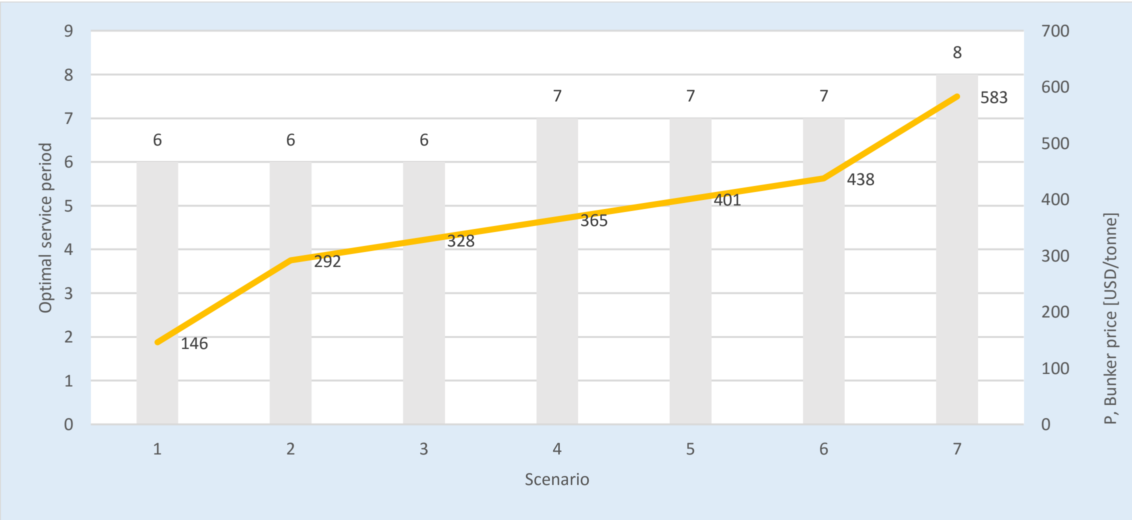


Figure 6.18: Fixed number of ships scenario, effect of P on the optimal service period (route AE2)

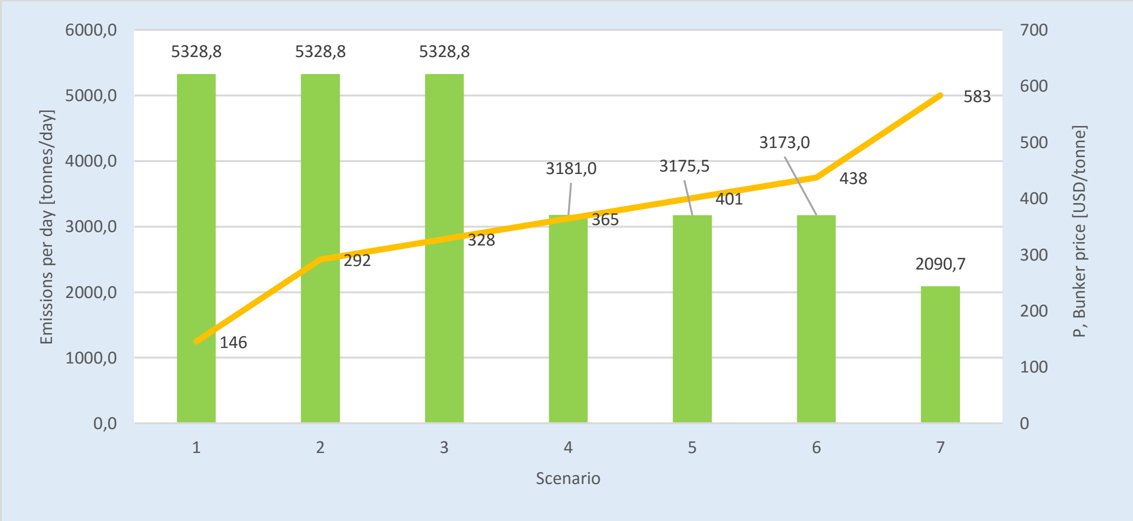


Figure 6.19: Fixed number of ships scenario, effect of P on the daily CO_2 emissions (route AE2)

The revenue in this scenario are not constant, being the service frequency variable, hence one must consider that a lower service frequency entails lower revenue. Consequently, the bunker price might has a weak effect on the optimal solution. Namely, even for high fluctuations of bunker price the service frequency as well as the average speed do not change. Figure 6.20, regarding the effect of bunker price on the average speed in the route NEUATL1, confirms such statement. Indeed, the average speed (one can see the same for the optimal service frequency) is constant despite of the increasing values of *P*. The table 6.10 reports the values of *P* employed in the analysis.

	Bunker price	
Scenario	**P [USD/tonne]**	**Variation**
1	145	-60%
2	291	-40%
3	328	-10%
4-base	364	/
5	401	+10%
6	437	+40%
7	583	+60%
8	656	+80%

Table 6.10: Fixed number of ships scenario, bunker price (route NEUATL1)

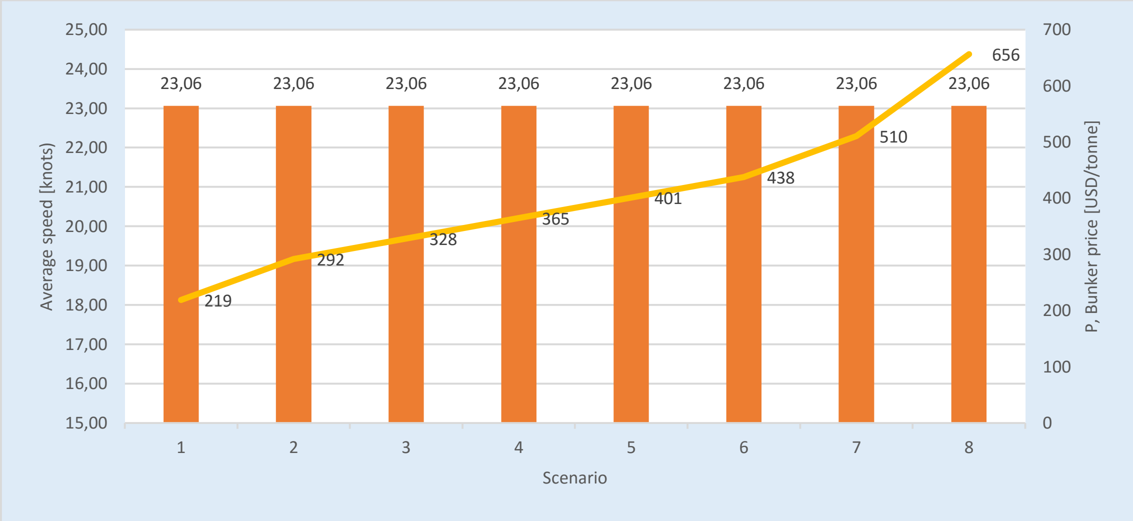


Figure 6.20: Fixed number of ships scenario, effect of P on the average speed (route NEUATL1)

On the contrary, the daily CO_2 emissions are slightly influenced by the bunker price, as shown in figure 6.21. Despite the average speed is constant, the speeds on each leg change, as shown in figure 6.22, because the influence of the inventory costs decreases if the bunker price increases. The section 6.2 deals with such effect. Indeed, the daily inventory costs on the leg 3 are higher than on the leg 8 (respectively, 31694 USD/day and 18779 USD/day) hence in the scenario 4-base, the speed is higher along the leg 3 in order to minimize the expenditure concerning the inventory costs. On the contrary, in the scenario 5, in which the bunker price is higher, the speed decreases on the leg 3 whereas it increases on the leg 8, taking the same value. Therefore, the different values of the daily inventory costs on the considered legs does not affect more on the optimal speeds.

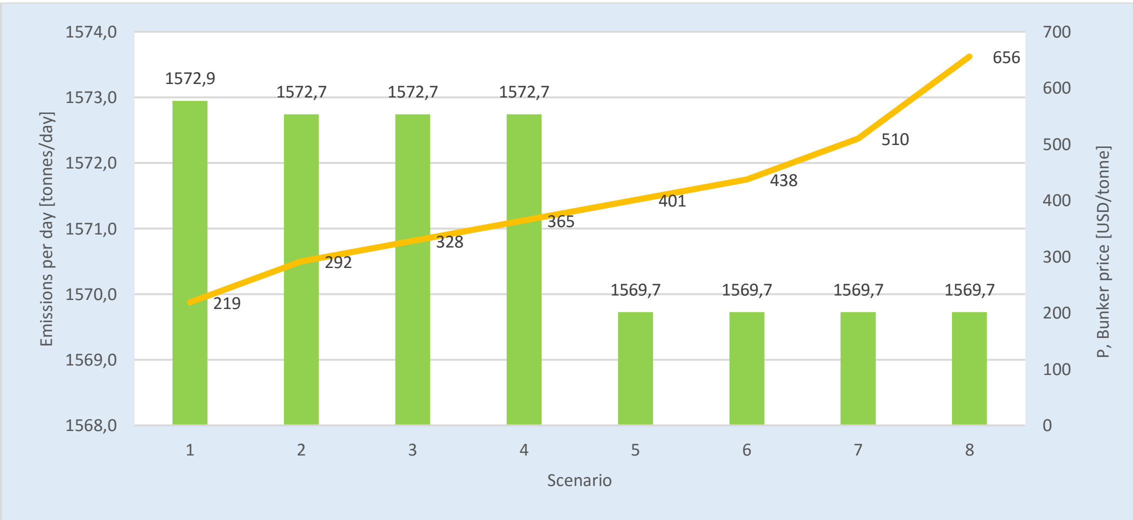


Figure 6.21: Fixed number of ships scenario, effect of P on the daily CO_2 emissions (route NEUATL1)

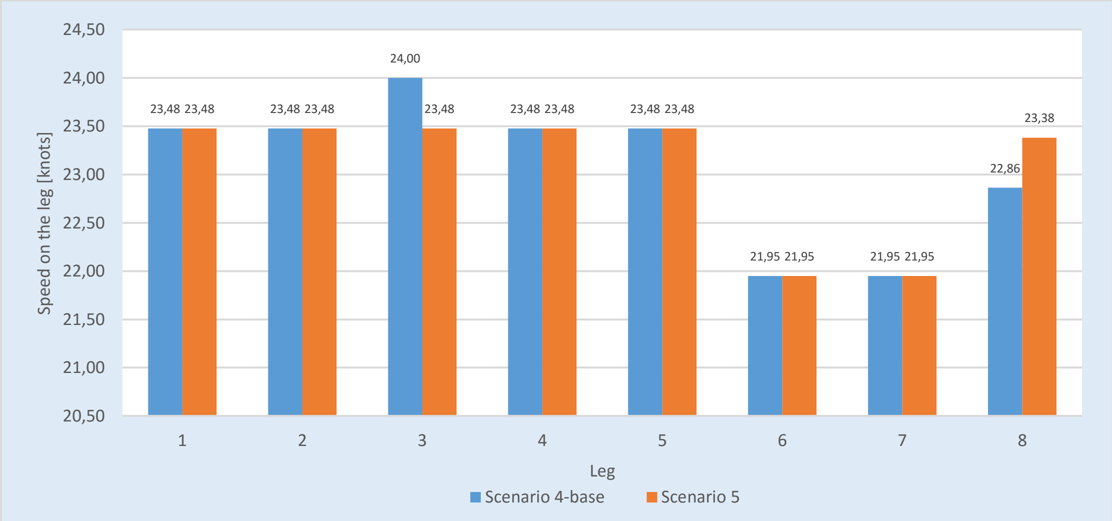


Figure 6.22: Fixed number of ships scenario, effect of P on the speeds on each leg (route NEUATL1)
Because of the bunker price rise, the speed on the leg 3 decrease whereas the speed on the leg 8 increases. Such effect is due to the sensibility reduction of the optimal speeds concerning the inventory costs when the price is higher

6.1.2.3 Freight rate effect

Since the service frequency is not constant, the revenue is also variable. As demonstrated in section 5.1.2, the freight rate's value influences the optimal solution in such scenario because increasing the service frequency entails to increase the revenue. Nevertheless, a higher service frequency entails that the ships have to speed up in order to provide the frequency required; therefore, the fuel expenditure rises as well as the daily CO_2 emissions. Consequently, for high freight rate's value the optimal solution is a higher frequency because the revenue increases more than the fuel expenditure. On the contrary. For low value of freight rate, the ship owner would like to provide a lower service frequency because for a higher frequency the fuel expenditure would be higher than the revenue increase. Therefore, the problem variables depend on the freight rate F as:

$$t_0 \longrightarrow \left(\frac{1}{F}\right) \tag{6.18}$$

$$v_{average} \longrightarrow (F) \tag{6.19}$$

$$E_d \longrightarrow (F) \tag{6.20}$$

Moreover, one can observe that the service frequencies available are limited whether the number of ships is constant. Indeed, as one can see from the equation 6.21, the speeds on each leg v_i are bounded above and below therefore for a specific value of N there is a specific range of available service period t_0.

$$t_0 = \frac{\sum_i \frac{L_i}{24\, v_i} + \sum_j t_j}{N} = \frac{T_0}{N} \tag{6.21}$$

For example, for the route TP1, in which the number of ships is impose to be equal to 5 (the number of ships actual deployed along the route TP1), the available service periods are 6, 7 and 8. Figure 6.23, 6.24 and 6.25 reports the effect of freight rate on the results regarding the route TP1. Table 6.11 contains the freight rates' values employed in the simulations.

		Freight rate		
Scenario	**F-EB [USD/TEU]**	**F-WB [USD/TEU]**	**Variation**	**$F_{average}$**
0	588,5	198	-45%	393
1	642	216	-40%	429
2	856	288	-20%	572
3	963	324	-10%	644
4-base	1070	360	/	715
5	1177	396	+10%	787
6	1284	432	+20%	858
7	1498	504	+40%	1001

Table 6.11: Fixed number of ships scenario, freight rate values (route TP1)

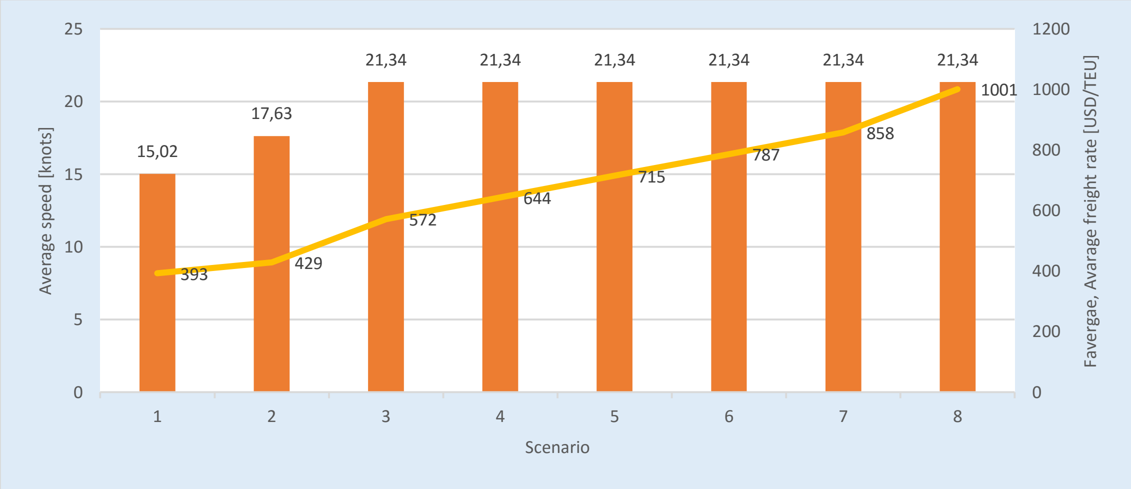


Figure 6.23: Fixed number of ships scenario, effect of the freight rate on the average speed (route TP1)

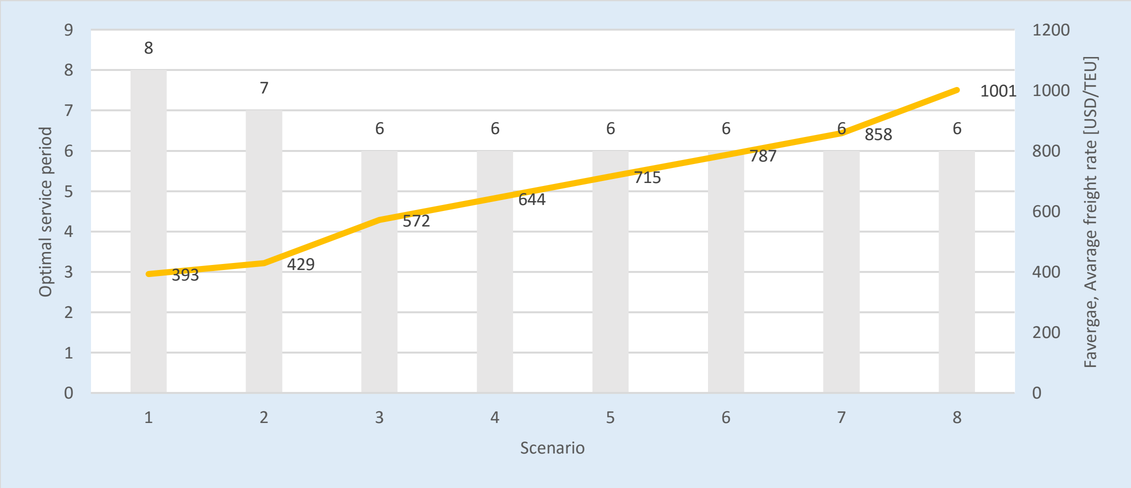


Figure 6.24: Fixed number of ships scenario, effect of the freight rate on the optimal service period (route TP1)

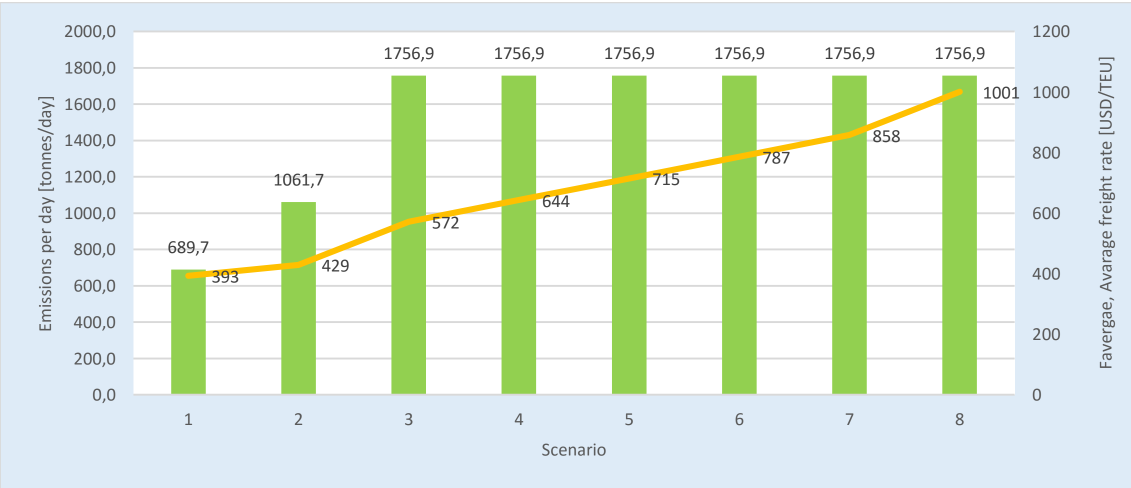


Figure 6.25: Fixed number of ships scenario, effect of the freight rate on the daily CO_2 emissions (route TP1)

Section 5.1.2 demonstrates that the optimal solution solely depends on the ratio between freight rate and bunker price. Such statement is true as long as the model does not consider the inventory costs and the handling costs, as made in section 5.1.2 indeed. When the model takes into account of inventory costs and handling costs, the optimal solution is different even if the ratio is constant. Namely, the optimal solution does not only depend on the ratio's value but also it depends on the actual value of freight rate and bunker price. Figures 6.26 and 6.27 show such effect for the route TP1 (the same effect can be see for the average speed). As one can see, if the model comprises the inventory and handling costs the optimal solution varies despite the ratio is constant. Table 6.12 contains the ratio's values employed in the analysis.

Ratio Faverage/P						
Scenario	**F-EB [USD/TEU]**	**F-WB [USD/TEU]**	**$F_{average}$ [USD/TEU]**	**P [USD/tonne]**	**Variation**	**Ratio $F_{average}$/P**
1	535	180	375,5	182,3	-50%	1,96
2-base	1070	360	715	364,6	/	1,96
3	2140	1430	1430	729,2	+100%	1,96

Table 6.12: Fixed number of ships scenario, daily operating costs and bunker prices (route TP1)

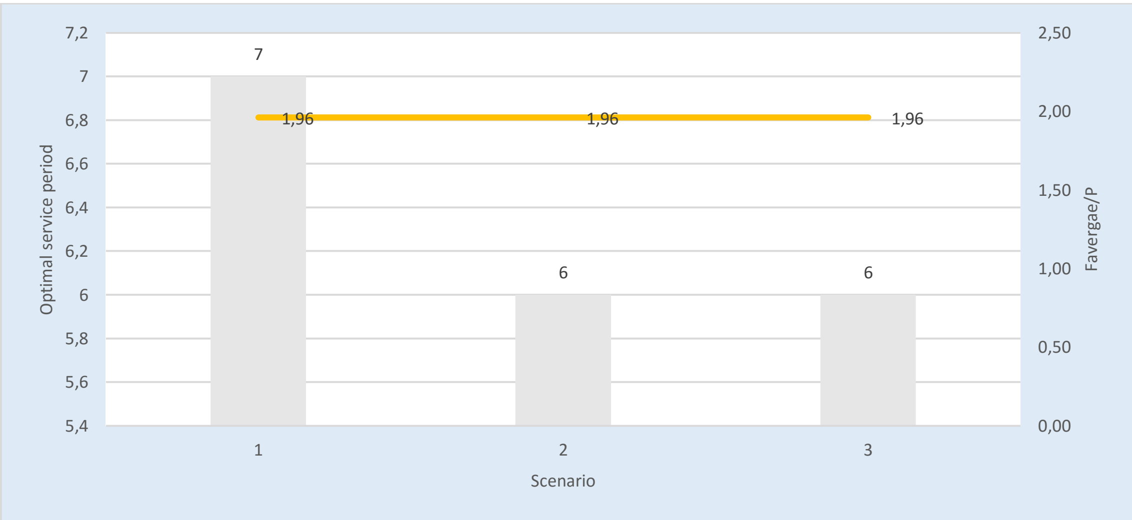


Figure 6.26: Fixed number of ships scenario considering inventory and handling costs (route TP1)

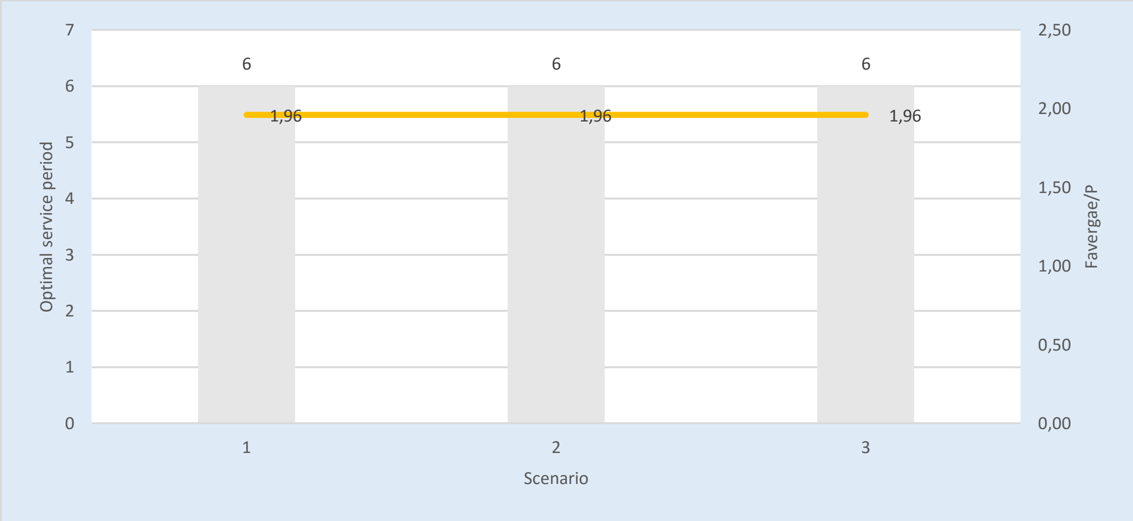


Figure 6.27: Fixed frequency scenario not considering inventory and handling costs (route AE2)

As said previously, when the model does not consider the inventory costs and the handling costs, the optimal solution is directly dependent on the ratio between the freight rate and the bunker price hence one can formulate the following equation:

$$t_0 \longrightarrow \left(\frac{P}{F}\right) \tag{6.22}$$

$$v_{average} \longrightarrow \left(\frac{F}{P}\right) \tag{6.23}$$

$$E_d \longrightarrow \left(\frac{F}{P}\right) \tag{6.24}$$

Figure 6.28 reports the effect of the ratio on the service period when the model neglects the inventory and the handling costs, the ratio also influences the average speed and the daily CO_2 emissions. Table 6.13 contains the values employed in the scenarios.

Ratio E/P

Scenario	F-EB [USD/TEU]	F-WB [USD/TEU]	$F_{average}$ [USD/TEU]	Variation	P [USD/tonne]	Variation	Ratio $F_{average}/P$
0	428	144	286	-60%	593	+60%	0,25
1	642	216	429	-40%	510	+40%	0,42
2	856	288	572	-20%	437	+20%	0,66
3	963	324	643,5	-10%	401	+10%	0,81
4-base	1070	360	715	/	364	/	0,99
5	1177	396	786,5	+10%	328	-10%	1,21
6	1284	432	858	+20%	291	-20%	1,48
7	1498	504	1001	+40%	218	-40%	2,30

Table 6.13: Fixed number of ships scenario, ratio between $F_{average}$ and P (route TP1)

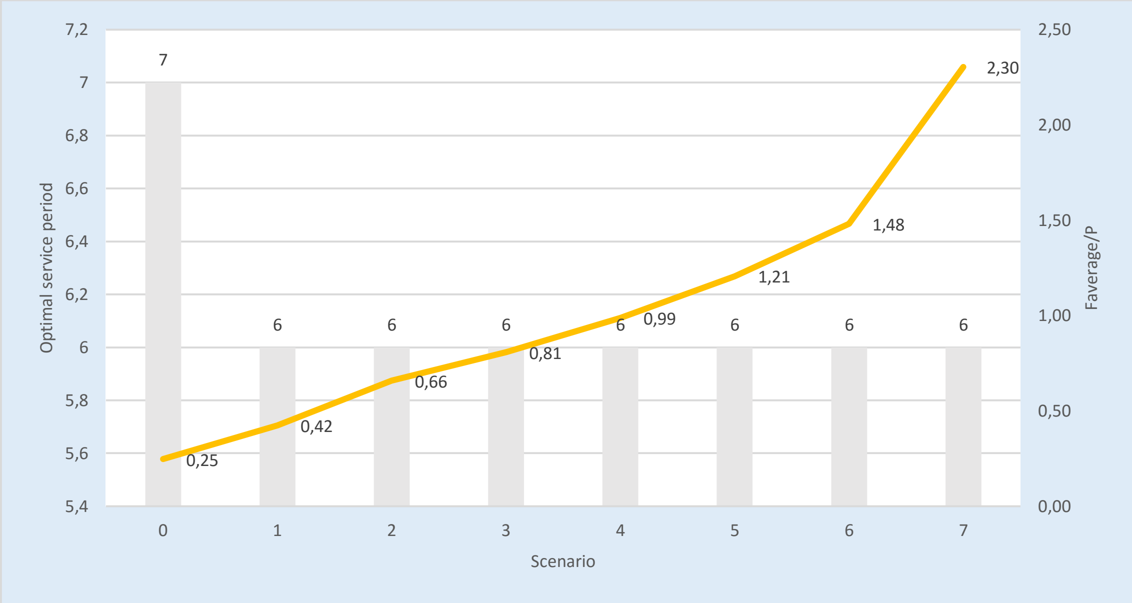


Figure 6.28: Fixed number of ships scenario not considering inventory and handling costs, effect of the ratio $F_{average}/P$ on the optimal service period (route TP1)

6.1.3 Number of Ships Bounded Above Scenario

The scenario analysed in this section has some limitation regarding the maximum number of ships. The limit on the number of ships is imposed in order to avoid that the optimal number of ships calculated by the model would reach unrealistic values (for example for the AE2 scenario, considering a service period of 3,5 days the number of ships might be equal to 24). The number of ships limit for each route is arbitrarily chosen as the minimum number of ships necessary to provide the maximum service frequency (i.e. a service period of 3,5). The values of the number of ships limit for each route are reported in table 6.14.

Number of ships limits	
Route	**Number of ships limit**
AE2	18
TP1	8
NEUATL1	7

Table 6.14: Number of ships limit for each scenario

Before analysing the effect of freight rate, bunker price and daily operating costs in the considered scenario, it is useful to be aware of the effect caused by a rise of the service frequency, which are depicted in figure 6.29. Providing a higher service frequency implies higher revenue, nevertheless in order to increase the service frequency it is necessary to deploy more vessels. Moreover, being the maximum number of ships bounded above, a higher service frequency also entails a higher average speed (namely, the speeds on the legs are higher). One can easily verify such statements through equation 4.37.

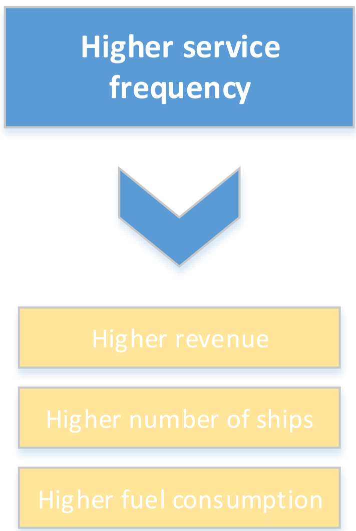


Figure 6.29: Effect of a higher service frequency

6.1.3.1 OPERATING COSTS EFFECT

As said in the previous section, a higher service frequency implies a higher number of vessels. Therefore, if the daily operating costs for one vessel E are high the optimal service frequency will be low. On the contrary, if the value of E is low, the increase in the daily total fixed operating costs caused by a higher service frequency will be lower than the increase in the revenue. Therefore, one can state that:

$$t_0 \longrightarrow (E) \tag{6.25}$$

Besides, a higher service frequency, as stated in section 6.1.3, implies a higher number of ships and a higher average speed hence daily CO_2 emissions.

Consequently, the following equations are valid:

$$N \longrightarrow \left(\frac{1}{E}\right) \tag{6.26}$$

$$v_{average} \longrightarrow \left(\frac{1}{E}\right) \tag{6.27}$$

$$E_d \longrightarrow \left(\frac{1}{E}\right) \tag{6.28}$$

Figures 6.30, 6.31, 6.32 and 6.33 report the results regarding the effect of E for the route AE2. The table 6.15 contains the values of the operating costs employed in the simulations.

	Daily operating costs	
Scenario	**E [USD/day]**	**Variation**
1	13823	-60%
2	20734,2	-40%
3	31101,3	-10%
4-base	34557	/
5	38012,7	+10%
6	48379,8	+40%
7	55291	+60%
8	58746,9	+70%

Table 6.15: Number of ships bounded above scenario, daily operating costs (route AE2)

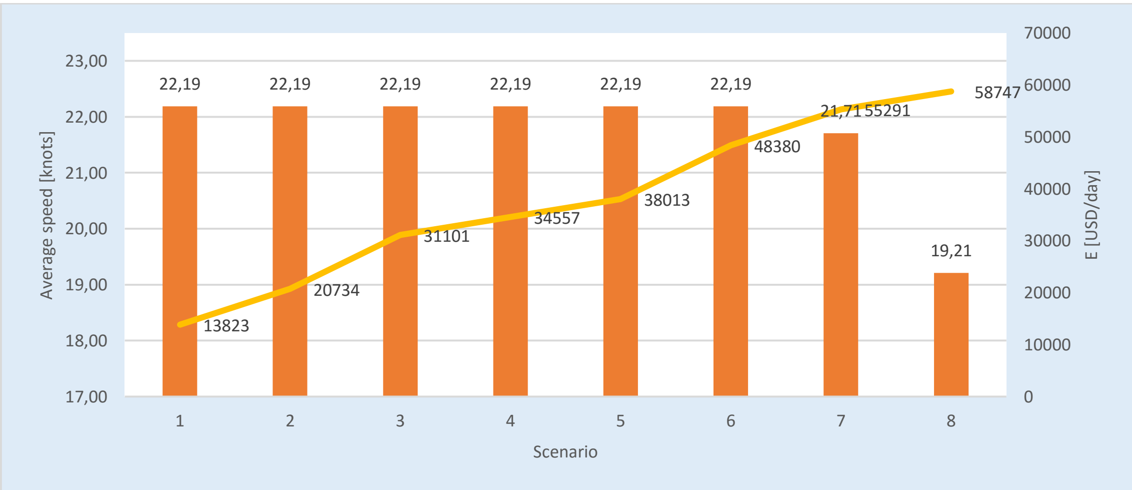


Figure 6.30: Number of ships bounded above scenario, effect of E on the average speed (route AE2)

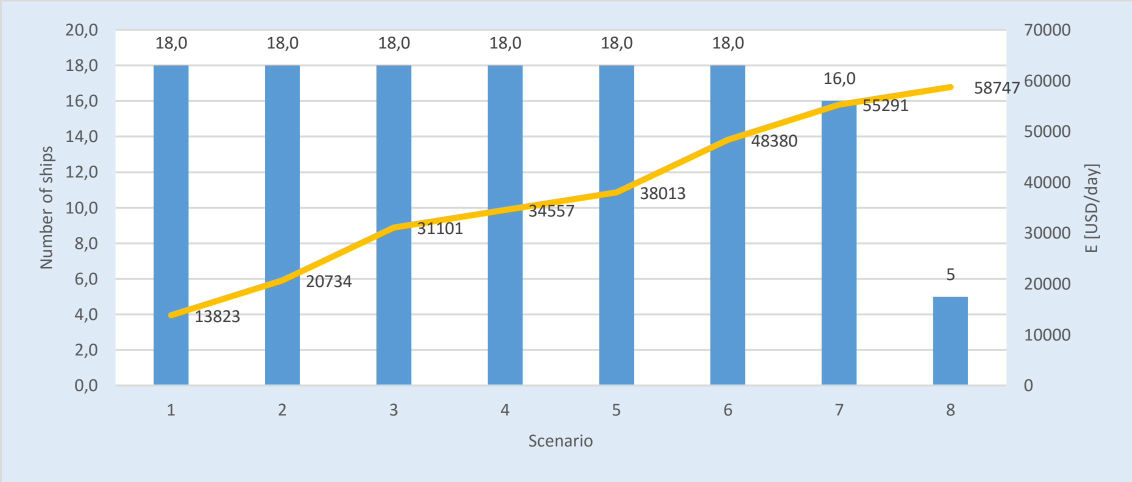


Figure 6.31: Number of ships bounded above scenario, effect of E on the number of ships (route AE2)

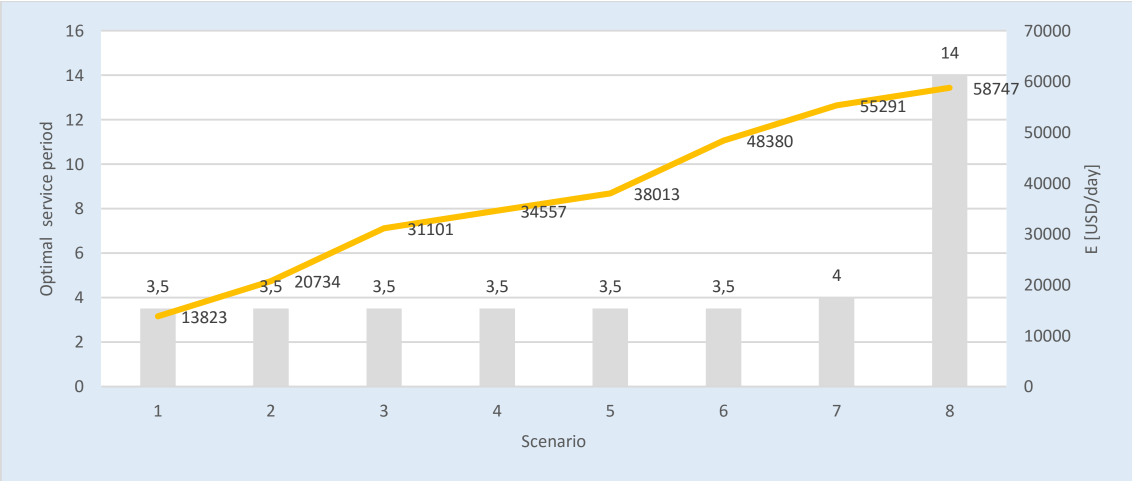


Figure 6.32: Number of ships bounded above scenario, effect of E on the optimal service period (route AE2)

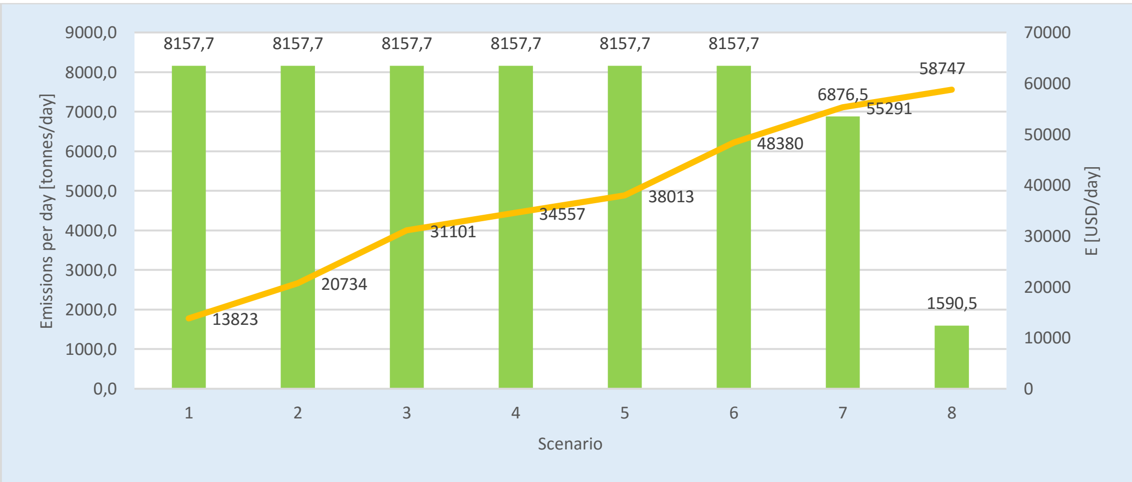


Figure 6.33: Number of ships bounded above scenario, effect of E on the daily CO_2 emissions (route AE2)

6.1.3.2 BUNKER PRICE EFFECT

In this scenario, the effect of the bunker price is similar to the effect in the previous two scenarios. Increasing the service frequency entails a higher number of ships and a higher average speed; therefore, if the value of *P* is high the advantage of having higher revenue is lower than the rise of the fuel expenditure. Consequently, one can write the equation:

$$t_0 \longrightarrow (P) \tag{6.29}$$

Since a higher service frequency entails to require a higher number of vessels and a higher average speed, hence higher daily emissions, the following equation are valid:

$$N \longrightarrow \left(\frac{1}{P}\right) \tag{6.30}$$

$$v_{average} \longrightarrow \left(\frac{1}{P}\right) \tag{6.31}$$

$$E_d \longrightarrow \left(\frac{1}{P}\right) \tag{6.32}$$

One can notice that the number of ships in this scenario is proportional to the inverse of *P* whereas in the fixed frequency scenario the number of ships is proportional to the bunker price. Such difference is due to the effect of *P* on the service frequency. Since the service frequency is lower for higher bunker price's values the number of ships required is lower. Figures 6.34, 6.35, 6.36 and 6.37 report the results regarding the effect of *P* for the route AE2. Table 6.16 contains the values of bunker price employed in the simulations.

Scenario	Bunker price P [USD/tonne]	Variation
1	146	-60%
2	292	-40%
3	328	-10%
4-base	365	/
5	401	+10%
6	438	+40%
7	583	+60%

Table 6.16: Number of ships bounded above scenario, bunker price (route AE2)

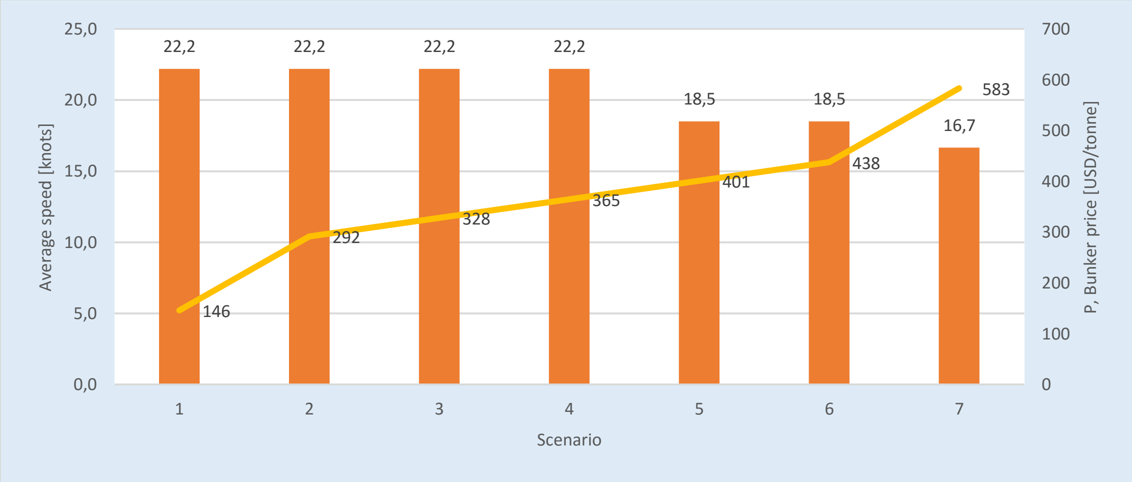


Figure 6.34: Number of ships bounded above scenario, effect of P on the average speed (route AE2)

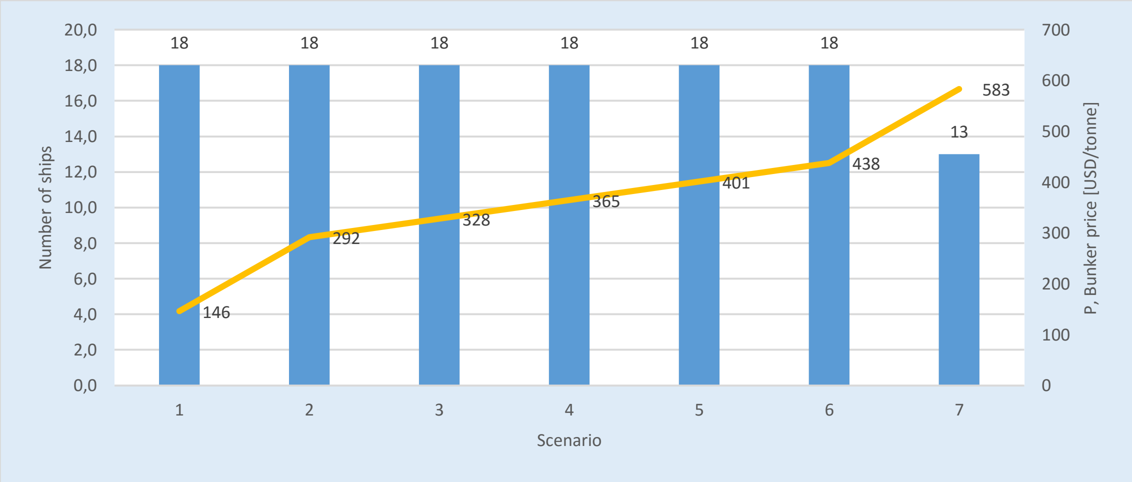


Figure 6.35: Number of ships bounded above scenario, effect of P on the number of ships (route AE2)

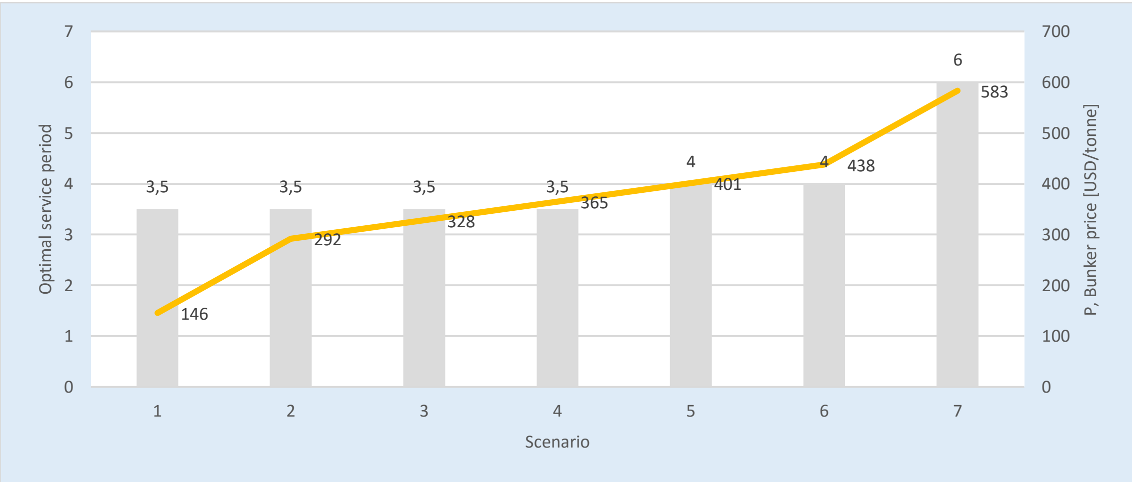


Figure 6.36: Number of ships bounded above scenario, effect of P on the service period (route AE2)

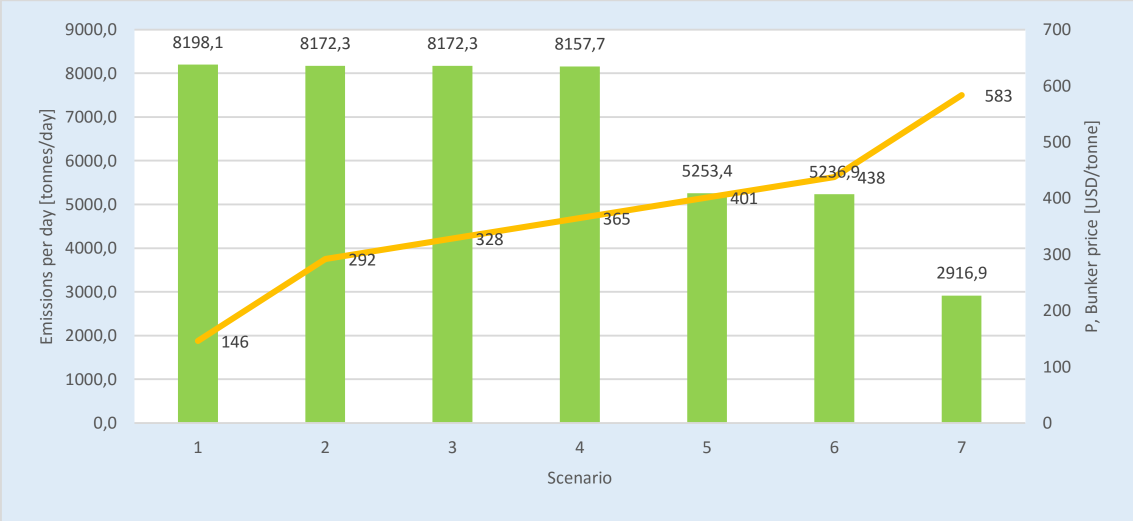


Figure 6.37: Number of ships bounded above scenario, effect of P on the daily CO_2 emissions (route AE2)

6.1.3.3 FREIGHT RATE EFFECT

It is straightforward that a higher freight rate leads the ship owner to increase the service frequency. Indeed, if the freight rate is high than the further incomes due to increasing the service frequency are higher, which means that the disadvantages involved in a higher service frequency (namely, more ships and a higher average speed) are lower than the benefits. Therefore, as stated by the following equation, the service period is inversely proportional to the freight rate:

$$t_0 \longrightarrow \left(\frac{1}{F}\right) \tag{6.33}$$

Consequently, the relationships between the freight rate and the other variables of the problem are:

$$N \longrightarrow (F) \tag{6.34}$$

$$v_{average} \longrightarrow (F) \tag{6.35}$$

$$E_d \longrightarrow (F) \tag{6.36}$$

Figures 6.38, 6.39, 6.40 and 6.41 report the results regarding the effect of F for the route TP1. Table 6.17 contains the values of the freight rate employed in the simulations.

	Freight rate			
Scenario	**F-EB [USD/TEU]**	**F-WB [USD/TEU]**	**Variation**	**$F_{average}$**
0	588,5	198	-45%	393
1	642	216	-40%	429
2	856	288	-20%	572
3	963	324	-10%	644
4-base	1070	360	/	715
5	1177	396	+10%	787
6	1284	432	+20%	858
7	1498	504	+40%	1001

Table 6.17: Number of ships bounded above scenario, freight rate values (route TP1)

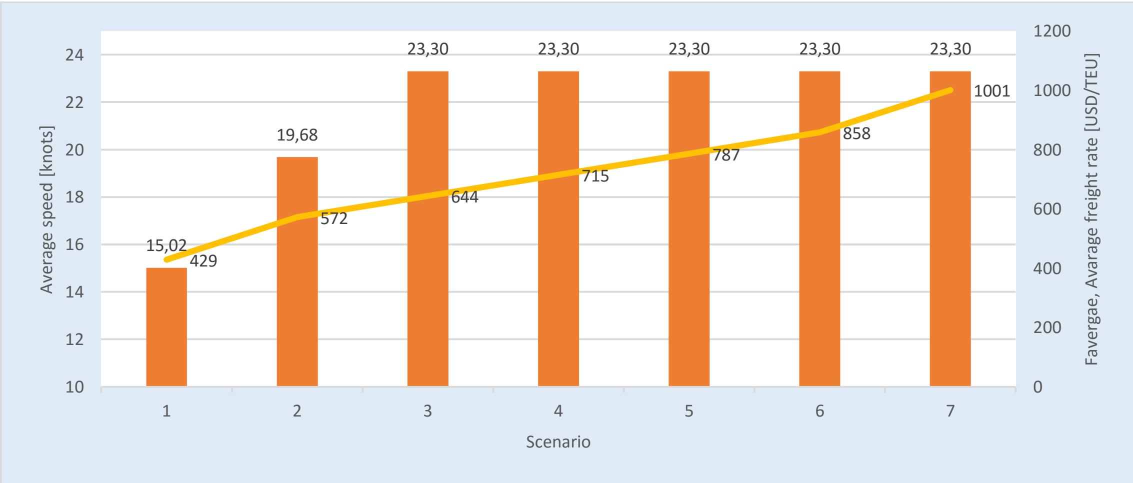


Figure 6.38: Number of ships bounded above scenario, effect of $F_{average}$ on the average speed (route TP1)

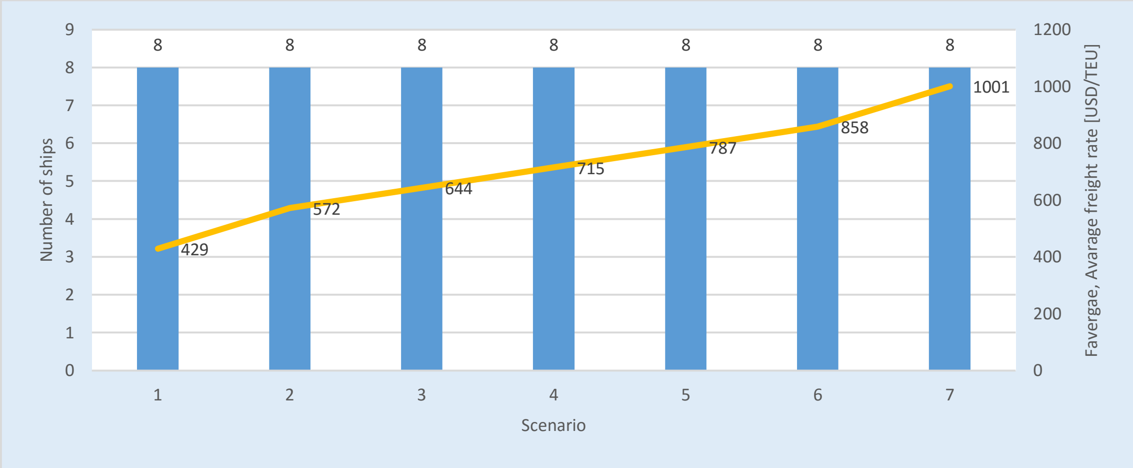


Figure 6.39: Number of ships bounded above scenario, effect of $F_{average}$ on the number of ships (route TP1)

The number of ships is constant because all the frequency involved has the same optimal number of ships

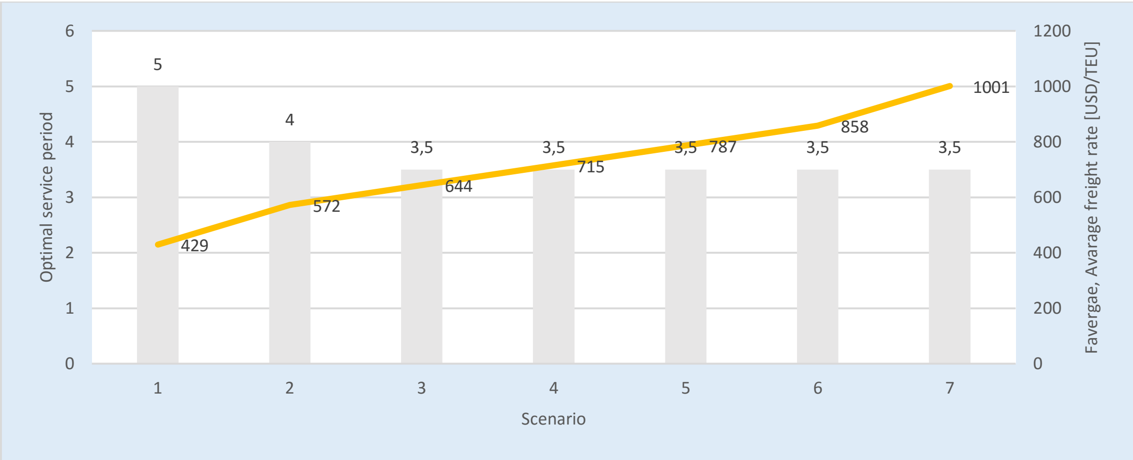


Figure 6.40: Number of ships bounded above scenario, effect of $F_{average}$ on the optimal service period (route TP1)

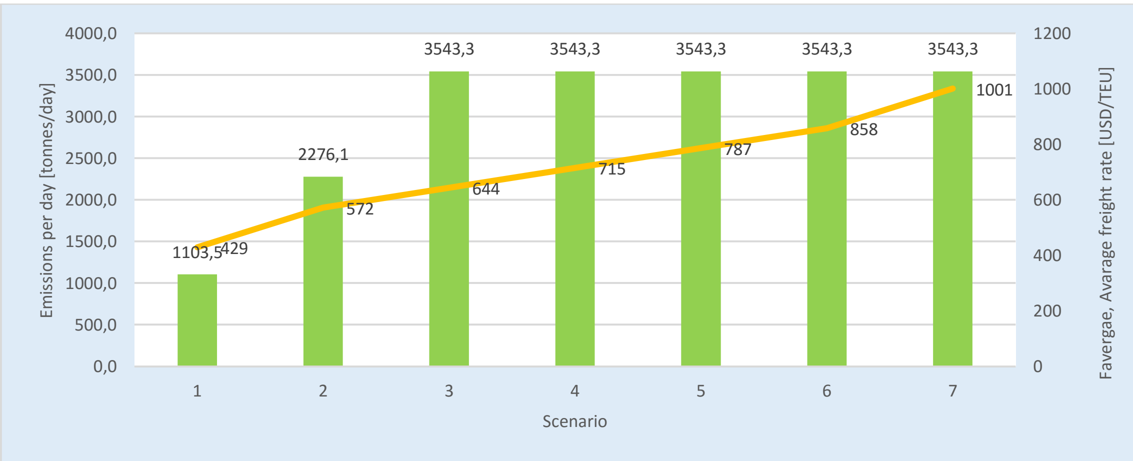


Figure 6.41: Number of ships bounded above scenario, effect of $F_{average}$ on the daily CO_2 emissions (route TP1)

6.1.3.4 UNLIMITED NUMBER OF SHIPS

Considering an unlimited number of ships mitigates the effect of the bunker price on the optimal service frequency. As seen in section 6.1.3.2, a higher bunker price make the high service frequency disadvantageous since higher service frequency entails employing more ships and increasing the average speed, hence higher fuel expenditure. However, if the number of ships is unlimited the average speed can be lower in the case of a higher service frequency whereas it can be higher for lower service frequency (for example, considering the route AE2 and considering a bunker price of 438 USD/tonne, in the scenario in which the number of ships is unlimited the average speed for a service period of 3,5 is 18,00 knots, whereas for a service frequency of 4 the average speed is 18,5 knots). Indeed, the effect of the upper limit on the number of ships is to force the ships to travel at a higher speed in order to maintain the required frequency since for service frequency the maximum number of ships could be higher (as said in section 4.2.3, for a certain service frequency there is a maximum value of *N* for which the speeds are the lowest possible). For example, figures 6.42, 6.43, 6.44 and 6.45 reports the comparison between the results of the *N* limited scenario and the *N* unlimited scenario, for which table 6.18 reports the bunker price employed. Observing such figures, one can see that the optimal service frequency is constant if the number of ships is free. Besides, the figures shown that the relationship between the bunker price and the average speed, the daily CO_2 and the number of ships is the same reported for the limited scenario in section 6.1.3.2.

	Bunker price	
Scenario	**P [USD/tonne]**	**Variation**
1	146	-60%
2	292	-40%
3	328	-10%
4-base	365	/
5	401	+10%
6	438	+40%
7	583	+60%

Table 6.18: Comparison between the unlimited number of ships scenario and the limited number of ships scenario, bunker price (route AE2)

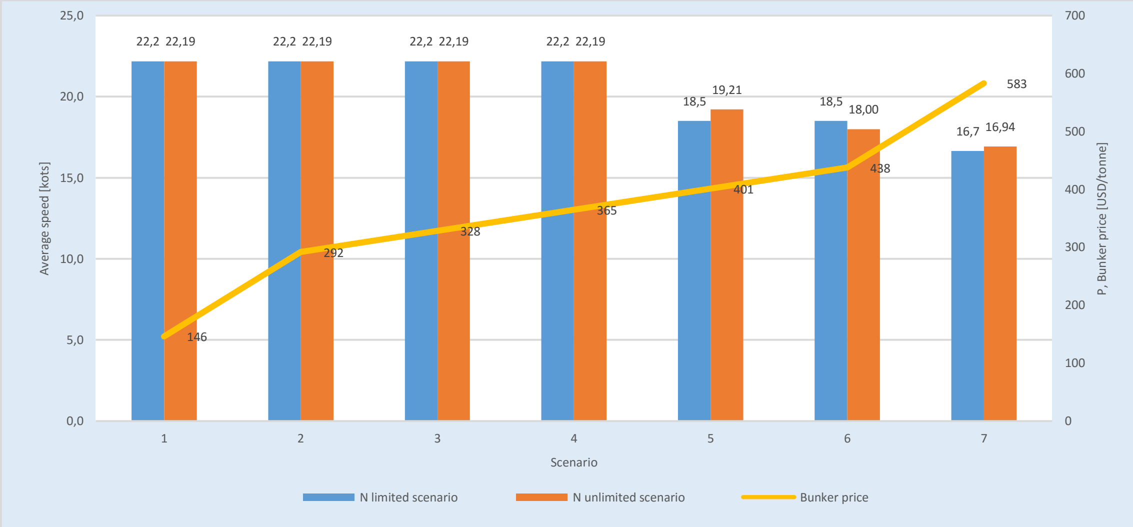


Figure 6.42: Comparison between the N limited scenario and the N unlimited scenario, effect of the bunker price on the average speed (route AE2)

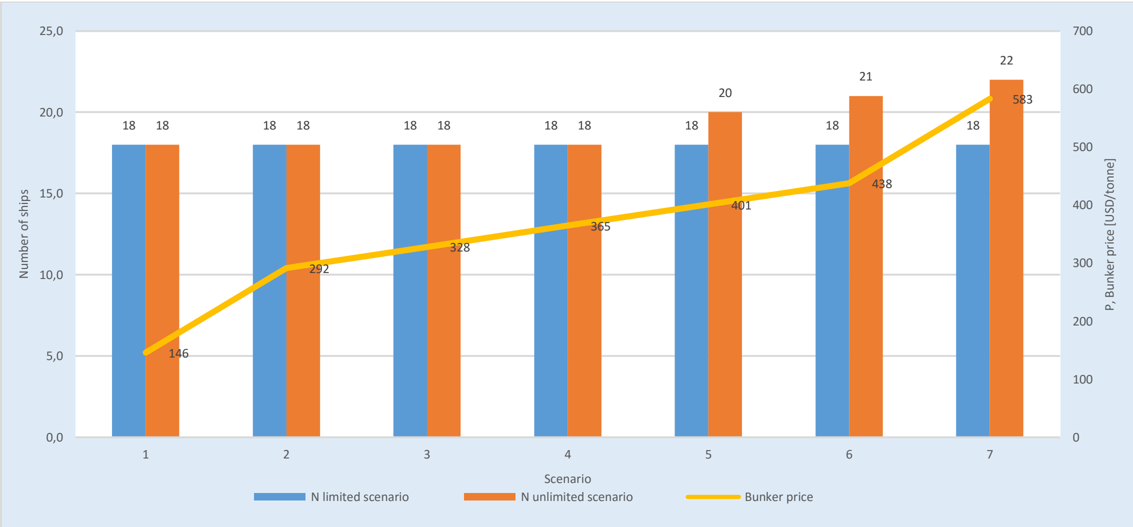


Figure 6.43: Comparison between the N limited scenario and the N unlimited scenario, effect of the bunker price on the number of ships (route AE2)

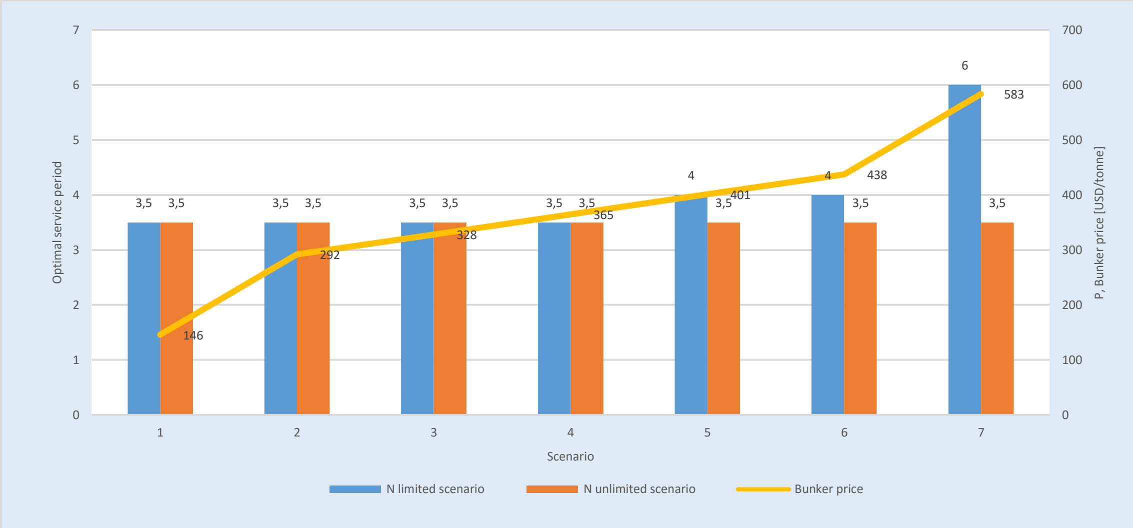


Figure 6.44: Comparison between the N limited scenario and the N unlimited scenario, effect of the bunker price on the optimal service period (route AE2)

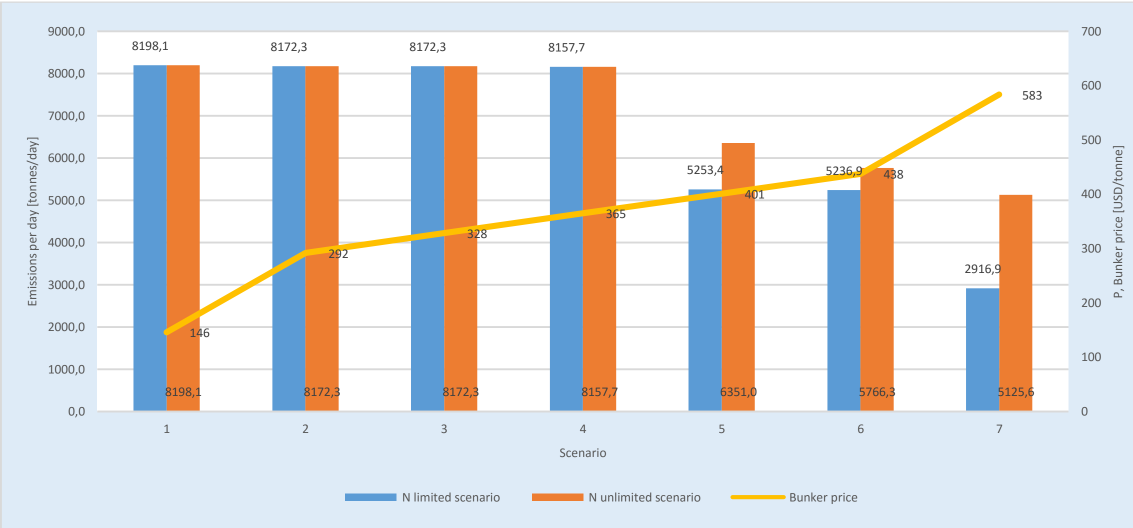


Figure 6.45: Comparison between the N limited scenario and the N unlimited scenario, effect of the bunker price on the daily CO_2 emissions (route AE2)

6.2 Effect of Inventory Costs

As one can see in the objective function, equation 6.37, given a service frequency and a number of ships the optimal sailing speeds along the legs v_i depend on two factors:

→ The bunker price P

→ The inventory costs

$$\dot{\pi} = Max_{v_i,t_0,N}\left\{\frac{1}{t_0}\left(\sum_x\sum_z F_{zx}\,c_{zx} - \sum_i P\,f(v_i)\,\frac{L_i}{24\,v_i} - \sum_j P\,Fp\,t_j - \sum_i \alpha_i\,C_i\,\frac{L_i}{24\,v_i} - \sum_j H\,C_j\right) - N\,E\right\} \quad (6.37)$$

The influence of the bunker price and the inventory costs are opposite: the fuel consumption factor leads to reduce the speeds v_i, respecting the service frequency, whereas the inventory costs factor leads to increase the speeds upon the legs in order to diminish the travel time on each leg hence the inventory costs undergone by the carrier. In order to assess the inventory costs' impact on the speeds v_i it is useful introducing the daily inventory costs the ship owner pays on the legs ith $I_{d,i}$ [USD/day]:

$$I_{d,i} = \alpha_i\,C_i \quad (6.38)$$

Where α_i is the daily inventory cost per TEU on the leg ith [USD/(day*TEU)] and C_i is the quantity of TEU transported on the leg ith [TEU]. The effect of the daily inventory costs on the speeds v_i is elementary to be comprehended: a higher value implies that the speed on the involved leg will be higher. One can verify the previous statement through figure 6.46, which depicts the speeds on the legs regarding the route NEUATL1.

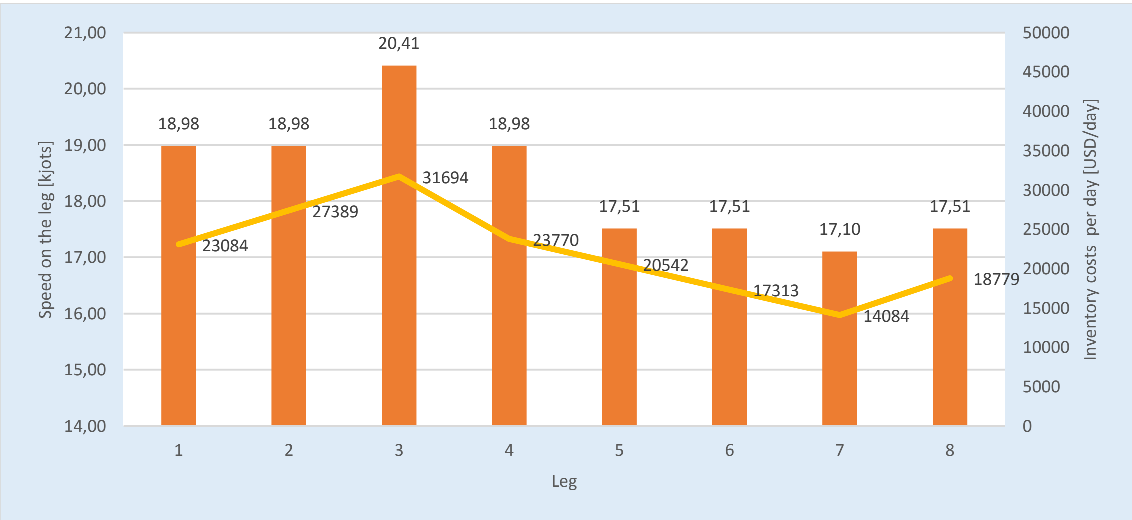


Figure 6.46: Effect of the inventory costs on the speeds along the legs (route NEUATL1)
The figure refers to a base scenario in which N=5 and t_0=6

Nevertheless, it is significant to assess the influence of the bunker price. The inventory costs weight on the optimal speeds on the legs is stronger for low values of bunker price whereas their influence is weak when the bunker price is high. Indeed, if the bunker price is high, the carrier slow down his ships in order to curb the fuel costs, which are higher than the inventory costs in such case.

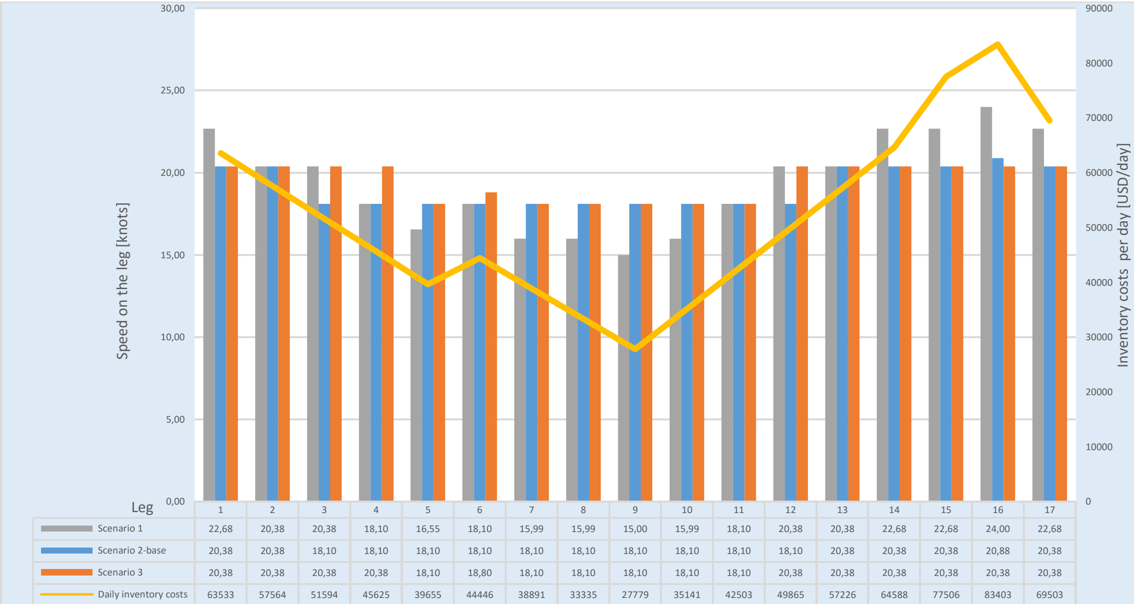
Figure 6.47 proves such statement. Figure refers to the route AE2; the scenarios are "base scenario" except for the bunker price, which has three different values reported in table 6.19. Besides, the scenarios consider a fixed service period and a fixed number of ships (the values are N=10 and t_0=7, which are the actual values for the route considered). In the scenario one, in which the bunker price is low, the optimal speeds closely follow the trend of the inventory costs; namely, the speeds are low along the legs on which the daily inventory costs are low, whereas the speeds are high along the legs on which the daily inventory costs are high. On the contrary, in the third scenario, in which the bunker price is high, the optimal speeds are nearly constant because in order to minimize the fuel expenditure the speeds must be as lower as possible on each legs. However, one can still see the effect of the inventory costs: on the legs from 5 to 11, on which the daily inventory costs are lower than on the other legs, the optimal speeds are lower. Finally, one can notice that the average speed is constant, considering a fixed number of ships and a fixed service frequency, because of the following constraint:

$$t_0 = \frac{\sum_i \frac{L_i}{24\, v_i} + \sum_j t_j}{N} = \frac{T_0}{N} \qquad (6.39)$$

Therefore, the inventory costs in such case affect the speeds on each leg but they does not influence the average speed.

	Bunker price	
Scenario	**P [USD/tonne]**	**Variation**
1	146	-60%
2-base	365	/
3	583	+60%

Table 6.19: Inventory costs effect scenario, bunker price (route AE2)



Leg	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
Scenario 1	22,68	20,38	20,38	18,10	16,55	18,10	15,99	15,99	15,00	15,99	18,10	20,38	20,38	22,68	22,68	24,00	22,68
Scenario 2-base	20,38	20,38	18,10	18,10	18,10	18,10	18,10	18,10	18,10	18,10	18,10	18,10	20,38	20,38	20,38	20,88	20,38
Scenario 3	20,38	20,38	20,38	20,38	18,10	18,80	18,10	18,10	18,10	18,10	18,10	20,38	20,38	20,38	20,38	20,38	20,38
Daily inventory costs	63533	57564	51594	45625	39655	44446	38891	33335	27779	35141	42503	49865	57226	64588	77506	83403	69503

Figure 6.47: Effect of the inventory costs and the bunker price on the optimal speeds (route AE2) The speeds are higher on the legs on which the daily inventory costs are higher

6.3 EFFECT OF MARKET-BASED MEASURES

The section deals with the effect of two possible market-based measures in order to reduce the CO_2 emissions produced by the ships. The analysis considers a fixed service period equal to 7 whereas it considers the number of ships as variable. Consequently, the scenario analysed are similar to the fixed service frequency scenarios. Such solutions market-based measures are:

→ **Bunker levy**: a bunker levy is a cost added to the bunker price per tonne. Such measure has the same effect of a fuel price's rise. The bunker prices employed in the study are reported in table 6.20 ;

Scenario	Bunker price P [USD/tonne]	Bunker levy [USD/tonne]
1-base	365	/
2	415	50
3	465	100
4-speed limit	365	/

Table 6.20: Bunker prices concerning the scenarios simulated in the comparison between a bunker levy policy and a speed limit policy

→ **Speed limit policy**: a speed limit policy means imposing a maximum speed to the vessels. Strictly speaking, such policy is not a market-based measures however it is considered in such way in order to compare his effects with respect to the bunker levy's effects. The CO_2 emissions are linked to the speed of the ship hence limiting the maximum speed entails a reduction concerning the CO_2 emissions. However, limiting the maximum speed implies a rise of the number of ships deployed. The study considers as upper limit a speed of 18 knots;

The study assesses the measures through their cost efficiency. The cost efficiency CE_i [USD/tonne] of such measures is calculated employing the equation 6.39. The difference between the daily revenue in the scenario 1 $\dot{\pi}_{1-base}$, which is the base scenario hence it does not involve any measure to reduce the CO_2 emissions, and the daily profits in the considered scenario $\dot{\pi}_i$ is the cost of implementing the measure. The difference between the daily CO_2 emissions in the scenario 1 $E_{d,1\text{-}base}$ and the daily CO_2 emissions in the considered scenario $E_{d,i\text{-}base}$ is the amount of emissions avoided through the measure. As explained in section 3.3.3, the ratio between these two values is the cost efficiency of the measure analysed:

$$CE_i = \frac{\dot{\pi}_{1-base} - \dot{\pi}_i}{E_{d,1-base} - E_{d,i}} \quad (6.40)$$

Since the equation 6.39 contains the daily profits as well as the daily CO_2 emissions, the result is the same in employing their values calculated over a specific time lapse. Indeed, in such case, each factor would be multiplied by the same duration of time.
Table 6.21 contains the results concerning the analysis for each route. The results given by the model show that limiting the speed at the maximum value of 18 knots allows obtaining the best results in each route involved. On the contrary, the bunker price policy seems to be inefficient as the cost of avoiding the emissions of one ton of CO_2 is by far higher than in the speed limit scenario. Besides, the bunker levy of 50 USD/tonnes is inapplicable since the cost efficiency is excessively high. Indeed, as shown in figure 5.57, despite the bunker levy, the fuel price is not enough to force the ship owner to deploy a new ship along the route, therefore in order to maintain the service frequency the average speed cannot largely vary. On the contrary, the 100-bunker levy scenario force the number of ships to increase, reducing the emissions. Nevertheless, the higher fuel expenditure reduces the carrier's income more than in the speed limit scenario because in such scenario the ship owner has only to afford the cost of deploying a new vessel. The results

concerning the route TP1 are extremely high because neither the 100-scenario nor the speed limit scenario leads to increase the number of ships. For such scenario would be necessary a higher bunker levy or similarly a lower upper limit concerning the speeds in order to achieve some interesting results.

Therefore, a market-based measure should take into account the specific characteristics of the routes involved. For example, for the route TP1 a specific speed limit should be imposed, lower than for the route NEUATL1 and AE2. Finally, one can observe that in the container ship industry, in which there is a mandatory service frequency, the only viable solution in order to curb the CO_2 emissions has to force the carriers to increase the number of ships deployed along their services. Indeed, given a service frequency, the average speed along the route is about constant unless the number of ships increase. Table 6.22 reports the results concerning the number of ships, the average speed, the daily profit and the daily CO_2 emissions for the route NEUATL1.

Comparison results	
Route AE2	
Scenario	**Cost efficiency [USD/tonne]**
2	9236
3	168,7
4-speed limited	32,44
Route TP1	
Scenario	**Cost efficiency [USD/tonne]**
2	/
3	22711
4-speed limited	6488,3
Route NEUATL1	
Scenario	**Cost efficiency [USD/tonne]**
2	159474,9
3	84,7
4-speed limited	20,1

Table 6.21: Cost efficiency of the analysis concerning the effect of market-based measures

Results route NEUATL1				
Scenario	**N**	**Average speed [knots]**	**Daily profit [USD/day]**	**Daily CO_2 emissions [tonnes/day]**
1-base	4	20,02	789509	911,1
2	4	20,02	774879	911,0
3	5	15,32	763887	608,5
4-speed limited	5	15,32	783429	608,5

Table 6.22: Results for the route NEUATL1 concerning the market-based measures effect

The results obtained in this paper can be compared with the results provided in (Cariou and Cheaitou, 2012). Such paper deals with the comparison between a bunker levy policy and a speed limit, however in such thesis the speed limit comprise only a specific area. Taking into account the differences between the model provided in the paper and the model contained in the thesis, the cost efficiency comparison between the two policies leads to the same results. (Cariou and Cheaitou, 2012) provide the results concerning the route Northern Europe/North America, which are reported in table 6.23. In the same table are reported the cost efficiencies obtained applying the two policies. The cost efficiencies are calculated as made for the results obtained in this paper, i.e. dividing the difference between the profit of the base scenario and the profit of the scenario in which the considered policy is applied by the difference of the CO_2 emissions in the two scenarios.

Results (Cariou and Cheaitou, 2012)			
Scenario	**Daily profit [USD/day]**	**Daily CO_2 emissions [tonnes/day]**	**Cost efficiency [USD/tonne]**
1-base	1451041	1072	/
2-bunker levy (95 USD/tonne)	1420926	901	176,1
3-speed limit	1442417	936	63,4

Table 6.23: Cost efficiencies for (Cariou and Cheaitou, 2012)

CHAPTER 7
CONCLUSIONS

The section summarizes the main results the results obtained in the previous section. Therefore, the results concerning the effect of the freight rate, the bunker price and the daily fixed operating costs are divided with respect to the scenario considered:

→ **Fixed frequency scenario:** increasing the daily fixed operating costs decreases the optimal number of ships, thus the daily expenditure to maintain the fleet diminish. Since the service frequency is constant, the average speed of the ships must be higher in order to provide such frequency, hence the daily CO_2 emissions are also higher. On the contrary, increasing the bunker price, the optimal number of ships increases because in order to curb the fuel costs the average speed must decrease. Therefore, being the average speed lower, the daily CO_2 emissions are lower. The freight rate does not affect the optimal solution as the service frequency is constant therefore the revenue is also constant. The previous statement is reassumed in the following equation:

$$N \longrightarrow \left(\frac{1}{E}, P\right) \quad whereas \quad N \longrightarrow^{NOT} (F) \tag{7.1}$$

$$v_{average} \longrightarrow \left(E, \frac{1}{P}\right) \quad whereas \quad v_{average} \longrightarrow^{NOT} f(F) \tag{7.2}$$

$$E_d \longrightarrow \left(E, \frac{1}{P}\right) \quad whereas \quad E_d \longrightarrow^{NOT} f(F) \tag{7.3}$$

Figure 7.1 depicts the number of ships' trend and the average speed's trend at different bunker prices for the route AE2.

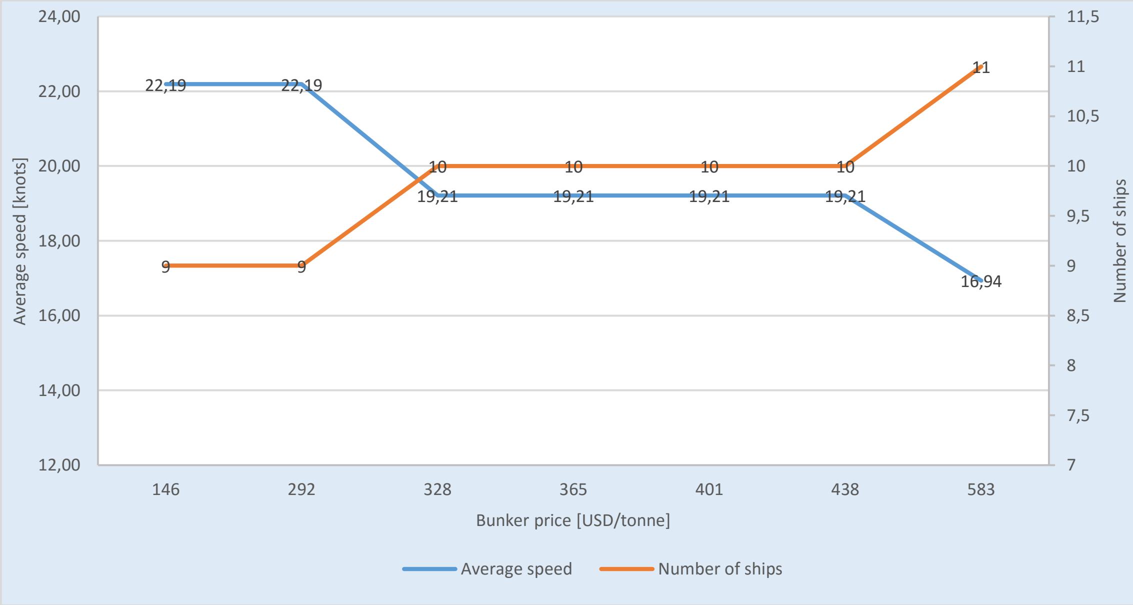


Figure 7.1: Fixed frequency scenario, optimal number of ships and optimal average speed at different bunker prices (route AE2)

→ **Fixed number of ships scenario:** Since the number of ships is constant, the daily operating costs do not affect the results. As observed in the fixed frequency scenario, a higher bunker price leads the operator to slow down his ships hence the average speed decreases. Consequently, the daily CO_2 emissions diminishes as the average speed is lower. The freight rate influences the optimal service frequency. Indeed, if the freight rate increases, the optimal service frequency will be lower. Nevertheless, the number of ships is constant, hence a higher service frequency entails to speed up the average speed in order to provide the required frequency. Therefore, the higher average speed implies higher fuel costs as well as the daily emissions. The previous statements can be mathematically written as:

$$t_0 \longrightarrow \left(\frac{1}{F}, P\right) \quad whereas \quad t_0 \longrightarrow^{NOT} (E) \tag{7.4}$$

$$v_{average} \longrightarrow \left(F, \frac{1}{P}\right) \quad whereas \quad v_{average} \longrightarrow^{NOT} (E) \tag{7.5}$$

$$E_d \longrightarrow \left(F, \frac{1}{P}\right) \quad whereas \quad E_d \longrightarrow^{NOT} (E) \tag{7.6}$$

Figure 7.2 depicts the service frequency' trend and the average speed's trend at different freight rate values for the route TP1.

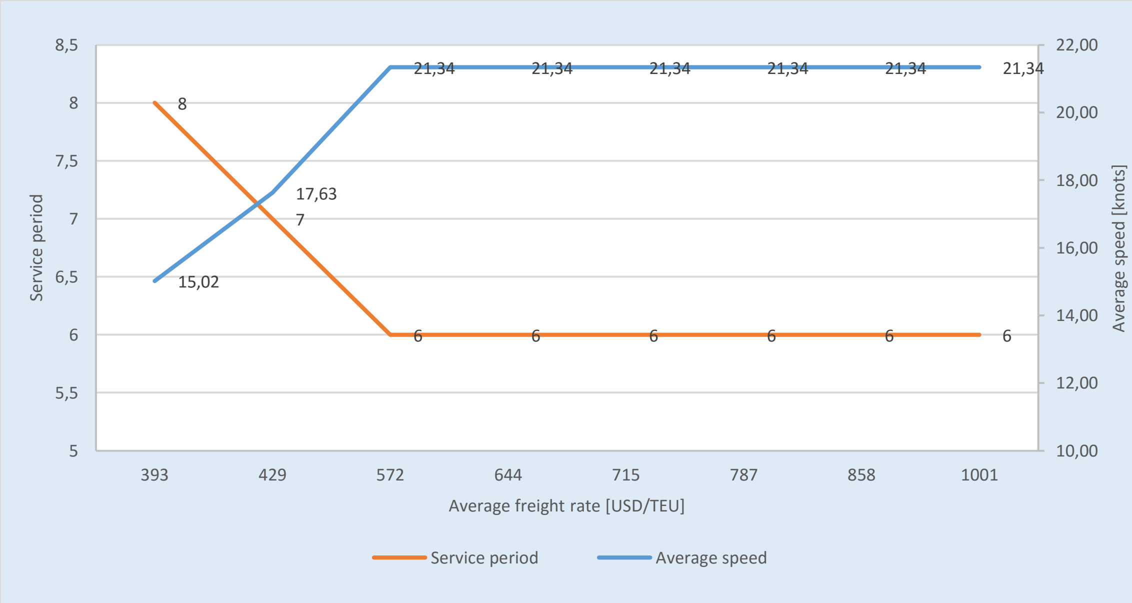


Figure 7.2: Fixed number of ships scenario, optimal service period and optimal average speed at different average freight rates (route TP1)

→ **Number of ships bounded above scenario:** considering the equation 7.7, one can see that if the service frequency is higher, the average speed must be higher because of the upper limit on the number of ships. Moreover, more ships are required in order to provide high service frequencies.

$$t_0 = \frac{\sum_i \frac{L_i}{24\,v_i} + \sum_j t_j}{N} = \frac{T_0}{N} \tag{7.7}$$

Since adopting a high service frequency implies that the number of ships must increase in order to provide the required service frequency, the optimal service frequency is indirectly proportional to the daily fixed operating costs. Consequently, the number of ships and the average speed (hence the emissions) are lower when the daily fixed operating costs are higher. The optimal service frequency is indirectly proportional to the bunker price hence the bunker price's effect is the same effect of the daily fixed operating costs. Indeed, a high bunker price leads the operator to decrease the average speed. Therefore, being the number of ships bounded above, the average speed cannot decrease unless the service frequency decreases.

The reduction of the average speed entails a reduction of the daily CO_2 emissions whereas the reduction concerning the service frequency implies a lower number of ships. On the contrary, the service frequency is directly proportional to the freight rate. Since a higher service frequency implies that the average speed and the number of vessels must be higher, the number of ships and the average speed are proportional to the freight rate's value. Obviously, the rise of the average speed entails that the emissions increase.
The previous statements are summarized by the following equations:

$$t_0 \longrightarrow \left(\frac{1}{F}, P, E\right) \tag{7.8}$$

$$v_{average} \longrightarrow \left(F, \frac{1}{P}, \frac{1}{E}\right) \tag{7.9}$$

$$N \longrightarrow \left(F, \frac{1}{P}, \frac{1}{E}\right) \tag{7.10}$$

$$E_d \longrightarrow \left(F, \frac{1}{P}, \frac{1}{E}\right) \tag{7.11}$$

Considering an unlimited number of ships mitigates the effect of the bunker price on the optimal service frequency hence on the other decisional variables. In such case, the average speed is not related to the service frequency because the operator can deploy the optimal number of ships for the considered service frequency. Employing a higher service frequency, the average speed might be lower than employing a lower frequency; consequently, the operator can curb the rise of the fuel expenditure due to the higher service frequency.

Figure 7.3 depicts the service frequency' trend and the average speed's trend at different freight rate values for the route TP1. Figure 7.4 shows the bunker price effect on the average speed and the service period for the route AE2.

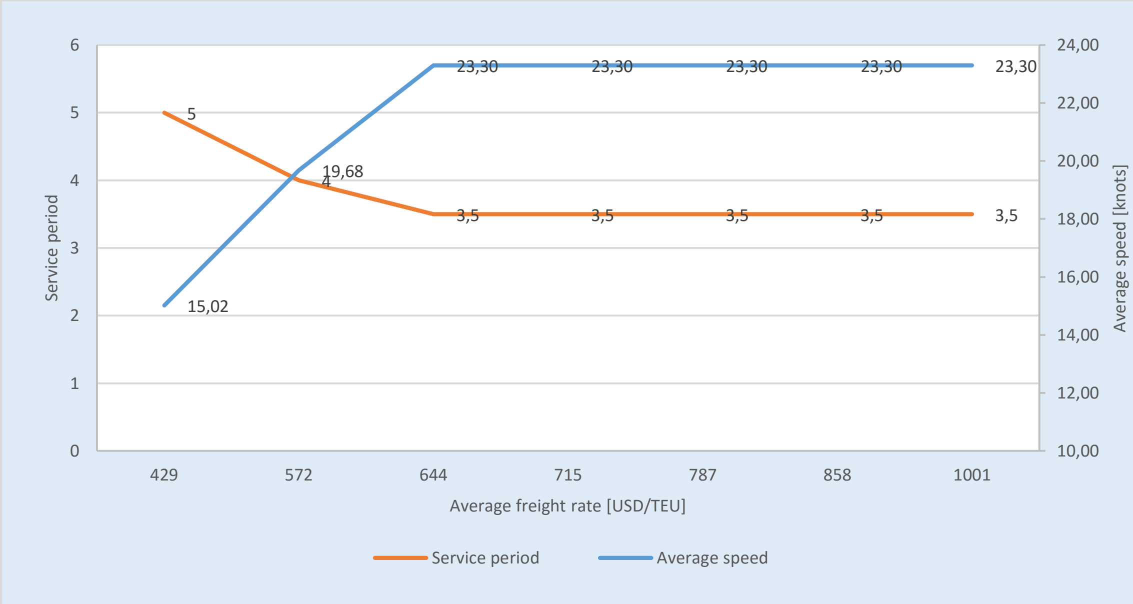


Figure 7.3: Number of ships bounded above scenario, optimal service period and optimal average speed at different average freight rates (route TP1)

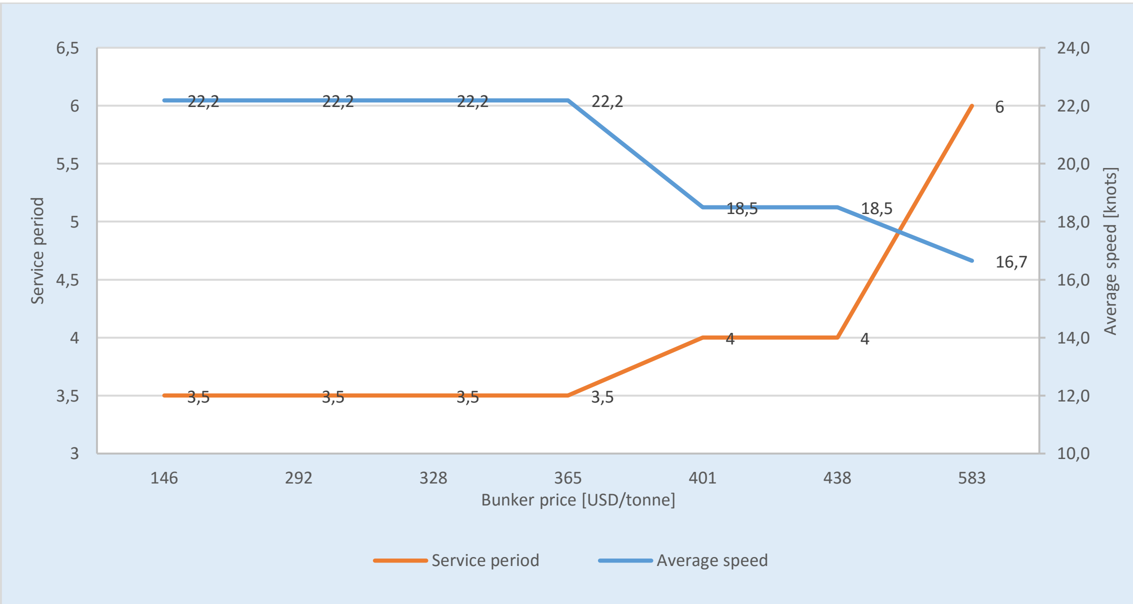


Figure 7.4: Number of ships bounded above scenario, optimal service period and optimal average speed at different bunker prices (route AE2)

Nevertheless, the influence of the freight rate, the bunker price and the daily operating fixed costs depends on the route's characteristics, such as the distances between the harbours and the transport demand considered. For example, the bunker price does not influence the optimal number of ships in the "number of ships bounded" scenario within the range of bunker price's values analysed. Therefore, the effects of these parameters should be analysed considering the actual features of the route involved.

Besides, one must notice that considering the service frequency as a variable entails that the transport demand is unlimited. Therefore, one must take into account the results obtained by the model can only be employed to analyse sort of scenario in which the transport demand, at least within the service frequency considered, as unlimited.

The inventory costs influence the optimal speeds along the legs. As depicts in figure 7.5, the optimal speed is higher on the legs on which the daily inventory costs are higher whereas the optimal speeds are lower on the legs with lower values of inventory costs. Nevertheless, the bunker price mitigates such effect because the rise of the fuel cost leads the operator to adopt speeds as lower as possible in order to minimize the fuel expenditure.

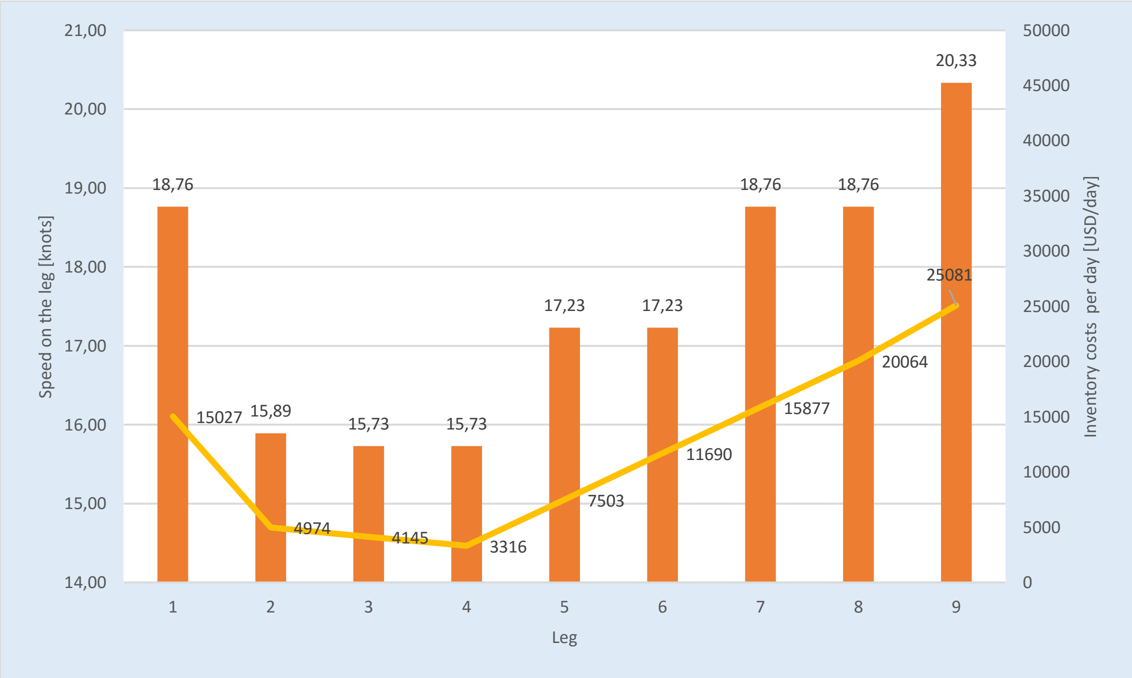


Figure 7.5: Effect of the inventory costs on the speeds along the legs (route TP1)
The figure refers to a base scenario in which the N=5, t_0=7 and the bunker price is equal to 219 USD/tonne

Finally, the results concerning the implementation of two market-based measures in order to reduce the CO_2 emissions, which are the bunker levy policy and the speed limit policy, show the economic advantage of imposing a speed limit. Indeed, imposing a speed limit, the carriers are forced to increase the number of vessels deployed along the route, which is the only way to reduce the emissions produced by the fleet. A bunker levy may produce the same effect however the reduction of the operator's profits are higher hence such solution is economically disadvantageous. Table 7.1 contains the results regarding the route AE2.

Comparison results	
Route AE2	
Scenario	**Cost efficiency [USD/tonne]**
2-bunker levy 50 [USD/tonne]	9236
3-bunker levy 100 [USD/tonne]	168,7
4-speed limited	32,44

Table 7.1: Costs efficiencies of the bunker levy policy and the speed limit policy (route AE2)

Nevertheless, the benefits of a speed limit policy are strictly related to the route's characteristics. The specific features of the considered route might make the speed limit policy as well as the bunker levy policy completely inefficient, i.e. the cost per one tonne of CO_2 avoided is extremely high. Furthermore, one should not claim that the speed limit policy is a better alternative with respect to the bunker levy policy. Indeed, the comparison is made taking into account only the economic impact on the carrier's profit; however, such analysis should also comprise other stakeholders and other benchmark values.

APPENDICES

APPENDIX - A

The percentages reported in figure 2.1 are computed from the following table provided in the third IMO GHG study 2014:

CO_2 Emissions [million tonnes]

Fuel	2007	2008	2009	2010	2011	2012
HFO	773,8	802,7	736,6	650,6	716,9	667,9
MDO	97,2	102,9	104,2	102,2	109,8	105,2
LNG	13,9	15,4	14,2	18,6	22,8	22,6

Table A.1: International emission for fuel type using bottom-up method
Adapted from: IMO-International Maritime Organization, Third IMO Greenhouse Gas Study 2014, Table 3

These emissions values are divided by the emissions factor reported in (IMO, 2014):

CO_2 Emissions Factors (IMO, 2014)

Fuel	Emissions Factor
HFO	3,114
MDO	3,206
LNG	2,750

Table A.2: emission factors
Adapted from: IMO-International Maritime Organization, Third IMO Greenhouse Gas Study 2014, Page 248

Thus, using the following equation the fuel consumption *FC* in million tonnes for each type of fuel are computed:

$$FC_i = \frac{E_i}{EF_i} \qquad \text{(A.1)}$$

Where *E* is the amount of emission in million tonnes and *EF* is the emissions factor of the fuel considered.

APPENDIX - B

The index reported in figure 3.4 is computed employing the data present in table B.1 and table B.2, which refer to the CO_2 emissions produced by the shipping transport and the load transported respectively.

Global and Shipping CO_2 Emissions [Mtonnes]

Year	Global	International shipping
2007	31409	885
2008	32204	921
2009	32047	855
2010	33612	771
2011	34723	850
2012	35640	796

Table B.1: Global and shipping CO_2 emissions in 2007-2012
Adapted from: IMO-International Maritime Organization, Third IMO Greenhouse Gas Study 2014, Table 1

International seaborne trade [Mtonnes]

	Container	Other dry cargo	Five major bulks	Oil and gas	Total
2007	1193	2141	1953	2747	8034
2008	1249	2173	2065	2742	8229
2009	1127	2004	2085	2642	7858
2010	1280	2022	2335	2772	8409
2011	1393	2112	2486	2794	8785
2012	1464	2150	2742	2841	9197

Table B.2: International seaborne trade in millions of tonne loaded in 2007-2012
Adapted from: UNCTAD-United Nations Conference on Trade and Development, Review of Maritime transport, Figure 1.2, 2015

Basically, the emission-activity index is computed for each year dividing the international emissions by the amount of cargoes loaded:

$$index = \frac{Yearly\ Emissions}{Yearly\ Load} \tag{B.1}$$

APPENDIX - C

```
function [m,A]=linearizzazione(a,b,error,Umax,Umin)
Qr = @(u) (1/24)*a*u.^(1-b);
Qr1 = @(u) (1/24)*a*(1-b)*u.^-b;
Qrmax = Qr(Umax);
for k=1:10000
  u(1)=Umin;
  Q(1)=Qr(Umin)-error;
  clear uc;
  clear ubk;
  if (Qrmax-Q(k))/(Umax-u(k)) >= Qr1(Umax)
    A(k)=Qrmax-Qr1(Umax)*Umax;
    m(k)=Qr1(Umax);
    if A(k)+m(k)*Umax >= Qrmax-error
      u(k+1)=Umax;
      Q(k+1)=A(k)+m(k)*Umax;
    break
  end
  else
    fx=@(ubj) (1/24)*a*(1-b)*(ubj.^-b)*(ubj-u(k))+Q(k)-(1/24)*a*ubj.^(1-b);
    ubj=bisection(fx,u(k),Umax,0.000001);
    ub(k)=ubj;
    Qb(k)=(1/24)*a*ub(k)^(1-b);
    A(k)=Q(k)-u(k)*((Qb(k)-Q(k))/(ub(k)-u(k)));
    m(k)=(Qb(k)-Q(k))/(ub(k)-u(k));
    Qnk=@(u) A(k)+m(k)*u;
    if A(k)+m(k)*Umax >= Qrmax-error
```

```
        u(k+1)=Umax;
        Q(k+1)=A(k)+m(k)*Umax;
      break
    end
    end
    if (Qrmax-Q(k))/(Umax-u(k)) <= Qr1(Umax)
     if Qnk(Umax)>(Qr(Umax)-error)
      A(k)=Q(k)-u(k)*((Qb(k)-Q(k))/(ub(k)-u(k)));
      m(k)=(Qb(k)-Q(k))/(ub(k)-u(k));
      if A(k)+m(k)*Umax >= Qrmax-error
        u(k+1)=Umax;
        Q(k+1)=A(k)+m(k)*Umax;
      break
    end
     else
      fx=@(uc) A(k)+m(k)*uc+error-(1/24)*a*uc^(1-b);
      uc=bisection(fx,ubj,Umax,0.000001);
      u(k+1)=uc;
      A(k)=Q(k)-u(k)*((Qb(k)-Q(k))/(ub(k)-u(k)));
      m(k)=(Qb(k)-Q(k))/(ub(k)-u(k));
      Q(k+1)=A(k)+m(k)*u(k+1);
     end
    end
end
j=length(m);
for k=1:j
    x=(u(k):0.000001:u(k+1));
    ux=Qr(x);
```

```
  y=@(x) A(k)+m(k)*x;
  y1=y(x);
  hold on
  plot(x,ux,'b')
  hold on
  plot(x,y1,'g')
  hold on
  plot(u(k),Q(k),'r*')
  hold on
  plot(u(k+1),Q(k+1),'r*')
end
xlswrite('pendenze',m)
xlswrite('Intercette',A)
A
M
```

APPENDIX - D

Appendix D contains the input parameters such as demand tables and payloads on the legs, for each route. The parameters must be considered as the base scenario values and any variation reported in the analysis refers to these figures.

→ AE2

Capacity Utilization [%]

	A to NE (Westbound)	NE to A(Eastbound)
1Q10	92%	62%
2Q10	104%	66%
3Q10	95%	54%
4Q10	78%	54%
Average	**92%**	**59%**

Table D.1: Average capacity utilization in 2010 on the Europe-Far East lane
Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table AE-20

Demand Table Eastbound

FROM/TO [TEU]	Colombo -6	Singapore -7	Hong Kong-8	Yantian -9	Xingang -10	Qingdao -11	Busan -12	Shanghai -13	Ningbo -14	Loaded
Felixstowe-1	130	230	230	230	230	230	230	230	230	1970
Antwerp-2	130	230	230	230	230	230	230	230	230	1970
Wilhelmshaven-3	130	230	230	230	230	230	230	230	230	1970
Bremerhaven-4	130	230	230	230	230	230	230	230	230	1970
Rotterdam-5	130	230	230	230	230	230	230	230	230	1970
Colombo-6	/	230	230	230	230	230	230	230	230	1840
Unloaded	650	1380	1380	1380	1380	1380	1380	1380	1380	

Demand Table Westbound

FROM/TO [TEU]	Algericias-17	Antwerp-2	Wilhelmshaven-3	Bremerhaven-4	Rotterdam-5	Felixstowe-1	Loaded
Xingang-10	460	460	460	460	460	460	2760
Qingdao-11	460	460	460	460	460	460	2760
Busan-12	460	460	460	460	460	460	2760
Shanghai-13	460	460	460	460	460	460	2760
Ningbo-14	460	460	460	460	460	460	2760
Yantian-15	460	460	460	460	460	460	2760
Tanjung Pelepes-16	210	210	210	210	210	210	1260
Unloaded	2970	2970	2970	2970	2970	2970	

Table D.2: Supposed demand tables for the AE2 lane

Capacity Utilization	
Leg-1	75%
Leg-2	70%
Leg-3	64%
Leg-4	59%
Leg-5	53%
Leg-6	60%
Leg-7	52%
Leg-8	45%
Leg-9	37%
Leg-10	45%
Leg-11	52%
Leg-12	60%
Leg-13	67%
Leg-14	75%
Leg-15	90%
Leg-16	97%
Leg-17	80%

Table D.3: Capacity utilization on each leg for the AE2 lane
The demand tables determine the capacity utilization table. As explained in section 5.3.1, the legs 5 and 6 are imposed to be the eastbound leg whereas the legs 15 and 16 are imposed to be the westbound leg. On such legs, the average capacity utilization is by 57% and by 93% respectively, hence these values are almost equal to the benchmark values reported in table D.1.

	Volume in TEUs [TEU]		Annual Value of Liner Cargo [USD]		Average Value per TEU [USD/TEU]	
	A to NE (Westbound)	**NE to A (Eastbound)**	**A to NE (Westbound)**	**NE to A (Eastbound)**	**A to NE (Westbound)**	**NE to A (Eastbound)**
1Q10	2122067	1112341	/	/	**$34.166,26**	**$29.389,30**
2Q10	2232096	1133848	/	/		
3Q10	2517504	1029319	/	/		
4Q10	2310642	1055249	/	/		
Average	**9182309**	**4330757**	**$313.725.201.717**	**$127.277.933.979**		

Table D.4: Average value per TEU in 2010 on the AE2 lane
Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table AE-1 and AE-15

Cargo Value [USD/TEU]	
Leg-1	33487
Leg-2	32702
Leg-3	31784
Leg-4	30697
Leg-5	29389
Leg-6	29389
Leg-7	29389
Leg-8	29389
Leg-9	29389
Leg-10	30982
Leg-11	32119
Leg-12	32972
Leg-13	33635
Leg-14	34166
Leg-15	34166
Leg-16	34166
Leg-17	34166

Table D.5: Average cargo value on each leg for the AE2 lane
The average value for the legs 5 and 6 is 29389 [USD/TEU] whereas the average value for the legs 15 and 16 is 34166 [USD/TEU]. These values are equal to the benchmark values in table D.4.

Freight rate benchmark values [USD/TEU]	
Felixstowe to Shanghai (eastbound)	*675*
Shanghai to Felixstowe (westbound)	*690*

Table D.6: Freight rate benchmark values for the AE2 lane
Data source: http://www.worldfreightrates.com, 18-12-2016

Freight Rate Table Eastbound

FROM/TO [USD/TEU]	Colombo-6	Singapore-7	Hong Kong-8	Yantian-9	Xingang-10	Qingdao-11	Busan-12	Shanghai-13	Ningbo-14
Felixstowe-1	380	458	532	534	604	625	650	675	681
Antwerp-2	373	451	525	527	597	618	643	668	674
Wilhelmshaven-3	355	434	507	509	580	601	626	651	657
Bremerhaven-4	352	431	504	506	577	597	623	647	654
Rotterdam-5	339	418	491	493	564	585	610	635	641
Colombo-6	/	79	152	154	225	245	271	295	302

Freight Rate Table Westbound

FROM/TO [USD/TEU]	Algeciras-17	Felixstowe-1	Antwerp-2	Wilhelmshaven-3	Bremerhaven-4	Rotterdam-5
Xingang-10	585	656	663	682	686	700
Qingdao-11	562	633	641	660	663	677
Busan-12	535	606	614	632	636	650
Shanghai-13	508	579	587	606	609	623
Ningbo-14	501	572	580	599	602	616
Yantian-15	462	533	540	559	563	577
Tanjung Pelepes-16	379	450	458	477	480	494

Table D.7: Freight rates tables for the AE2 lane
The freight rates table contains the freight rates employed in the model

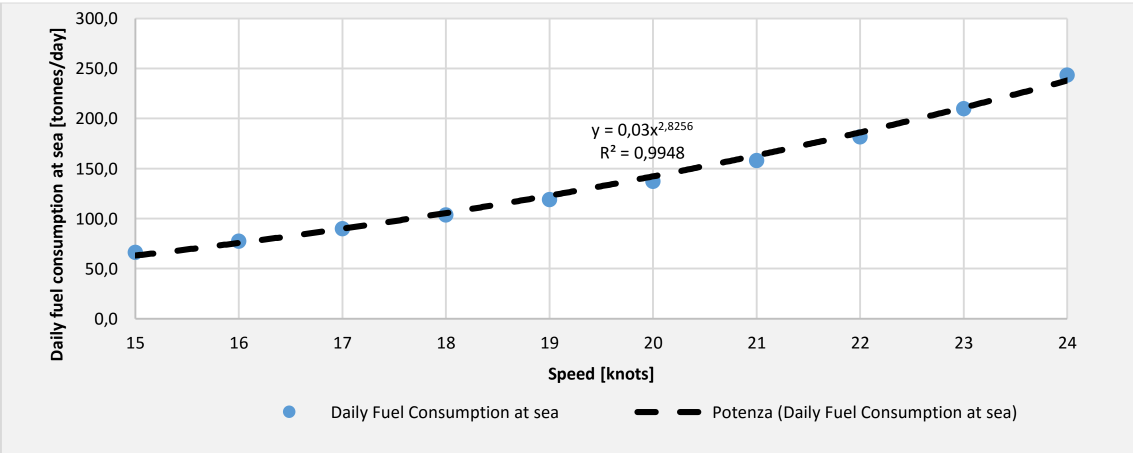


Figure D.8: Daily fuel consumption at sea for the AE2 lane
The black line is the interpolating function whereas the blue points depict the daily fuel consumption at different speed, obtained by the spreadsheet provided in https://www.shipowners.dk/en/services/beregningsvaerktoejer

Daily Fuel Consumption											
Speed [knots]	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Auxiliary at sea [tonne/day]	7,9	7,9	7,9	7,9	7,9	7,9	7,9	7,9	7,9	7,9	7,9
Auxiliary at port [tonne/day]	27,9	27,9	27,9	27,9	27,9	27,9	27,9	27,9	27,9	27,9	27,9
Main engine [tonne/day]	58,2	69,4	81,9	95,7	111,0	129,2	149,9	173,8	201,8	235,6	277,4
Main engine and auxiliary at sea [tonne/day]	66,0	77,3	89,8	103,6	118,9	137,0	157,8	181,7	209,7	243,4	285,2

Table D.9: Daily fuel consumption data for the AE2 lane

Harbor time, tp [h]	
Leg-1	45
Leg-2	40
Leg-3	16
Leg-4	18
Leg-5	36
Leg-6	16
Leg-7	25
Leg-8	17
Leg-9	18,5
Leg-10	50
Leg-11	23
Leg-12	18
Leg-13	12
Leg-14	24
Leg-15	15
Leg-16	31
Leg-17	24

Table D.10: Times at ports for the AE2 lane

	TEU capacity [TEU]	IMO number	Deadweight [tonnes]	Length Overall [m]	Breadth Extreme [m]	Year Built	Main engine [kW]
Msc Zoe	19437	9703318	199281	395,46	59,08	09-apr-15	1x MAN-B&W/Hyundai 11S90ME-C10 - 2 stroke 11 cylinder diesel engine - 67.100 kW / 83.780 hp
Msc Jade	19224	9762326	200148	398,4	59,07	10-dec-15	
Merete Maersk (triple E)	18300	9632064	194916	399,2	60	22-aug-14	2x Doosan 7S80ME-C - 7 cylinder 800 x 3.450 mm diesel engine each 23.310 kW / 31.692 hp at 72 rpm Manufacturer: Doosan Engine Co., Ltd.
Msc Mirja	19600	9762338	194308	398,49	59,01	2016*	
Evelyn Maersk	15550	9321512	158200	397,71	56,55	29-mar-07	1x Doosan Sulzer 14RT-FLEX96C - 14 cylinder 960 x 2.500 mm engine - 80.080 kW at 102,0 rpm Manufacturer Name: Doosan Engine Co. Ltd
Msc Ditte	19300	9754953	200148	398,4	59,08	22-jun-16	
Mathilde Maersk (triple E)	18300	9632179	196000	399,2	59	30-jun-15	2x MAN-B&W/Doosan 7S80ME-C9.4 - 2 stroke 7 cylinder 800 x 3.450 mm diesel engines each 23.310 kW at 72,0 rpm Manufacturer: Doosan Engine Co., Ltd.
Mogens Maersk (Triple E)	18300	9632090	194679	399	60	17-sep-14	
Msc London	16980	9606302	186650	399	54	13-jul-14	1x MAN-B&W-STX11S90ME-C9 - 2 stroke 11 cylinder diesel engine 59.780 kW
Msc Reef	19600	9754965	200148	398,4	59,08	2016*	

Table D.11: Vessels characteristics for the AE2 lane
Data Sources:

- *The transport capacity, the IMO number and the built year are reported in https://my.maerskline.com (*data from https://www.marinetraffic.com)*
- *The deadweight, the length overall and the breadth extreme are provided in https://www.marinetraffic.com*
- *The power is reported in http://www.scheepvaartwest.be*

Accessed: 10-12-2016

→ **TP1**

	Capacity Utilization [%]	
	US to A (Westbound)	**A to US(Eastbound)**
1Q10	54%	79%
2Q10	65%	100%
3Q10	55%	86%
4Q10	52%	74%
Average	**57%**	**85%**

Table D.12: Average capacity utilization in 2010 on the Asia-North America lane
Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table TP-20

Demand Table Westbound

FROM/TO [TEU]	Yokohama-3	Busan-4	Kaoshiung-5	Yantian-6	Xiamen-7	Shanghai-8	Loaded
Vancouver-1	350	350	350	350	350	350	2100
Seattle-2	350	350	350	350	350	350	2100
Unloaded	700	700	700	700	700	700	

Demand Table Eastbound

FROM/TO [TEU]	Vancouver-1	Seattle-2	Loaded
Kaoshiung-5	600	600	1200
Yantian-6	600	600	1200
Xiamen-7	600	600	1200
Shanghai-8	600	600	1200
Busan-9	600	600	1200
Unloaded	3000	3000	

Table D.13: Supposed demand tables for the TP1 lane

Capacity Utilization

Leg-1	72%
Leg-2	59%
Leg-3	49%
Leg-4	40%
Leg-5	47%
Leg-6	54%
Leg-7	61%
Leg-8	68%
Leg-9	85%

Table D.14: Capacity utilization on each leg for the TP1 lane

The demand tables determine the capacity utilization table. As explained in section 5.3.2, the leg 2 is imposed to be the westbound leg whereas the leg 9 is imposed to be the eastbound leg. On such legs, the average capacity utilization is by 59% and by 85% respectively, hence these values are almost equal to the benchmark values reported in table D.10.

	Volume in TEUs [TEU]		Annual Value of Liner Cargo [USD]		Average Value per TEU [USD/TEU]	
	US to A (Westbound)	A to US(Eastbound)	US to A (Westbound)	A to US(Eastbound)	US to A (Westbound)	A to US(Eastbound)
jan-10	430109	955535	/	/	$8.645,23	$30.514,61
feb-10	459281	866915	/	/		
mar-10	500822	872455	/	/		
apr-10	498739	943258	/	/		
maj-10	487786	1051020	/	/		
jun-10	464090	1094163	/	/		
jul-10	4654390	1087477	/	/		
aug-10	467541	1200048	/	/		
sep-10	448756	1128130	/	/		
okt-10	530360	1141159	/	/		
nov-10	519741	1059959	/	/		
dec-10	523521	951023	/	/		
Average	**9985136**	**12351142**	**$86.323.832.060**	**$376.890.329.191**		

Table D.15: Average value per TEU in 2010 on the TP1 lane
Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table TP-1 and TP-15

	Cargo Value [USD/TEU]
Leg-1	21510
Leg-2	8645
Leg-3	8645
Leg-4	8645
Leg-5	16598
Leg-6	22457
Leg-7	26954
Leg-8	30515
Leg-9	30515

Table D.16: Average cargo value on each leg for the TP1 lane
The average value for the legs 2 is 8645 [USD/TEU] whereas the average value for the legs 9 is 30515 [USD/TEU]. These values are equal to the benchmark values in table D.14.

	Freight rate benchmark values [USD/TEU]
Shanghai to Seattle (eastbound)	*1070*
Seattle to Shanghai (westbound)	*360*

Table D.17: Freight rate benchmark values for the TP1 lane
Data source: http://www.worldfreightrates.com, 19-12-2016

Freight Rate Table Westbound

FROM/TO [USD/TEU]	Yokohama-3	Busan-4	Kaoshiung-5	Yantian-6	Xiamen-7	Shanghai-8
Vancouver-1	225	260	308	325	339	367
Seattle-2	218	253	301	318	332	360

Freight Rate Table Eastbound

FROM/TO [USD/TEU]	Vancouver-1	Seattle-2
Kaoshiung-5	1283	1311
Yantian-6	1212	1240
Xiamen-7	1155	1183
Shanghai-8	1042	1070
Busan-9	946	974

Table D.18: Freight rates tables for the TP1 lane
The freight rates table contains the freight rates employed in the model

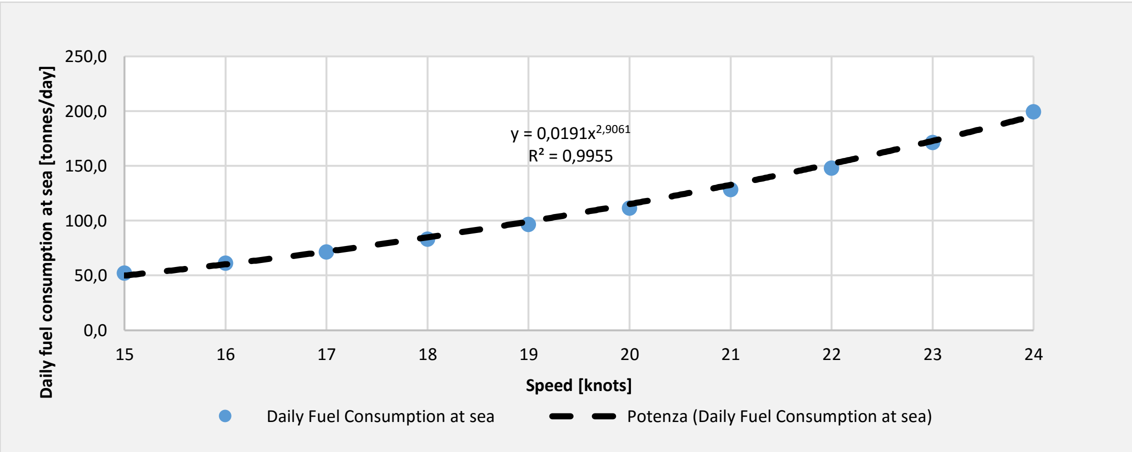


Figure D.19: Daily fuel consumption at sea for the TP1 lane
The black line is the interpolating function whereas the blue points depict the daily fuel consumption at different speed, obtained by the spreadsheet provided in https://www.shipowners.dk/en/services/beregningsvaerktoejer

Daily Fuel Consumption											
Speed [knots]	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**
Auxiliary at sea [tonne/day]	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9	6,9
Auxiliary at port [tonne/day]	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6	12,6
Main engine [tonne/day]	45,4	54,3	64,6	76,4	89,7	104,6	121,7	141,3	164,5	192,7	228,2
Main engine and auxiliary at sea [tonne/day]	52,3	61,2	71,5	83,3	96,6	111,5	128,5	148,2	171,3	199,5	235,1

Table D.20: Daily fuel consumption data for the TP1 lane

Harbor time, tp [h]	
Leg-1	8,5
Leg-2	53
Leg-3	5
Leg-4	14
Leg-5	11
Leg-6	20
Leg-7	12
Leg-8	12
Leg-9	14

Table D.21: Times at ports for the TP1 lane

Vessels	***IMO number***	***TEU Capacity***	***Deadweight [tonne]***	***Length Overall [m]***	***Breadth Extreme [m]***	***Power [kW]***
MSC Roberta	8511287	4500	43567	244	32	23147
MSC Heidi	9309473	8870	114106	331,99	43,2	68510
E.R. Vancouver	9285691	7849	93638	300,06	43	68640
MSC Danang	*9348687	*5085	68411	294,03	32,2	41130
Maersk Denpasar	*9348663	*5085	68463	294,08	32,2	41130

Table D.22: Vessels characteristics for the TP1 lane
Data Sources:

- *The transport capacity is reported in https://my.maerskline.com (*data from https://www.msc.com/search-schedules)*
- *The IMO number is reported in https://my.maerskline.com (*data from http://www.containership-info.com)*
- *The deadweight, the length overall and the breadth extreme are provided in https://www.marinetraffic.com*
- *The power is reported in http://www.containership-info.com*

Accessed: 12-12-2016

→ NEUATL1

	Capacity Utilization [%]	
	US to E (Eastbound)	E to US(Westbound)
jan-10	78%	72%
feb-10	81%	76%
mar-10	103%	95%
apr-10	92%	94%
maj-10	87%	95%
jun-10	88%	96%
jul-10	86%	97%
aug-10	92%	96%
sep-10	89%	86%
okt-10	79%	81%
nov-10	83%	88%
dec-10	82%	79%
Average	**87%**	**88%**

Table D.23: Average capacity utilization in 2010 on the North Europe-US lane
Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table TA-23

Demand Table Westbound

FROM/TO [TEU]	Norfolk-4	Charleston-5	Miami-6	Houston-7	Loaded
Antwerp-1	350	350	350	350	1400
Rotterdam-2	350	350	350	350	1400
Bremerhaven-3	350	350	350	350	1400
Unloaded	1050	1050	1050	1050	

Demand Table Eastbound

FROM/TO [TEU]	Antwerp-1	Rotterdam-2	Bremerhaven-3	Loaded
Charleston-5	340	340	340	1020
Miami-6	340	340	340	1020
Houston-7	340	340	340	1020
Norfolk-8	340	340	340	1020
Unloaded	1360	1360	1360	

Table D.24: Supposed demand tables for the NEUATL1 lane

Capacity Utilization	
Leg-1	87%
Leg-2	88%
Leg-3	89%
Leg-4	66%
Leg-5	66%
Leg-6	65%
Leg-7	65%
Leg-8	86%

Table D.25: Capacity utilization on each leg for the NEUATL1 lane

The demand tables determine the capacity utilization table. As explained in section 5.3.3, the leg 3 is imposed to be the westbound leg whereas the leg 8 is imposed to be the eastbound leg. On such legs, the average capacity utilization is by 89% and by 86% respectively hence these values are almost equal to the benchmark values reported in table D.21.

	Volume in TEUs [TEU]		Annual Value of Liner Cargo [USD]		Average Value per TEU [USD/TEU]	
	US to E (Eastbound)	**E to US(Westbound)**	**US to E (Eastbound)**	**E to US(Westbound)**	**US to E (Eastbound)**	**E to US(Westbound)**
jan-10	89779	96901	/	/	**$33.599,48**	**$55.087,12**
feb-10	91318	100124	/	/		
mar-10	114419	123355	/	/		
apr-10	108787	124368	/	/		
maj-10	103587	124576	/	/		
jun-10	102343	124408	/	/		
jul-10	100425	131563	/	/		
aug-10	105748	129134	/	/		
sep-10	103063	116013	/	/		
okt-10	109533	128647	/	/		
nov-10	104484	128143	/	/		
dec-10	102651	113699	/	/		
Average	**1236137**	**1440931**	**$41.533.561.828**	**$79.376.740.068**		

Table D.26: Average value per TEU in 2010 on the NEUATL1 lane

Adapted from: Federal Maritime Commission, Study of the 2008 Repeal of the Liner Conference Exemption from European Union Competition Law, Table TA-3 and TA-15

Cargo Value [USD/TEU]	
Leg-1	40901
Leg-2	48062
Leg-3	55087
Leg-4	55087
Leg-5	48062
Leg-6	40901
Leg-7	33599
Leg-8	33599

Table D.27: Average cargo value on each leg for the TP1 lane
The average value for the legs 3 is 55087 [USD/TEU] whereas the average value for the legs 9 is 33599 [USD/TEU]. These values are equal to the benchmark values in table D.24.

Freight rate benchmark values [USD/TEU]	
Miami to Rotterdam (eastbound)	*1150*
Rotterdam to Miami (westbound)	*1260*

Table D.28: Freight rate benchmark values for the NEUATL1 lane
Data source: http://www.worldfreightrates.com, 19-12-2016

Freight Rate Table Westbound

FROM/TO [USD/TEU]	Norfolk-4	Charleston-5	Miami-6	Houston-7
Antwerp-1	1063	1173	1289	1543
Rotterdam-2	1034	1144	1260	1514
Bremerhaven-3	968	1079	1194	1449

Freight Rate Table Eastbound

FROM/TO [USD/TEU]	Antwerp-1	Rotterdam-2	Bremerhaven-3
Charleston-5	1210	1230	1275
Miami-6	1130	1150	1195
Houston-7	955	974	1020
Norfolk-8	641	661	706

Table D.29: Freight rates tables for the NEUATL1 lane
The freight rates table contains the freight rates employed in the model

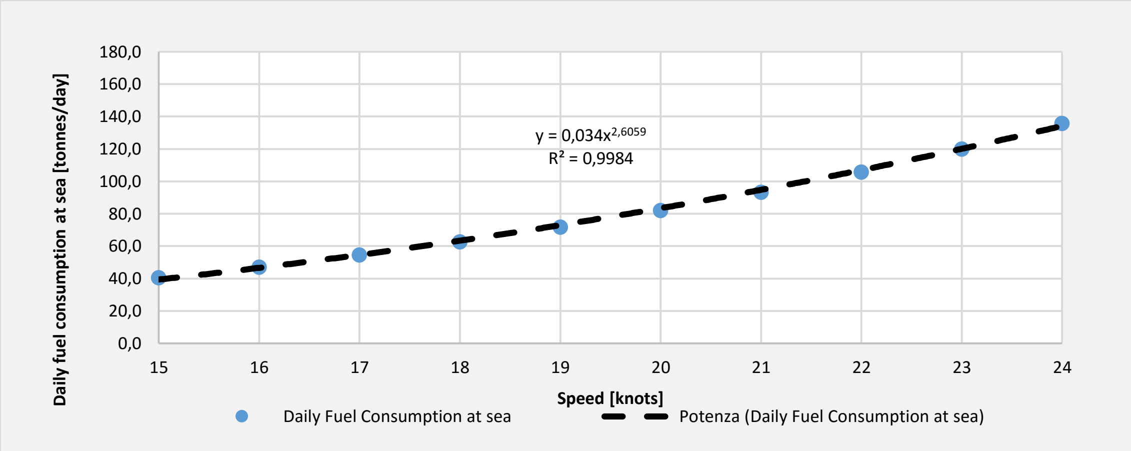


Figure D.30: Daily fuel consumption at sea for the NEUATL1 lane
The black line is the interpolating function whereas the blue points depict the daily fuel consumption at different speed, obtained by the spreadsheet provided in https://www.shipowners.dk/en/services/beregningsvaerktoejer

Daily Fuel Consumption

Speed [knots]	15	16	17	18	19	20	21	22	23	24	25
Auxiliary at sea [tonne/day]	6,4	6,4	6,4	6,4	6,4	6,4	6,4	6,4	6,4	6,4	6,4
Auxiliary at port [tonne/day]	24,3	24,3	24,3	24,3	24,3	24,3	24,3	24,3	24,3	24,3	24,3
Main engine [tonne/day]	34,1	40,7	48,1	56,3	65,4	75,6	86,9	99,4	113,5	129,4	147,7
Main engine and auxiliary at sea [tonne/day]	40,4	47,1	54,5	62,7	71,7	82,0	93,3	105,8	119,8	135,7	154,0

Table D.31: Daily fuel consumption data for the NEUATL1 lane

Harbor time, tp [h]

Leg-1	16
Leg-2	20
Leg-3	16
Leg-4	11
Leg-5	10
Leg-6	10
Leg-7	24
Leg-8	18

Table D.32: Times at ports for the NEUATL1 lane

Vessels	IMO number	TEU Capacity [TEU]	Deadweight [tonne]	Length Overall [m]	Breadth Extreme [m]	Power [kW]
Maersk Carolina	9155133	4824	62229	292,08	32,3	43070
Maersk Wisconsin	9193252	4658	61987	292,08	32,35	43070
Maersk Montana	9305312	4824*	61499	292,08	32,35	45764
Maersk Iowa	9298686	4650	61454	292,08	32,35	45764
Maersk Missouri	9155121	4824	62229	292,08	32,3	43070

Table D.33: Vessels characteristics for the NEUATL1 lane
Data Sources:

- *The transport capacity is reported in https://my.maerskline.com (*data from https://www.msc.com/search-schedules)*
- *The IMO number is reported in https://my.maerskline.com*
- *The deadweight, the length overall and the breadth extreme are provided in https://www.marinetraffic.com*
- *The power is reported in http://www.containership-info.com*

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