



## **A Numerical Tool for the Planning of Container Ship Fleets**

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## **ABSTRACT**

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Containerized shipping is an extremely valuable and competitive market. This environment creates a unique need for efficiency in every stage of planning and designing liner routes. This dissertation allowed the development of a strategic planning tool to support the design of containership liner routes. The tool solves the problem of sizing the ship and fleet for a round voyage. The inputs are the round voyage data, including expected freight rates, the cargo flows between ports, as well as the data on ports and canals. As outputs, the tool returns several possible fleets with the respective performance indicators in a range of cost scenarios and operational speeds.

The algorithm of the tool is explained, as well as the performance indicators of the fleet and the modelling of the economic variables. The tool determines the technical characteristics of the containerships required for the route using a database of existing ships, allowing a full characterization of the ships, required in order to calculate performance indicators. The tool is highly customizable, completely general, and needs no other programs to run. This dissertation also includes in appendix a user manual which details the preparation of the inputs and the reading of the outputs.

An extremely important part of the development of any tool is its validation, which is done with three randomized input trials, demonstrating the good functioning of the tool. The tool is then applied in three case studies dealing with different liner service: an intra-Asian route, a Northern Europe to East Asia route and a route between mainland Portugal, the island of Madeira, and the Azores archipelago. Conclusions are drawn and recommendations for further development of the tool are provided.

**Keywords:** Containerships, Liner shipping, Ship dimensioning, Fleet sizing, Fleet performance.



## RESUMO

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O transporte de contentores é um mercado extremamente valioso e competitivo. Este ambiente cria uma necessidade única de eficiência em todas as fases do planeamento e do projeto de rotas. Esta dissertação permitiu o desenvolvimento de uma ferramenta de planeamento estratégico para apoiar o desenho de rotas de navios de contentores. A ferramenta resolve o problema de dimensionamento do navio e da frota para uma viagem redonda. Os dados de entrada são os dados da viagem redonda, incluindo as taxas de frete esperadas, os fluxos de carga entre os portos, bem como os dados sobre portos e canais. Como saídas, a ferramenta devolve várias frotas possíveis com os respetivos indicadores de desempenho em vários de cenários de custo e velocidades operacionais.

O algoritmo da ferramenta é explicado, assim como os indicadores de desempenho da frota e a modelação das variáveis económicas. A ferramenta determina as características técnicas dos navios de contentores necessários para a viagem, utilizando um base de dados de navios existentes, permitindo uma caracterização completa dos navios, que é necessária para o cálculo de indicadores de desempenho. A ferramenta é altamente personalizável, completamente geral e não requer outros programas para ser executada. Esta dissertação também inclui em apêndice um manual do utilizado onde é detalhada a preparação dos dados de entrada e a leitura dos resultados.

Uma parte extremamente importante do desenvolvimento de qualquer ferramenta é sua validação, que é feita com três testes com dados de entrados aleatórios, demonstrando o bom funcionamento da ferramenta. A ferramenta é então aplicada em três casos de estudo com diferentes características: uma rota intra-asiática, uma rota do norte da Europa para a Ásia Oriental, e uma rota entre Portugal continental, a ilha da Madeira, e o arquipélago dos Açores. São elaboradas conclusões e fornecidas recomendações para o desenvolvimento da ferramenta.

**Palavras-chave:** Navios de contentores, Serviços de linha, Dimensionamento de navios, Dimensionamento de frotas, e Desempenho de frotas.



## LIST OF SYMBOLS

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- [...] - when referring to a values, the brackets enclose the units of that value.
- t - unit of mass, in metric tonnes (or simply tons), where a ton is equivalent to one thousand kilograms
- USD - stands for ‘United States Dollar’ which is the standard unit of currency
- m - unit of length, expressed in meters
- $m^3$  - unit of volume expressed in cubic meters
- kn - unit of velocity, expresses in knots, where each knot is equal to 0.5144 meters per second
- NM - unit of distance, in nautical miles, where each nautical mile is 1852 meters
- kW - unit of power, in kilowatts
- kg - unit of mass, in kilograms
- TEU - unit of volume, expressed in the number of twenty feet container would fit in a space



# TABLE OF CONTENTS

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ACKNOWLEDGEMENTS.....	III
ABSTRACT.....	V
RESUMO.....	VII
LIST OF SYMBOLS.....	IX
TABLE OF CONTENTS.....	XI
LIST OF FIGURES.....	XV
LIST OF TABLES.....	XIX
1. INTRODUCTION.....	1
1.1. CONTEXT.....	1
1.2. OBJECTIVES.....	3
1.3. STRUCTURE OF THE DISSERTATION.....	3
2. STATE OF THE ART.....	5
2.1. CONTAINERS AND CONTAINERSHIPS.....	5
2.2. TRADE ROUTES AND ROUND VOYAGES.....	6
2.3. SHIP COSTS.....	10
2.4. FLEET SIZING PROBLEM AND OPTIMIZATION OF ROUND VOYAGES.....	11
3. METHODOLOGY.....	15
3.1. GENERAL.....	15
3.2. THE FLEET SIZING PROCESS.....	17
3.2.1. EXPLANATION WITH EXAMPLES.....	17
3.2.2. EXPLANATION WITH DETAILED ALGORITHM.....	18
3.3. ESTIMATION OF SHIP CHARACTERISTICS.....	23

3.3.1. SERVICE SPEED AND OPERATING SPEEDS.....	24
3.3.2. ROUND VOYAGE TIMES AND VALID OPERATING SPEEDS.....	26
3.3.3. MAXIMUM LENGTH OVERALL, MAXIMUM BREADTH, AND MAXIMUM DRAFT.....	27
3.3.4. RATIO OF 14 TONS CONTAINERS TO THE NOMINAL CAPACITY.....	28
3.3.5. SHIPBUILDING COST.....	29
3.3.6. OTHER SHIP CHARACTERISTICS.....	32
3.4. SHIP COSTS AND REVENUES.....	37
3.4.1. OPERATING COSTS.....	37
3.4.2. CAPITAL COSTS.....	40
3.4.3. VOYAGE COSTS.....	41
3.4.3.1. PORT COSTS.....	41
3.4.3.2. FUEL COSTS.....	42
3.4.3.3. CANAL COSTS.....	47
3.4.4. REVENUES.....	47
3.5. PERFORMANCE INDICATORS.....	48
3.6. ALGORITHM.....	48
4. NUMERICAL RESULTS.....	51
4.1. TESTS OF THE TOOL.....	51
4.2. APPLICATIONS OF THE TOOL.....	59
4.2.1. INTRA-ASIAN CASE STUDY.....	59
4.2.1.1. INPUTS OF THE INTRA-ASIAN CASE STUDY.....	59
4.2.1.2. RESULTS OF THE INTRA-ASIAN CASE STUDY.....	63
4.2.2. NORTHERN EUROPE TO EAST ASIA CASE STUDY.....	66

4.2.2.1. INPUTS OF THE NORTHERN EUROPE TO EAST ASIA CASE STUDY.....	66
4.2.4. RESULTS OF THE NORTHERN EUROPE TO EAST ASIA CASE STUDY.....	72
4.2.3. PORTUGUESE CASE STUDY.....	73
4.2.3.1. INPUTS OF THE PORTUGUESE CASE STUDY.....	73
4.2.3.2. RESULTS OF THE PORTUGUESE CASE STUDY.....	76
5. CONCLUSIONS AND FURTHER WORKS.....	79
REFERENCES .....	81
APPENDIX I – USER MANUAL.....	87
APPENDIX II – 1 <sup>ST</sup> TRIAL'S CIL MATRIX.....	101



## LIST OF FIGURES

---

FIGURE 1 – INTERNATIONAL SEABORNE TRADE.....	1
FIGURE 2 – STAGES OF A SHORT SHIPPING CYCLE .....	2
FIGURE 3 – EXAMPLES OF LINE BUNDLING SERVICES .....	7
FIGURE 4 – EXAMPLE OF A CIRCULAR SERVICE .....	8
FIGURE 5 – EXAMPLES OF A PENDULUM SERVICE .....	8
FIGURE 6 – EXAMPLES OF A HUB AND FEEDER SERVICE .....	9
FIGURE 7 – EXAMPLES OF AN INTERLINING SERVICE .....	9
FIGURE 8 – EXAMPLES OF A RELAY SERVICE. EXTRACTED FROM .....	10
FIGURE 9 – DESIGN SPEED [KN] OVER THE SHIP SIZE [TEU]. .....	24
FIGURE 10 – SERVICE SPEED [KN] OVER SHIP SIZE [TEU]. .....	25
FIGURE 11 – EXTRAPOLATED SERVICE SPEED [KN] CURVE AND LOWEST SERVICE SPEED [KN] CURVE OVER SHIP SIZE [TEU]. .....	25
FIGURE 12 – LENGTH OVERALL [M] OVER SHIP SIZE [TEU] AND THE MAXIMUM LENGTH OVERALL LINE.....	27
FIGURE 13 – MAXIMUM BREADTH [M] OVER SHIP SIZE [TEU] AND THE MAXIMUM BREADTH LINE. ....	28
FIGURE 14 – MAXIMUM DRAFT [M] OVER SHIP SIZE [TEU] AND THE MAXIMUM DRAFT LINE. ....	28
FIGURE 15 – RATIO OF 14 TON CONTAINERS TO SHIP SIZE OVER SHIP SIZE .....	29
FIGURE 16 – CONSTRUCTION COST PER TEU [USD] OVER THE SHIP SIZE [TEU] .....	29
FIGURE 17 – EXTRAPOLATED CONSTRUCTION COST PER TEU [USD] OVER THE SHIP SIZE [TEU].....	30
FIGURE 18 – SHIPBUILDING PRICE [USD] OVER THE YEARS AND QUARTERS, OVER THE SHIP SIZE. ....	30
FIGURE 19 – SHIPBUILDING COST [MILLION USD] OVER SHIP SIZE [TEU]. .....	31
FIGURE 20 – SHIPBUILDING COST PER TEU [MILLION USD] OVER SHIP SIZE [TEU] .....	31
FIGURE 21 – SHIPBUILDING COST PER TEU [USD] OVER SHIP SIZE [TEU]. COMPARISON OF SANTOS WITH MURRAY.....	31
FIGURE 22 – SHIPBUILDING COSTS [USD] OVER THE SHIP SIZE [TEU]. .....	32
FIGURE 23 – NUMBER OF CRANES OVER SHIP SIZE [TEU]. .....	33

FIGURE 24 – LENGTH BETWEEN PERPENDICULARS [M] OVER SHIP SIZE [TEU], DATA AND TREND .....	33
FIGURE 25 – BREADTH [M] OVER SHIP SIZE [TEU], DATA AND TREND .....	33
FIGURE 26 – DEPTH [M] OVER SHIP SIZE [TEU], DATA AND TREND .....	34
FIGURE 27 – MAIN ENGINE POWER [kW] OVER SHIP SIZE [TEU]......	34
FIGURE 28 – GENERATOR POWER [kW] OVER SHIP SIZE [TEU] .....	34
FIGURE 29 – NUMBER OF GENERATORS OVER SHIP SIZE [TEU] .....	35
FIGURE 30 – DISPLACEMENT [T] OVER SHIP SIZE [TEU] .....	35
FIGURE 31 – LIGHTWEIGHT [T] OVER SHIP SIZE [TEU] .....	35
FIGURE 32 – FUEL CAPACITY [ $m^3$ ] OVER SHIP SIZE [TEU] .....	36
FIGURE 33 – BALLAST CAPACITY [ $m^3$ ] OVER SHIP SIZE [TEU] .....	36
FIGURE 34 – GROSS TONNAGE OVER SHIP SIZE [TEU] .....	36
FIGURE 35 – NET TONNAGE OVER SHIP SIZE [TEU] .....	37
FIGURE 36 – DAILY OPERATING COST PER TEU [USD] OVER THE SHIP SIZE [TEU] .....	37
FIGURE 37 – EXTRAPOLATED DAILY OPERATING COSTS PER TEU [USD], OVER SHIP SIZE [TEU] .....	38
FIGURE 38 – DAILY OPERATIONAL COSTS PER TEU [USD] OVER SHIP SIZE [TEU] .....	38
FIGURE 39 – EXTRAPOLATED DAILY OPERATING COSTS PER TEU [USD], OVER SHIP SIZE [TEU] .....	39
FIGURE 40 – DAILY OPERATING COSTS PER TEU [USD] OVER SHIP SIZE [TEU]. COMPARISON OF MURRAY'S AND MERK ET AL.'S DATA, CORRECTED FOR INFLATION.....	39
FIGURE 41 – DAILY OPERATING COSTS [USD] OVER THE SHIP SIZE [TEU], FOR THE THREE COST SCENARIOS ..	40
FIGURE 42 – HF CONSUMPTION AT 23 KNOTS [T PER DAY PER TEU] OVER THE SHIP SIZE [TEU] .....	44
FIGURE 43 – EXTRAPOLATED BASE IFO CONSUMPTION (AT 23 KNOTS) [T/DAY] OVER THE SHIP SIZE [TEU] ...	44
FIGURE 44 – CONCEPTUAL DIAGRAM OF THE TOOL'S ALGORITHM. ....	50
FIGURE 45 – TOOL OUTPUTS OF THE FIRST TRIAL. ....	56
FIGURE 46 – TOOL OUTPUTS OF THE SECOND TRIAL. ....	57
FIGURE 47 – TOOL OUTPUTS OF THE THIRD TRIAL. ....	58
FIGURE 48 – REPRESENTATION OF THE GEOGRAPHIC LOCATION OF THE PORTS AND OF THE VOYAGE IN THE INTRA-ASIAN ROUTE.. .....	60

FIGURE 49 – MAIN RESULTS FOR THE INTRA-ASIAN ROUTE IN THE FORTY FIVE DAYS LONG CIRCULAR VOYAGE, WITH ONE VESSEL WITH 9 300 TEUs OF CAPACITY, AT 17 KNOTS. ....	63
FIGURE 50 – MAIN RESULTS FOR THE INTRA-ASIAN ROUTE IN THE THIRTY DAY LONG CIRCULAR VOYAGE, WITH ONE VESSEL WITH 6 200 TEUs OF CAPACITY, AT 17 KNOTS. ....	64
FIGURE 51 – MAIN RESULTS FOR THE INTRA-ASIAN ROUTE IN THE FIFTEEN DAY LONG CIRCULAR VOYAGE, WITH ONE VESSEL WITH 3100 TEUs OF CAPACITY, AT 16 KNOTS. ....	65
FIGURE 52 – MAIN RESULTS FOR THE INTRA-ASIAN ROUTE IN THE SEVEN DAY LONG CIRCULAR VOYAGE. ....	65
FIGURE 53 – REPRESENTATION OF THE GEOGRAPHIC LOCATION OF THE PORTS AND OF THE VOYAGE IN THE EAST ASIA TO NORTHERN EUROPE ROUTE. ....	67
FIGURE 54 – SUEZ CANAL'S CROSSING FEE [USD] AS A FUNCTION OF THE GROSS TONNAGE. ....	70
FIGURE 55 – MAIN RESULTS FOR THE NORTHERN EUROPE TO EAST ASIA ROUTE. ....	72
FIGURE 56 – REPRESENTATION OF THE GEOGRAPHIC LOCATION OF THE PORTS AND OF THE CIRCULAR WITH PENDULUM VOYAGE IN THE PORTUGUESE CASE STUDY....	74
FIGURE 57 – MAIN RESULTS FOR THE FIFTEEN DAY LONG CIRCULAR WITH PENDULUM VOYAGE IN THE PORTUGUESE ROUTE. ....	78



## LIST OF TABLES

---

TABLE 1 – SIZE OF THE MAIN TRADE ROUTES OF THE WORLD, IN THOUSANDS OF TEUs TRANSPORTED IN 2017 .....	6
TABLE 2 – EXAMPLES OF RV, NCF, AND CIL MATRICES. ALL NOTES IN BLUE ARE NOTES, AND NOT PART OF THE MATRICES.....	21
TABLE 3 – MDO CONSUMPTION OF CRANES.....	46
TABLE 4 – CARGO FLOW MATRICES FOR THE TRIALS.....	52
TABLE 5 – ROUND VOYAGES FOR THE TRIALS.....	52
TABLE 6 – LOAN DATA FOR THE THREE TRIALS.....	52
TABLE 7 – PORT CHARACTERISTICS FOR THE TRIALS.....	53
TABLE 8 – LEG DISTANCES [NAUTICAL MILES] FOR THE TRIALS.....	53
TABLE 9 – FREIGHT RATES FOR THE TRIALS.....	53
TABLE 10 – CANAL DATA FOR THE TRIALS.....	54
TABLE 11 – HANDMADE OUTPUTS OF THE FIRST TRIAL.....	54
TABLE 12 – HANDMADE OUTPUTS OF THE SECOND TRIAL.....	55
TABLE 13 – HANDMADE OUTPUTS OF THE THIRD TRIAL.....	55
TABLE 14 – DATA OF THE PORTS OF THE INTRA-ASIAN ROUTE.....	61
TABLE 15 – DISTANCES BETWEEN PORTS OF THE NORTHERN EUROPE TO EAST ASIA ROUTE, IN NAUTICAL MILES.....	61
TABLE 16 – CARGO FLOW MATRICES FOR THE INTRA-ASIAN ROUTE.....	62
TABLE 17 – FREIGHT RATE MATRICES FOR THE INTRA-ASIAN ROUTE [USD / CONTAINER].....	62
TABLE 18 – ROUND VOYAGES FOR THE INTRA-ASIAN ROUTE.....	62
TABLE 19 – DATA OF THE PORTS OF THE NORTHERN EUROPE TO EAST ASIA ROUTE.....	68
TABLE 20 – DISTANCES BETWEEN PORTS OF THE NORTHERN EUROPE TO EAST ASIA ROUTE.....	68
TABLE 21 – CARGO FLOW MATRICES FOR THE INTRA-ASIAN ROUTE.....	69
TABLE 22 – SUEZ CANAL INPUT VALUES.....	70
TABLE 23 – FREIGHT RATE MATRICES FOR THE NORTHERN EUROPE TO EAST ASIA ROUTE.....	71
TABLE 24 – ROUND VOYAGE FOR THE NORTHERN EUROPE TO EAST ASIA ROUTE.....	72

TABLE 25 – ANNUAL SHIP COSTS [MILLION USD], DEVIATION IN THE MAXIMUM AND MINIMUM COST SCENARIOS, AND COST SPLITS IN THE THREE SCENARIOS IN THE VOYAGE OF THE NORTHERN EUROPE TO EAST ASIA ROUTE .....	73
TABLE 26 – DATA OF THE PORTS OF THE PORTUGUESE ROUTE.....	74
TABLE 27 – DISTANCES BETWEEN THE PORTS OF THE PORTUGUESE ROUTE .....	74
TABLE 28 – CARGO FLOWS FOR THE PORTUGUESE ROUTE.....	75
TABLE 29 – FREIGHT RATES OF THE PORTUGUESE ROUTE.....	75
TABLE 30 – VOYAGES OF THE PORTUGUESE ROUTE. ....	76
TABLE 31 – MAIN RESULTS FOR THE VOYAGES OF THE PORTUGUESE CONDITION.....	76
TABLE 32 – 1 <sup>ST</sup> TEST. EMPTY NCF MATRIX.....	101
TABLE 33 – 1ST TEST. FIRST STEP OF THE NCF MATRIX.....	101
TABLE 34 – 1ST TEST. SECOND STEP OF THE NCF MATRIX.....	101
TABLE 35 – 1ST TEST. NEXT STEPS OF THE NCF MATRIX. ....	101
TABLE 36 – 1ST TEST. FINAL STEP OF THE NCF MATRIX .....	101
TABLE 37 – 1ST TEST. EMPTY CiL MATRIX.....	102
TABLE 38 – 1ST TEST. FIRST STEP OF THE CiL MATRIX.....	102
TABLE 39 – 1ST TEST. SECOND STEP OF THE CiL MATRIX.....	103
TABLE 40 – 1ST TEST. STEPS OF THE CiL MATRIX. ....	103
TABLE 41 – 1ST TEST. 1 <sup>ST</sup> CARGO DISTRIBUTION OF THE CiL MATRIX. ....	104
TABLE 42 – 1ST TEST. 2 <sup>ND</sup> CARGO DISTRIBUTION OF THE CiL MATRIX.....	104
TABLE 43 – 1ST TEST. 2 <sup>ND</sup> CARGO DISTRIBUTION IN THE CiL MATRIX. ....	105
TABLE 44 – 1ST TEST. 3 <sup>RD</sup> CARGO DISTRIBUTION IN THE CiL MATRIX. ....	105
TABLE 45 – 1ST TEST. FINAL STEP OF CARGO DISTRIBUTIONS IN THE CiL MATRIX.....	106
TABLE 46 – 1ST TEST. FINAL CARGO DISTRIBUTIONS IN THE CiL MATRIX .....	106

# 1. INTRODUCTION

## 1.1. CONTEXT

Every year ten thousand millions of tons of goods are transported by sea (Figure 1). Of these, seventeen percent are containerized cargo, representing more than half of the total value of all seaborne trade (Statista, 2010). Both these values are on the rise.

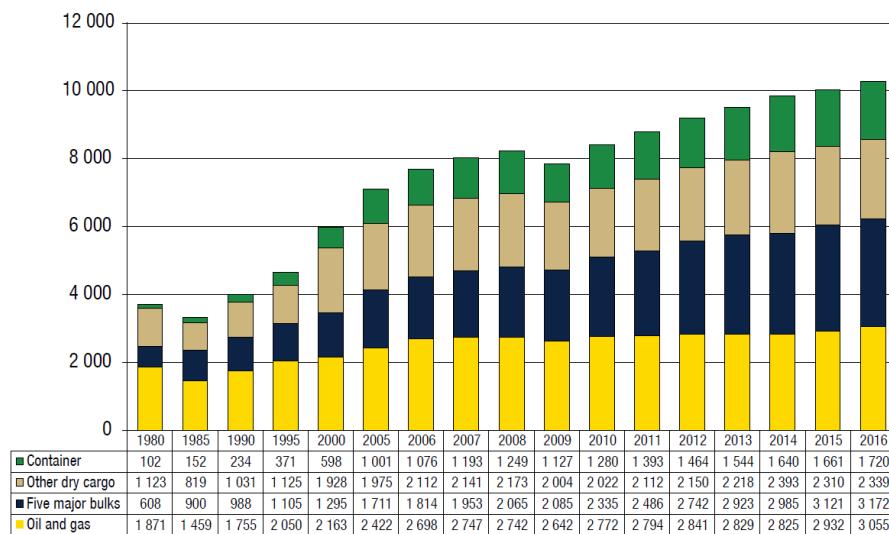


Figure 1 – International seaborne trade (UNCTAD, 2017).

Although containerized cargo was originally a part of the general dry cargo, it has become a type of cargo on its own right. Unlike bulk cargo, in which one ship transports a large parcel of cargo (which ideally fills the whole ship) from one destination to another, containers are very small units of cargo, each with a specific port of origin and a specific ports of destination. Therefore, container ships transport at once goods of different kinds, from different companies, from different origins, and to different destinations. These are mostly consumption goods, thus explaining why this cargo is so valuable. The majority of containers is transported by dedicated containerships and handled by dedicated container terminals.

Container ships are operated by shipping companies, which sell transportation service, forming the supply side of the shipping market. There are no monopolies but there are some very big players like APM-Maersk, with 17.8 percent of market share, and MSC, with 14.4 percent of market share (Alphaliner, 2018). In fact, the ten largest companies hold more than 90% of the total market (MI News Network, 2018) and there has been a tendency to consolidate the industry, on one hand by acquisition of smaller companies, as when Maersk acquired Hamburg-Sud (Maersk Line, 2017), on the other by forming alliances, which are coalitions of shipping companies for mutual support and coordination.

As a market, shipping is heavily characterized by economic cycles, which strongly influence the level of freight rates (i.e. the price of shipping services). There are three types of cycles: the long, the seasonal,

and the short (Stopford, 2013). Long cycles reflect long term changes due to long term changes in technology and in regional economies. These tend to last decades. Seasonal cycles are fluctuations of the freight rate in certain seasons of the year (as happens, for example, in agricultural goods). The short cycles are the most important. They last about five years and can turn the prospects of the market in a single year. These cycles are divided in four phases (Figure 2). In the peak phase the ship operators make money, in the trough they lose it. Thus shipping companies can collectively go for years at a loss. This is all the more interesting because these cycles are driven by the supply of vessels. In the peak companies overbuild ships in order to not lose market share and in the trough they scrap them. Meaning that the anticipation of a peak may cause companies to start building early and thus dampen that peak. Add to these cycles the fact that shipping is sensitive to economic and political events (e.g., the 2008 financial crisis) and the freight rate becomes a fickle value, difficult to predict and with vast consequences on the profitability of companies.

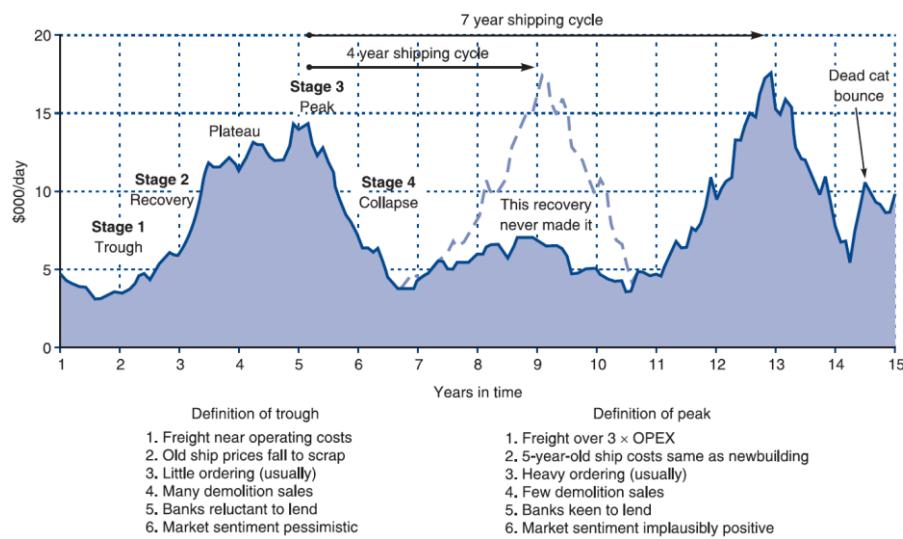


Figure 2 – Stages of a short shipping cycle (Stopford, 2013).

Regardless of these uncertainties, the facts are that containerized cargo is growing, with ships built larger than ever and ports breaking cargo handling records annually, that many companies operate their ships in a free market; and that the freight rates change in unpredictable cycles which determine whether ships make or lose money. One is thus tempted to ask how shipping companies can succeed. As seen in 2016, with the collapse of Hanjin Shipping (IImer, 2017), size and diversity are not sufficient. To strive a company must be competitive.

There are many ways for a company to improve its competitiveness, but none is as important as improving the efficiency of its ships. Efficiency is a multi-parcel equation centred on the ship and its operations. Nowadays most container ships work in liner services, meaning that these ships operate in scheduled and, more or less, regular round voyages. Thus, the appropriate sizing of the fleet and its

vessels, taking in consideration the route, the ports, and the demand for transportation is a key issue for shipping companies. This thesis aims at contributing to solve these problems.

## **1.2. OBJECTIVES**

This thesis focuses on producing a decision making tool which solves the problem of sizing the fleet and the individual ships within the context of a round voyage and that calculates the performance indicators of that fleet. The tool considers the data of the round voyage, of the ports, of the cargo flows, of the loans, of the canals, amongst others, and returns several fleets which can complete the round voyage, accompanied by the respective performance indicators. It also returns the annual ship costs and other outputs which may be relevant and useful to the user.

The tool handles two primary issues: the sizing of a vessel to a round voyage; and the calculation of the performance indicators, the ship costs, and all other outputs for a fleet of vessels. The first is mostly a computational problem, and is handled by a process called cargo distribution algorithm, which simply determines the smallest vessel size which can carry all the cargo in-between every port of the round voyage. This is, in its essence, a problem of programing and relies on logic and a small number of simple mathematical relations. The second issue is much less of programing and much more of modelling, requiring extensive use of formulas and empirical relations as to produce a mathematical relation between the outputs and both the inputs and the size of the vessel. The tool, which solves these two issues, is flexible and allows the user to define a set of ports and then choose any round voyage with these defined ports. The user is then presented with the economic results of the operation of such regular line and may take decisions based upon the results.

The two principal objectives for this dissertation are: to explain the development of the tool and to show the application of the code to real world design problems.

## **1.3. STRUCTURE OF THE DISSERTATION**

This subsection explains the structure of the dissertation by summarizing the content and aims of each chapter and of the respective sections. The first chapter is the present Introduction.

The second chapter is the State of the Art. This chapter reviews works, projects, and academic and scientific research on the relevant topics. The goal here is to see which specific topics are discussed and how each is treated: the base assumptions taken, the methodologies used, and the kind of results obtained. The information of this chapter was used to adjust the goals of the current project to match the perceived need.

The third chapter is the Methodology. This chapter explains in detail the methods used to relate the outputs to the inputs. Due to its size and variety of topics, it is divided in six sections. The first is named General and is dedicated to defining the desired outputs. The second is the Fleet Sizing Process which explains the reasoning by which the tool processes the inputted data of the round voyage and of the

cargo flows in-between each port to determine the required capacity in TEUs of each vessel in the fleet. The third section is the Estimation of Ship Characteristics, which details how the code estimates ship characteristics (such as the service speed, the length overall, or the shipbuilding costs) from a containership database (Santos, 2018) and other published data. The fourth section, Ship Costs and Revenues, and the fifth, Performance Indicators, explain how the tool calculates the performance indicators, the ship costs, and the revenues from the required ship size, in TEUs, the ship characteristics, and the voyage data. The last section is the Algorithm whose purpose is to broadly show the tool's code structure.

The fourth chapter is entitled Numerical Results, which contains the trials and the application of the tool to various case-studies. The first section is the Tests of the Tool which deals with the trials to the code. These are critically important and key aspects of the development of the tool, for they conclusively proves that the tool works. To perform such validation three randomized trials are executed, comparing the numerical outputs with the results of manual calculations of the same outputs. The next section is for case studies where the tool can be applied. The sub sections of this section are Inputs of the Intra-Asian Case Study, Results of the Intra-Asian Case Study, Inputs of the Northern Europe to East Asia Case Study, Results of the Northern Europe to East Asia Case Study, Inputs of the Portuguese Case Study, and Results of the Portuguese Case Study. Some of these subsections are dedicated to presenting the inputs of each case study (e.g., the distances between ports, the cargo between the ports, or the round voyage) and how such data was found, extrapolated, or guessed, while the other subsections show the outputs for each case and the respective discussion.

The fifth and chapter section of the text is the Conclusions and Recommended Works. The goal there is twofold: on the one hand it is to present the major conclusions of this project; and on the other, it is to suggest further works or research which could improve the tool, either by adding new features to the code, improving the existent ones, or modifying the required input data.

## **2. STATE OF THE ART**

---

The purpose of this chapter is twofold. First it aims to give a sense of the state of the collective knowledge on the subject of liner shipping. That is, to explore the kind of models which exist to describe liner shipping and its components. Second it places this thesis' work within the context of other current projects and of modern research, as to see what kind of tool is in demand and what outputs should it yield to be innovative and useful.

To achieve these, this chapter explains the basic elements of liner shipping and reviews a number of academic works on the topic of optimization of liner services. Because this is not a systematic review it is not exhaustive, thus focusing only on the key elements and information necessary to fully contextualize the tool within the state of the art.

### **2.1. CONTAINERS AND CONTAINER SHIPS**

Containers is a term referring to the intermodal container used to transport small parcels of dry goods. Until the advent of the container, all general dry cargo was carried in many different types of packages (e.g., boxes, pallets, and casks) which made cargo handling both difficult and expensive. With the advent of long supply chains it became profitable to use a standard package which could be transported by different modes of transportation (mainly, truck, ship, and rail). So, in the 1950s, the intermodal container was invented, and its rapid and widespread adoption made it an industry standard.

The containers are of many types. The ISO 668 sets the size standards for four types of containers: the twenty feet container, the forty feet container, the forty feet high-cube container, and the forty five feet high cube container (ISO, 2013). Aside from these internationally standard containers, there are other container sizes which are usually specific to a certain region or trade. The vast majority of containers, however, are either a twenty feet container or a forty feet containers. That is the reason why the capacity of a container ship is measured in Twenty feet Equivalent Units (TEU). Note that the TEU is a measure of space and not of mass. In this thesis a twenty feet ISO standard container is designated as a TEU, a forty feet ISO standard container is designated as a FEU, and one FEU is two TEUs. The other container sizes are not considered.

Alongside the size, there are two more important characteristics of a container. The first is its weight. While the contents of a container are varied, they tend to be full, as the shipping cost to the shipper of the goods is paid per containers, which allows one to draw an important distinction between full (also called laden) containers and empty containers. The second distinction is between regular containers and refrigerated containers (called refer containers). These refrigerated containers also come in TEU and FEU sizes with the important caveat that they require power, which is relevant since that power is provided by the vessel.

Containers are transported by container ships (in some small exceptional voyages they may be transported in general cargo ships). These vessels are grouped by classes (FMS, 2014). The smallest containerships are the feeders. With capacities between five hundred TEUs and three thousand TEUs, these ships are usually geared, meaning they have cranes on board, which suites them to visit the smaller ports, which may have very few or no cranes at all. These are the vessels usually employed in feeder routes. The next class of ship is the panamax, which is used to refer to ships designed to pass in the old Panama Canal, before the expansion of the locks. These vessels have capacities between three thousand and five thousand TEUs. The next class are the post panamax, for ships that were too large to cross the old Panama Canal and their capacities range from five thousand and ten thousand TEUs. When the Panama Canal expanded, a new class of ships was created, the new panamax class which could now cross the improved canal, with the vessels ranging from ten to fourteen thousand TEUs. The final class of vessels are the ultra large container vessels (the ULCV) which, as of the present year, goes from fourteen thousand to twenty two thousand TEUs.

## **2.2. TRADE ROUTES AND ROUND VOYAGES**

A trade route is the term referring to the transportation of cargo from some ports in the one region to some ports in another. Since trade is global there are as many trade routes as there are regions, however there are some major routes of trade, through which flow the majority of the goods. The main economic regions of the world for container shipping are Asia, North America, Northern Europe, the Mediterranean, South America, and the Middle East. The size of each route is in Table 1.

Route	West Bound	East Bound	North Bound	South Bound	Total
Asia-North America	7 490	19 482			26 572
Asia-North Europe	9 924	5 139			15 063
Asia-Mediterranean	5 504	2 409			7 913
<hr/>					
Asia-Middle East					
North Europe-North America	3 284	2 120			5 404
Asia-East Coast South America			730	1,344	2 074
Western Europe -East Coast South America			830	850	1 680
North America-East Coast South America			794	474	1 268

*Table 1 – Size of the main trade routes of the world, in thousands of TEUs transported in 2017 (Shipping Council, 2018).*

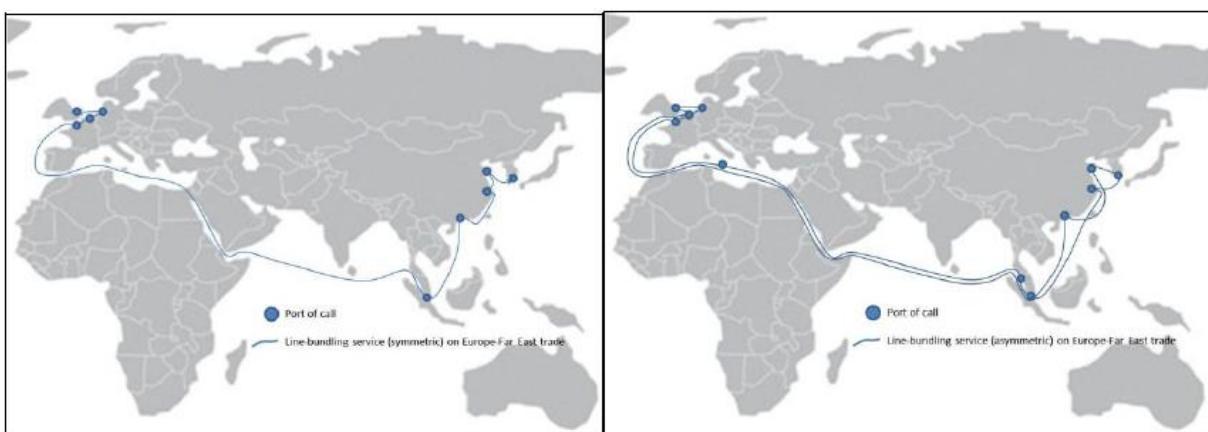
Table 1 does not represent all the container trade in the world, since there are many intra-regional shipments and shipments to other regions, such as Australia / New Zealand and Africa. However, from

it one can see that Asian, and in particular East Asia (China, Japan, South Korea, Taiwan, and other Asian manufacturing hubs), is at the centre of global container trade.

An important point is that each region has many ports. Shipping companies operating in these routes do so by means of lines of service, which are simply voyages where the ships deployed call the ports in that voyage and transport cargo in-between them. These lines usually take the form of round voyages, and each company can have many lines within each trade route. Maersk, for example, had seventeen lines calling on the port of Hong Kong, four of which were regional lines within East Asia (Fremont, 2007).

Although a round voyage can connect ports in any combination the company wishes, they tend to take certain configurations. A round voyage is a repetition of a certain number of port calls in which the vessel returns to the same state after that certain number of port. So a voyage that calls port A, then port B, then port C, then back to port A, and then repeats is a round voyage. It is also a round voyage the one which starts in port A, then calls port B, then port A, then port C, then back to A, and then repeats. In every case, in a round voyage the ships start in one port A under certain conditions, then move to another port B, while calling some ports along the way, and then returns to port A under the same conditions, calling some port along the way.

Ducruet and Notteboom wrote on the developing of liner service networks and make a distinction between service networks with one line and services with many lines (Ducruet & Notteboom, 2012). The first type of individual liner service is the line bundling service which can be symmetrical or asymmetrical (Figure 3). If the service is symmetrical, then the ships call all ports when moving in one direction, that is when going from port A to port B, and all ports again when returning, that is when returning from B to A. If the service is asymmetric, then the ports called in one direction, from port A to port B, are not the same as the ports called when returning, when going from port B to port A.



*Figure 3 – Examples of line bundling services (Ducruet & Notteboom, 2012).*

There are also circular services, where the ships only call each port once per voyage, where after port B the ships call on port A (Figure 4). A particular case of these circular services are the round-of-the world services, which are circular and where the ships circumnavigate the globe in every round voyage.



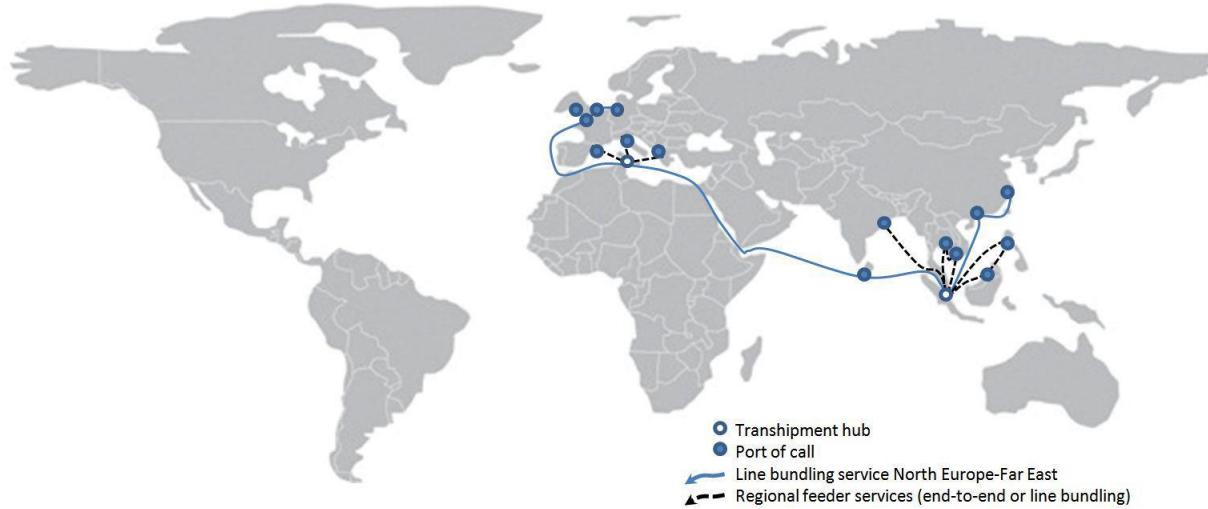
*Figure 4 – Example of a circular service (Ducruet & Notteboom, 2012).*

Finally there are the pendulum services, which are a variant of the line bundling services, where the ships call a port which is not in-between port A and port B (Figure 5).



*Figure 5 – Examples of a pendulum service (Ducruet & Notteboom, 2012).*

However, these are single liner services, and much can be done if many lines are combined to serve the same network of ports. The best example of this coordination are the hub and feeder (or hub and spoke) line services (Figure 6). These are very popular in networks where the ports are dispersed over a region or where there are both large and small ports, which is what happens in most regions. The idea is to increase the profitability by drawing many line services to serve the port network. In the hub and feeder line services, the larger ports, the hub ports, are connected by a line bundling service, either symmetric or asymmetric, along some more isolated ports in between. The smaller ports, the feeder ports, are grouped by geography and each of these groups are connected to a hub port by a dedicated line service. This allows for each individual line service in the network to be served by adequate vessels. The larger ships call on the hub ports, the small ships feed the cargo from the smaller ports to the hub ports, and fewer and smaller vessels are required.



*Figure 6 – Examples of a hub and feeder service (Ducruet & Notteboom, 2012).*

In a different network, where the ports may be divided in many regions, an interlining service may be the best option (Figure 7). In this service regions are connected by line bundling services, each connecting the ports of two regions, with the lines connecting in the interlining hub port.



*Figure 7 – Examples of an interlining service (Ducruet & Notteboom, 2012).*

Alternatively a company can always a relay service, where two line bundling services between the same regions are set up, with the line services connecting in relay ports (Figure 8).



*Figure 8 – Examples of a relay service. Extracted from (Ducruet & Notteboom, 2012).*

In practice, companies combine the systems above in the best way possible. As seen with the case of Maersk (Fremont, 2007), companies and alliances have a large number of line services, all of them connected. Of importance to this thesis, these combinations of line services improve profits by allowing the employment of vessels of different sizes in the same network, which requires the solving of the fleet sizing problem.

### 2.3. SHIP COSTS

A common method for estimating ship costs is to break the costs into categories and then estimate each category individually. Although different categories are used by different authors, in essence all containerships pay the same charges, regardless of what particular designation one gives them. There are three kinds of costs: the ones that are fixed, which the vessel must pay regardless of its level of activity; the ones that depend on the voyage, which are the costs of dislocation, of port calling, and of canal crossing; and the costs that depend on the cargo handled, which depend on the terminal and on the cargo carried.

The fixed costs are the operating costs plus the capital costs. Santos determines the annual operating costs into the further subcategories of crewing costs, stores and consumables costs, maintenance and minor repairs cost, major repairs costs, insurance costs, and administration costs (Santos, 2016). Pocuca uses those same subcategories of the operational cost only with on a daily basis (Pocuca, 2006). These methods are accurate but require knowledge of many operational details, like the crew wages or the dockyard prices, which companies have been reluctant to reveal. For this reason some, like Murray and Merk et al., use empirical data on the total operating costs and discard the subcategories (Murray, 2015) (Merk, et al., 2015).

The capital costs relate to the value of the asset i.e., the ship. It is rare, if it ever happened, to have a ship purchased without financing, particularly in the form of loans. The capital costs are meant to consider these loan costs alongside the initial investment (most ship loans do not cover the entire shipbuilding cost), and the shipbreaking (i.e., scrapping) revenue.

The cargo handling costs relate primarily to the costs of moving, storing, and servicing containers. Santos comments that ships do not always pay all of these costs, usually sharing some of them with the shipper of the container depending on the service the ship is offering (e.g., the shipper may be responsible for delivering the container to the port in advance of the ship's arrival, or the shipping company may handle the land transport to the port).

The voyage costs represent the costs of the voyage. Santos divides them in fuel costs, port calling costs, and canal costs. The fuel costs depend on many factors, chiefly on the operating speed. The port charges and the canal costs depend on the specific pricing scheme used by the canal or port. Note that these port charges are to be paid for each call, irrespective of the cargo handled in said call.

#### **2.4. FLEET SIZING PROBLEM AND OPTIMIZATION OF ROUND VOYAGES**

Given the importance of using a good round voyage and of sizing the fleet to that route, it is not surprising that many studies have been on these topics. This section is dedicated to this research.

One is that of Fagerholt, which aims to optimize a feeder route connecting Norway's smaller ports to its largest port: Oslo. (Fagerholt, 2004). Here, the author sets weekly cargo flows from each feeder port in a circular round voyage and optimizes the round voyage by approaching the problem as a multi trip vehicle routing problem. The optimization aimed at minimizing the objective function (the sum of the operating costs of the fleet) with a constraint on the duration of the round voyage, ensuring that all ports are called in a week, and using a homogeneous fleet. This study was entirely on the route optimization process and did not touch on the fleet sizing problem.

Hsu & Hsieh proposed a model which determines the optimal round voyage, the ship size, and the sailing frequency by minimizing both the shipping costs and the inventory costs (Hsu & Hsieh, 2007). This model was then applied to a set of ports in the Pacific to East Asia trade route and the aim was to optimize the round voyage by solving a two objective optimization problem. For the ship costs, the authors considered the capital costs, the operating costs, the fuel costs at sea and the fuel costs in the ports. Curiously, the ship size was discretized into six levels, each with fixed capacity, costs, and service speed, ranging from one thousand one hundred and sixty TEUs of capacity to five thousands six hundred and fifty TEUs.

Martins et al used genetic algorithms to optimize small fleet voyages by solving the vehicle routing problem and the cargo stowage problem (Martins, et al., 2010). The authors use a port network of five ports, all under a thousand miles away from all other ports, which is to be served by a single line service.

The cargo flows and port tariffs are known. Interestingly they characterize each container by the origin port, the destination port, the weight, and the deadline for delivery. This study presents a simple cost analysis of the vessels and an analysis of the problem of the stowage of containers on board of the vessel, considering the stability requirements of the vessel. This work considers two different discrete ship sizes and is focused on the problem of optimizing the round voyage.

Polat et al. analysed the setting of feeder networks in the Baltic Sea and East Mediterranean Sea (Polat, et al., 2014). The main goal was to propose ports which could be used as hubs of a feeder network in those geographical area. To this effect, they utilized a numerical optimization method for the port network, with the costs as the objective function, and under the restrictions of the duration of the round voyage and of the cargo flows. These authors also discretized the ship size into three types of vessels, one with twelve hundred TEUs, other with twenty six hundred TEUs, and another with four thousand and three hundred TEUs, and each type of vessel has fixed characteristics. Curiously they model the off hire as a function of the number of calls. From the results section it is clear that this feeder route is a multi-circular lines service with around eight lines of service. This study is focused on the route optimization problem, and not so much on the fleet sizing problem. These same authors later repeated the study with similar conclusions (Polat, et al., 2012).

Plum et al used two novel methods to study the formulation of round voyages (Plum, et al., 2014). The authors aimed at optimizing a single line bundling service between ports in eastern coast of the United States and European ports in the western Mediterranean Sea. They approached the shipping costs as an elementary shortest path problem with resource constraints. On the whole this study is exclusively on the optimization of round voyages.

Agarwal & Ergun applies three different algorithms (the greed heuristic, the column generation, and the benders decomposition) to optimize a single line bundling service route between Japan and Northern Europe (Agarwal & Ergun, 2008). While the study considers different numbers of port and of ships, it is focused on the performance of the three algorithms.

Koza designed a model which aimed at optimizing round voyages, the number of ports in it, and port call scheduling (Koza, 2017). The model optimized by use of a column generation matheuristic, using the total annual costs as an objective function. These costs included the inventory costs, the canal costs, the port costs, and the fuel costs. The presented results include both the number of ships and their capacity for services in four different routes.

Ye, et al. use two optimization methods to model to solve the problem of managing the container flow and of deploying ships on a tactical level on a network of ports (Ye, et al., 2007). It consider the costs of cargo handling, the operating costs, and the revenues to estimate the overall profit, which is the objective function. While it presumes that only dry TEU container exist it does make the distinction between laden an empty containers.

Within the context of the research, one can see that there are many works on the optimization of round voyages and that fewer works deal with the fleet sizing problem. And those who do, do so by fixing the vessel capacity. While perfectly adequate for specific routes, this discretization prevents using these models for other routes. It is in this context that this thesis is useful, for the proposed tool is generic, and sizes the fleet for any given round voyage, in any given route, with any given ports. The tool does not boast any process to generate round voyages (which are currently a user input), focusing on sizing the fleet to a specific round voyage and calculating a series of potential objective values.



## **3. METHODOLOGY**

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### **3.1. GENERAL**

This chapter discusses the algorithms implemented in the tool. This section discusses what outputs are required of the tool, while the following sections explain the steps and models used to calculate each one of them.

The main question when opening a new liner route is to know what fleet should the company deploy. This problem is complex due to the infinite number of combinations of ship size and of number of ships which can carry all the cargo. Thus, the first assumption is that the fleets are homogeneous, i.e., in a fleet all vessels are equal. Noting that employing two one thousand TEUs vessels and employing one vessel with nine hundred TEUs and one with eleven hundred TEUs is roughly the same, the tool can safely assume fleet homogeneity, leaving the user the responsibility of interpreting the outputs in the light of any existing vessels he may wish to employ.

On the matter of the number of vessels, economies of scale work on the premise that larger ships tend to be more efficient (Cullinane and Khanna, 2000), which seems to suggest that the optimal solution is the one with the largest vessels. This suggestion is tested in the Sensitivity Analysis section, though even if it turns out true, it is likely that an interested company already owns vessels and wishes to employ them. As an example, it is preferable to employ the two vessels, with one thousand TEUs each, which are owned and purchase a third one thousand TEUs vessel, than it is acquiring two newbuilt fifteen hundred TEUs vessels. Since the tool is generic and does presume any of the company's assets, it addresses this issue by presenting various fleets, each with its own number of vessels, thus presenting more options to the user.

The tool's code is written in FORTAN95 and compiled by CheckMate, using Silverfrost's Plato application and calculates, for each fleet and for each round voyage, seven types of information, as follows. First, the tool shows the size of the vessels in TEUs and the number of vessels in each fleet. The tool considers homogeneous fleets with increasing number of ships, up to an inputted limit, and for each number of ships calculates the required size of each of the vessels.

Second, the tool shows the performance indicators of that fleet in three different cost scenarios for the possible speeds. These indicators are values which measure economic performance of a fleet and can be used to compare two fleets. The principal performance indicator is the net profit (i.e., how much money does the fleet make in a year) which is always followed by the net profit margin (i.e. how much money the fleet makes as a fraction of the gross revenues). Relating the costs to the characteristics of the voyage, the next two indicators are the Cost per TEU, which measures the shipping cost of every handled TEU, and the Cost per Mile, which measures the relative voyage costs of each vessel. These four indicators are standard and, given the scope of the tool, are sufficient to measure the performance of the fleet.

While the previous indicators include the costs of capital, the next four indicators are the net profit, the net profit margin, the cost per TEU, and the cost per mile if the vessels are not purchased. These indicators reflect the performance without the capital costs.

The final indicators are two important operational criteria: the Buffer Time [hours] and the Buffer Ratio. Notteboom and Vernimmen wrote on the irregularities of liner schedules and how they may lead ships to spontaneously skipping ports of a round voyage; (Notteboom & Vernimmen, 2009), which is both a loss of revenue and also an loss of overall competitiveness against other more reliable liner services. Since most delays are not within the ship's control, it is important to have extra time in the round voyage. That time is called the Buffer Time, and its ratio to the total time of the round voyage is the Buffer Ratio. Unlike the other performance indicators, which one aims either to maximize or minimize, what counts as reasonable buffers is subjective.

Third, the tool shows the ship costs for the three different cost scenarios and shows the revenues. The categories of costs for each vessel are: the operational costs, the capital costs, the port costs, the canal costs, and the fuel costs. These are presented as annual and for each vessel and, since some performance indicators depend on these expenses, they are useful to understand which parcels of the cost are the more relevant. Alongside these costs are also the total costs and the voyage costs all of which are annual and for each vessel.

Fourth, the tool shows ship characteristics which are estimated from an extensive database of container vessels (Santos, 2018). These characteristics are relevant both to the estimation of the costs and to eventual ship designing efforts.

Fifth, the tool shows the time of the round voyage and the percentages of time which the vessel spends sailing, in port, handling cargo, and crossing canals. Sixth, the tool displays possible conflicts between the vessel's size and size restrictions of the ports or the canals.

And seventh, the cargo carried by each vessel, in each leg of the round voyage, discriminated by type of cargo (i.e., full TEUs, empty TEUs, full FEUS, empty FEUs, full TEU reefers, empty TEU reefers, full FEU reefers, and empty FEU reefers), by origin, and by destination. This information is useful to design operational schedules.

The costs are estimated for three cost scenarios: one where costs are at their maximum, one where costs are in the average, the one where costs are at their minimum. Many of these costs rely on values of the ship, which in turn are estimated with empirical relations. However, the real values can significantly deviate from the average value, because no two vessels are equal and even if they share the capacity, they have different costs. Thus, knowing the expected value of a characteristic is insufficient since the real value of that characteristic can be significantly different, which in turn affects the costs. By using

cost scenarios, the tool presents the average value of each cost alongside the maximum and minimum values, showing the range of values that each costs and each performance indicators can take.

Concerning the different sailing speeds for which the performance indicators and ship costs are calculated, note that the fuel costs are the critical cost of a ship, due to their significance (they can be a third of all costs, Santos, 2016) and to the vessels ability to change them. A ship can radically improve its fuel expenditure by reducing its speed. The same fleet sailing at twenty two knots can lose money, while at eighteen knots turn a profit. Given how the operating speed is a choice of the ship operator, it is important that the indicators for the fleet performance and the ship costs are presented for the different operating speeds. In the tool is implemented a process which checks if a speed allows for the fleet to serve the round voyage in the defined time of round voyage and rejects any speed which does not.

To summarize: for each voyage the tool considers fleets with increasing number of vessels, and for each number of vessels considers different sailing speeds. For each consideration it estimates the maximum, minimum and expected values of the performance indicators of the fleet, and of the vessel costs. Besides, it estimates the ship characteristics, the times in the round voyage, and the cargo carried in each leg, as well as checking if these vessels may conflict with size restrictions in ports and canals.

### **3.2. FLEET SIZING PROCESS**

This section explains the computational process by which the tool finds the required ship size (*RSSize*). That process is coded within the ‘**Fleet\_Designing**’ subroutine, which, amongst other tasks, uses the input data to distribute the cargo to be transported. Only with the distributed cargo can one find the required ship size.

This part of the code (called the cargo distribution process) is the most complex procedure in the whole tool. Given its centrality, it is important to explain in the dissertation the many steps, variables, and cycles involved. This explanation, however, is complex and unintuitive and so it is convenient to also present the algorithm through examples. Thus, the cargo distribution process is explained in two manners, the first using examples and the second with the detailed algorithm.

#### **3.2.1. EXPLANATION WITH EXAMPLES**

To explain the fleet sizing process let us take a scenario where we wish to make round voyages amongst four ports: port 1, port 2, port 3, and port 4. Let us assume, for simplicity, that in this round voyage containers are only loaded in port 1 and then unloaded in the all others: 200 TEUS from port 1 to port 2, 300 TEU from 1 to 3, and 400 TEUS from 1 to 4 (these values are for a round voyage).

In the case where a ship calls a very large number of ports in a succession of ports, a round voyage is a set of  $n$  ports where, for an arbitrary integer  $m$ , the  $m^{\text{th}}$  port called after any call on the succession of ports is the same port as  $(m+n)^{\text{th}}$  port called after that same call on the succession of ports. This means

that each port may be called more than once, that the “starting” port call of the round voyage can be any port call, and that round voyages are sets of port calls which the ship repeats in a cycle.

The simplest round voyage we can produce is in the vector [1 2 3 4], which simply tells the tool that the round voyage starts at port 1, then the ships go to 2, then 3, then 4, and then back to 1, where a new round voyage begins. In this simple round voyage there is no cargo distribution; all cargo must be carried, and thus the vessel loads all 900 TEUs at the first call, then unloads 200 TEUs in the second call, then 300 in the third, and 400 in the fourth. Writing the carried cargo in each leg of the voyage in a vector results in [900 700 400 0]; meaning the vessel carries on board 900 TEUs between the first and second calls, 700 between the second and the third, 400 between the third and the fourth, and 0 TEUs between the fourth and fifth calls (this leg is the return to the start, from port 4 to port 1). Looking at the vector of the cargo in the legs, it is clear that we would need a vessel with 900 TEUs of capacity. Note: in reality the code would add to this 900 TEUs value a margin for stability (from a variable called *R14tSS*, which is discussed in the next subsection) and a margin for clearance of 20%. To keep the explanation simple these margins are ignored.

Let us now consider a different example: a round voyage vector of [1 2 3 1 4]. Here, the vessel loads the cargo for ports 2 and 3 in the first call and the cargo for port 4 in the fourth call, resulting in this cargo in legs vector: [500 300 0 400 0]. So, in the first call of the round voyage (in port 1) the vessel loads 200 TEUs for port 2 and 300 TEUs for port 3. In the second call (at port 2) it unloads the 200 TEUs for that port, and in the third call it unloads the 300 TEUs remaining on board. In the next leg (from 3 to 1) the vessel is empty, and in the next call (the fourth call, which is in port 1) it loads the 400 TEUs for port 4. Thus the required vessel capacity is 500 TEUs, plus margins. If the round voyage was [4 1 2 3 1], which is the same round voyage just starting in a different port, the cargo in legs would be [0 500 300 0 400].

Now, let us consider a more complex round voyage: [1 2 3 1 2 4]. In this voyage the cargo for port 2 must be distributed some is loaded in the first call of the voyage and the rest in the third call of the voyage. Let us distribute this cargo as the tool would. Here is the empty vector of the cargo in legs: [0 0 0 0 0 0]. Let us add the cargo from port 1 to port 4, which is to be loaded in the fourth call of the voyage: [0 0 0 400 400 0]. Let us now add the cargo for port 3: [300 300 0 400 400 0]. Now we must add the cargo for port 2, some of which is loaded in the first call and some in the fourth. The best way to minimize the maximum required capacity of the vessel is to distribute this cargo as to minimize the maximum cargo carried in the legs. So, if we load 150 TEUs for port 2 at the first call and load 50 TEUs in the fourth, the resulting cargo in legs vector is: [450 300 0 450 400 0]. In this way the vessels need only 450 TEUs of capacity, plus margins.

This is, in essence, the fleet sizing process. The cargo distribution process is the implementation in code of the reasoning of the examples above, only the tool accepts up to one hundred ports where every port

may carry any number of TEUs for any other port and may be called any number of times in the round voyage. The tool considers eight different types of containers: full TEUs, empty TEUs, full FEUs, empty FEUs, full reefer TEUs, empty reefer TEUs, full reefer FEUs, and empty reefer FEUs.

For a detailed example of this process with all the vectors and matrices the tool uses for the cargo distribution, please consult the example in Appendix I.

### **3.2.2. EXPLANATION WITH DETAILED ALGORITHM**

The distribution of cargo is the most complex part of the code and consists of iterative productions of the **TCiL** and the **CF** matrices, which can be defined by the following statements:

1. **TCiL(i)** (total containers in leg) is the total number of containers carried by the ship between the  $i^{\text{th}}$  call of the round voyage and the  $(i+1)^{\text{th}}$  call, in TEUs. The maximum value of this vector, plus some margins, is the required capacity of the vessel;
2. A **CF(i,j)** is the number of containers for port  $i$  to be loaded at call  $j$ . This matrix is calculated for each **XXXy** type of containers (see below) and is then stored back in the **XXXy** matrix (thus changing the meaning of the **XXXy** matrices. This is to save space and speed the computation).

Each iteration handles a specific kind of cargo depending the cargo flow matrix which is considering. Originally, this **XXXy** matrix can be defined by the following statements:

1. **XXXy(i,j)** is the yearly number of containers type **XXXy** from port  $j$  to port  $i$ ;
2. **XXX** refers to the type of container and is TEU for twenty feet unit containers, FEU for forty feet unit container, RET for twenty feet unit reefer containers, and REF for forty feet unit containers;
3.  $y$  refers to the state of the container and is either ‘**e**’ for empty containers or ‘**f**’ for fully loaded containers.

Note: For the purposes of this subsection, the property ‘type of a container’ is the **XXXy** of that container and the property ‘kind of a container’ is three values jointly: the type of the container, its port of origin, and its port of destination. As mentioned, the meaning of the **XXXy** matrices changes in the end of this part of the subroutine.

The **XXXy** matrix is used to generate the matrix **AA** (where, **AA(i,j)** is the number of containers of kind **XXXy** to be transported from port  $j$  to port  $i$  by a single ship in a round voyage). It also turns each FEU container into two TEU containers.

The next step is to produce the normalized cargo flows matrix, **NCF** (where the entries of the matrix **NCF(i,j)** are 1 if cargo to port  $i$  is loaded at  $j^{\text{th}}$  call of the round voyage, and 0 otherwise), which states

the kinds of containers that are loaded in each call, according to their destination using the following steps:

1. Runs a for / do loop where **a** goes from 1 to **NCalls**;
  - a. Sets **np1** as the **a<sup>th</sup>** call in the round voyage (thus **np1** is the indicator of the port of origin);
  - b. Sets **x** to 0; checks every other call looking for the next time that same port is called (this is through a **b = 1** to **NCalls** loop); if it finds such a call, it sets **x** as the number of that call;
  - c. If it doesn't find another call on port **np1** (meaning that port is only called once during the round voyage), **x** will remain 0 and the code sets all entries (except for all container types destined to a port that isn't on the round voyage) on the **NCF**'s **a<sup>th</sup>** column as 1, meaning that those kinds of cargoes are to be loaded in that call.
  - d. If it does find an **x**, then it must now consider the types of cargo to be loaded (the '**b = a** to **x**' loop). These correspond to the ports called between the **a<sup>th</sup>** and the **x<sup>th</sup>** calls (in the code these are designated, iteratively, as **np2**). The code then sets in the **NCF** that all cargoes from the **a<sup>th</sup>** port to an **np2** port are to be loaded at the **a<sup>th</sup>** call.
  - e. Continues the loop: **a = a + 1**, until **a = NCalls**

The **NCF** tells the code which containers are loaded in each call, but not how many. The goal now is to use the **NCF**, the **AA**, and an auxiliary matrix Cargo in Legs (**CiL**) to determine the **CF** and **TCiL** matrices.

The **CiL** matrix can be defined by the following statements:

1. If **i <= NPorts<sup>2</sup>** and **j <= NCalls**, then **CiL(i,j)** is the cargo carried between calls **j** and **j+1**, from port 'lowest integer higher or equal to (**i / NPorts**)' to port (**i - a \* NPorts**), for the highest integer **a** such as (**i - (a+1) \* NPorts**) < 0;
2. If **i = NPorts<sup>2</sup> + 1**; **CiL(i,j)** represents the total number of containers carried between calls **j** and **j+1**;
3. If **j = NCalls + 1**, **CiL(i,j)** is the number of times the type of cargo of the **i<sup>th</sup>** row is loaded in the round voyage.

Note: The reason why the **CiL** matrix may seem confusing is that FORTRAN 95 does not handle 3D matrices, and for each call the code must account for kinds of containers which are discriminated by both their origin and their destination. Since each entry of the **CiL** has three dimensions (leg of the round voyage, the origin of that kind of containers, and the destination of that kind of containers) which have to be compressed in a 2D matrix, the solution is to compile the destination and the origin in a single value: **i \* NPorts + j**, where **i** is the origin port and **j** the destination (see Table 2). For instance, the first

row of **CiL** concerns cargo from port 1 to port 1, the second row concerns cargo from port 1 to port 2, and the row number **NPorts** concerns the cargo from port 2 to port 1, and so on.

In the **CiL** each row, except the last one, refers to a type of cargo and, using the **RV** vector and the **NCF** matrix, these rows' entries can be filled with an integer to match the legs on which that cargo type is transported on board the vessel. From the **NCF** matrix it is known how many times any type of cargo is loaded on the vessel and that number will be stored on the last column of **CiL** (i.e., **CiL(:, NCalls + 1)**).

Note that each time a cargo is loaded, it is carried on board in a number of consecutive legs, here, collectively designated as a group of legs. Some groups of legs may consist of only one leg (e.g., if cargo is unloaded on the call after the one on which was loaded) and a cargo type which is loaded '**n**' times will have '**n**' groups of legs. To simplify algorithmic computations, the entries of the row of any cargo type (with '**n**' groups of legs) will display 0 if that cargo type is not carried in that leg, '**m**' if that leg belongs to the **m<sup>th</sup>** group of legs, and the value of '**n**' if it is in the column **NCalls + 1** (see the example in Table 2).

<b>RV =</b>	[ 2	1	3	1	2	4	1	3	4 ]
<b>NCF=</b>									
From									
To port 1	[ 1	0	1	0	1	1	0	1	1 ]
To port 2	0	0	1	1	0	0	1	1	1 ]
To port 3	1	1	0	0	1	1	1	0	1 ]
To port 4	0	0	1	1	1	0	1	1	0 ]
<b>CiL =</b>									
From									
Port 1	[ 0	0	0	0	0	0	0	0	0 ]
	0	0	0	1	0	0	2	2	2 ]
	0	1	0	0	0	0	2	0	2 ]
	0	0	0	1	1	0	2	0	2 ]
From	1	0	0	0	2	2	0	0	2 ]
Port 2	0	0	0	0	0	0	0	0	0 ]
	1	1	0	0	2	2	0	0	2 ]
	0	0	0	0	1	0	0	0	1 ]
From	2	0	1	0	0	0	0	2	2 ]
Port 3	0	0	1	1	0	0	0	2	2 ]
	0	0	0	0	0	0	0	0	0 ]
	0	0	1	1	1	0	0	2	2 ]
From	2	0	0	0	0	1	0	0	2 ]
Port 4	0	0	0	0	0	0	0	1	1 ]
	2	2	0	0	0	1	1	0	2 ]
	0	0	0	0	0	0	0	0	0 ]
	500	300	300	400	400	400	500	500	600 ]
									Total cargo carried (in previous iterations)

Table 2 – Examples of **RV**, **NCF**, and **CiL** matrices. All notes in blue are notes, and not part of the matrices.

The next step of the algorithm is to divide the number of containers of each type by its groups of legs in such a way that satisfies two conditions: that the sum of the cargo in all groups of legs includes all the cargo to be carried on the round voyage; and that the total cargo in each leg (i.e.,  $\text{CiL}(\text{NPorts}^2 + 1, :)$ ) be as balanced as possible. To achieve this, the code runs the following steps for all cargo types (i.e., rows of the **CiL** matrix). Note: there are three auxiliary vectors in this operation: the **MCL**, the **MCL2**, and the **AMC**. The **MCL(i)** is the maximum amount of cargo in the  $i^{\text{th}}$  group of legs. As for the **MCL2**, as it is explained the **CiL** matrix is the first filled with identifiers of the groups of legs, as see in Table 2, and then with the cargoes. To explain the aims of the auxiliary vectors, consider an entry of the **CiL** matrix belonging to a group of legs and that has a ‘2’. If the code wants to add 100 TEU to this entry, the entry would become 102 TEU, which are 2 TEU more than what the ship would actually carry. The task of the vector **MCL2** is to remember that there was a ‘2’ in that entry before cargo was added, and to subtract 2 from the entry after the cargo is added, so that in the end the matrix displays 100 TEU and not 102 TEU. For the **AMC**, consider now a different entry with a ‘3’ in it, where cargo is not added. If no cargo is added that entry must display a ‘0’ after the cargo is distributed. The task of the **AMC** is to remember if cargo was added to this entry (**AMC(:)** will be 1 if so and 0 if no cargo was added) and, after the cargo is distributed, sets to ‘0’ all the entries where cargo isn’t added.

1. Check  $\text{CiL}(:, \text{NCalls})$  for the type of cargo with the smallest number of groups of legs;
  - a. Check  $\text{CiL}(y, \text{NCalls})$  for the number of groups of legs;
  - b. If there are no groups of legs (for example cargo from port n to port n)
    - i. Do nothing
  - c. If there is only one group of legs:
    - i. look for the first leg of the group; check the origin port; place all corresponding containers in the **AA** matrix ;
    - ii. On all legs of the group add the containers in the **AA** matrix to the maximum cargo in each leg (i.e. in the  $\text{CiL}(\text{NPorts}^2 + 1, :)$ );
    - iii. Set **AMC(i) = 1**, where i are the legs of the group of legs.
  - d. If there are more than one group of legs:
    - i. For each group of legs, find the leg where the most containers are carried (i.e. in the  $\text{CiL}(\text{NPorts}^2 + 1, :)$ ); store that value in the **MCL** matrix;
    - ii. Check how many containers of that type are carried in a round voyage (in the **AA** matrix); call it **AA(k,w)**;
    - iii. Sets **MCL2(:)= CiL (:,1: NCalls)**;
    - iv. Check what is the group of leg with the smallest volume of cargo (in the **MCL** matrix); call that value **SVC**;
    - v. Check what is the group of leg with the second smallest volume of cargo (in the **MCL** matrix); call that value **SSVC**;

- vi. Since the goal is to keep the number of containers throughout the legs as uniform as possible, the code now moves cargo from  $\mathbf{AA}(k,w)$  to  $\mathbf{SVC}$  until  $\mathbf{SVC} = \mathbf{SSVC}$  or  $\mathbf{AA}(w,k) = 0$ ;
- vii. Sets the **AMC** of that entry to 1

Note: **SVC** = **SSVC** means all groups of legs have the same maximum cargo carried, and in these cases the code evenly distributes the containers in  $\mathbf{AA}(k,w)$  through the groups of legs

viii. Repeat ii until  $\mathbf{AA}(k,w) = 0$  (i.e. all containers have been allocated).

2. Set  $\mathbf{CiL}(y, \mathbf{NCalls}+1) = 1001$  (to avoid step one from picking up this cargo type again);
3. Repeat 1 until all entries in  $\mathbf{CiL}(:, \mathbf{NCalls} + 1)$  are either 0 or 1001

After the cycle repeats for all **NPorts**<sup>2</sup> types of cargo (i.e all cargo destinations combined with all cargo origins); the code executes three more steps:

1. Produces the **NCF** matrix from the **CiL** matrix:
  - a. Do a loop ' $i = 1 : \mathbf{NCalls}$ ' ( $i$  is the call of origin, recall that  $\mathbf{CF}(i,j)$  is cargo from the  $j^{\text{th}}$  call to the  $i^{\text{th}}$  port);
  - b. Do a  $j$  loop ' $j = 1, \mathbf{NCalls}$ ';
  - c. Calculate the **PTo** (port of destination) of that  $j^{\text{th}}$  line of the **CiL**
  - d.  $\mathbf{CF}(PTo,i) = \mathbf{CiL}(j,i)$
2. Sates the **XXXy** matrices to the **CF** matrices;
3. Save the distributed containers in each leg (from  $\mathbf{CiL}(\mathbf{NPorts}^2 + 1, :)$ ) in the appropriate row of the **TChL** matrix (recall that each row of the **TChL** correspond to a **XXXy** type of containers, and each column to a round voyage leg) and in the **TCiL** vector, so the current distribution is considered in the following iteration.

After the code runs for all types of containers (i.e., TEU and FEU, normal and reefer, full and empty) the **TCiL** vector contains in its entries the amount of TEUs carried in each leg of the round voyage. Thus, finding the required ship size (i.e., variable **RSSize**) is a two-step process. First, the code must check if the ratio of full containers to empty containers is below what the user has specified (the variable **R14tSS** whose value is discussed in the next subsection). Then the code adds a twenty percent margin to capacity and rounds it to the nearest hundred, thus resulting in the **RSSize**.

### 3.3. ESTIMATION OF SHIP CHARACTERISTICS

This section explains the models used by the tool to estimate some ship characteristics, some of which are outputs while others are used later to estimate the ship costs. The considered characteristics are: the valid operating speeds [kn], the maximum length overall [m], the maximum breadth [m], the maximum draft [m], the 14 ton Ratio, the shipbuilding cost [USD], the average length between perpendiculars [m], the average breadth [m], the average depth [m], the main engine power [KW], the generators' powers

[kW], the displacement [t], the lightship weight [t], the fuel capacity [ $\text{m}^3$ ], the ballast capacity [ $\text{m}^3$ ], the net tonnage, and the gross tonnage.

These characteristics are estimated using databases, in particular that of Santos which boasts an extensive list of characteristics, including all of the above, for four hundred and eighty two vessels (Santos, 2018).

### 3.3.1. SERVICE SPEED AND OPERATING SPEEDS

As mentioned in the previous section, the outputs are calculated for many speeds. The goal of this subsection is to find the speeds at which a vessel can sail. The tool only considers natural numbers for the speeds.

An important distinction is between the service speed (also called the design speed) and the operating speed. The service speed is the speed for which the main engine works at maximum capacity, and is taken as the maximum speed the vessel can sail at. The operating speed is the speed at which the vessel actually sails. Thus, a ship has one service speed and many operating speeds (e.g., a vessel designed to sail at twenty two knots can have an operating speed of sixteen, seventeen, twenty, or even twenty two knots). The tool calculates the outputs to various operating speeds which are between the service speed (which is the highest operating speed) and the lowest operating speed.

Murray (Figure 9) presents the service speed of a vessel [kn] against the ship size [TEU] (Murray, 2015). However, this information is insufficient, since it is only for the service speed and it does not express how low the operating speed can be, because it does not contain any data points for ships with capacities below five thousand TEUs.

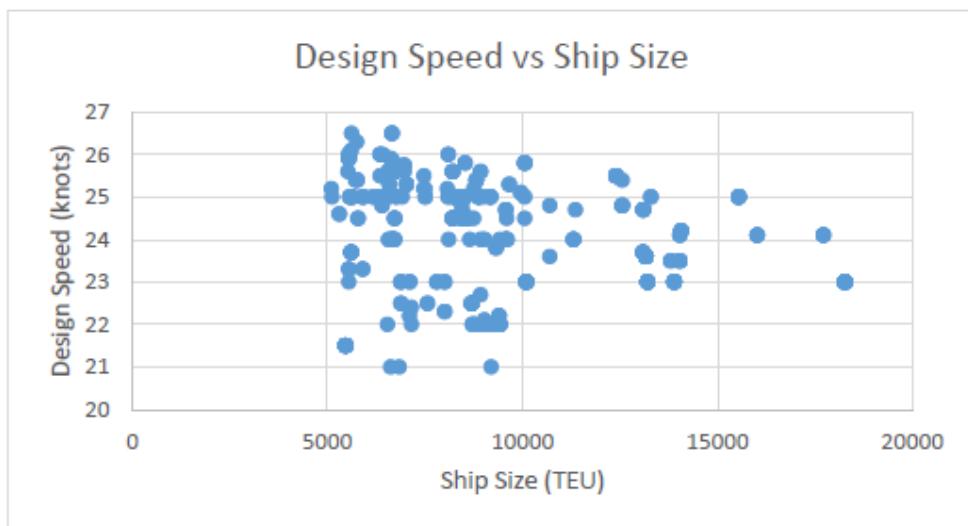
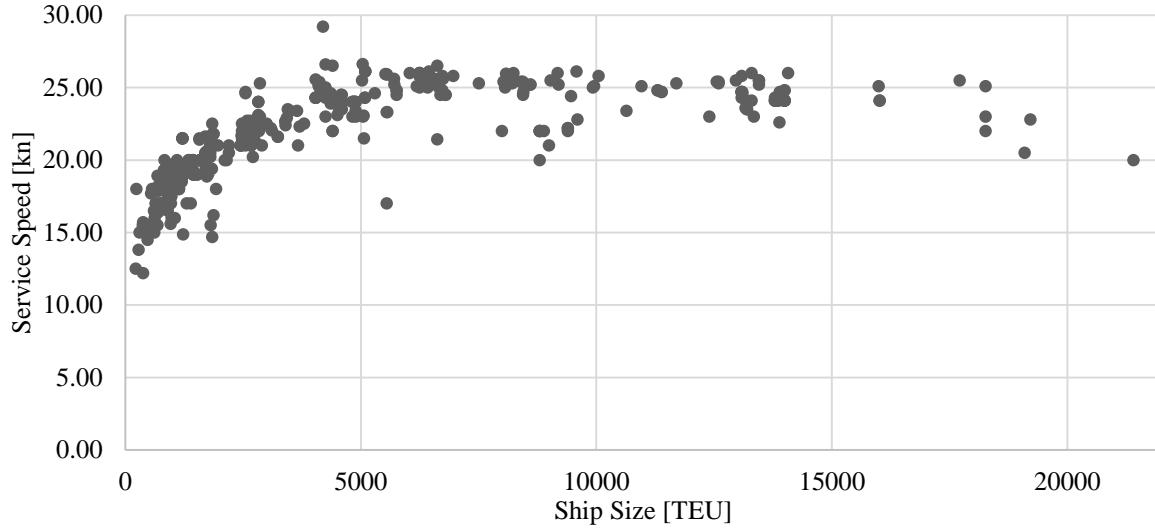


Figure 9 – Design Speed [kn] over the Ship Size [TEU]. From Murray (2015).

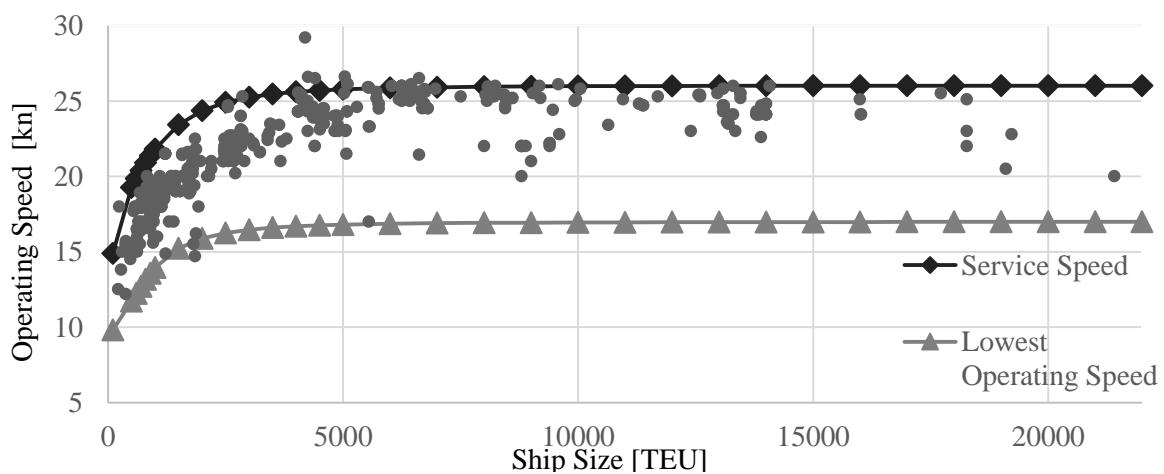
Santos, from an extensive database of ship characteristics (Santos, 2018), represents the service speed of vessels for the full range of capacities (Figure 10). The figure shows the values of the service speed

over the ship size. This data is insufficient for it gives the design speed but not the lowest operating speeds of those vessels. To find those lowest operating speed, the model uses Dagkinis and Nikitakos' data, which shows that all ship sized between four thousand and ten thousand TEUs can sail between seventeen and twenty five and seventeen knots (Dagkinis & Nikitakos, 2015).



*Figure 10 – Service Speed [kn] over Ship Size [TEU], from (Santos, 2018).*

Cross examining these three sources, Murray's data confirms that of Santos and that of Dagkinis and Nikitakos', but the information for small containerships is still scarce. However, since the high points in Santos' data represent design speeds for the vessels are bigger than four thousand TEUs (which Murray confirms), one may assume that the same holds true for the points in vessels smaller than four thousand TEUs. Thus, a line drawn on the top values of Santos's data can be taken as the line of the design speed over the ship size. Knowing that, the lowest operating speed in large vessels is seventeen knots, one can draw a similarly shaped line for the lowest operating speed, a line that returns seventeen knots for large vessels and ten knots for very small ones. These two lines are in Figure 11.



*Figure 11 – Extrapolated Service Speed [kn] curve and Lowest Service Speed [kn] curve over Ship Size [TEU], using database of Santos (2018).*

Mathematically, the curves from the Figure 11 are defined in the following equations:

$$DSpeed(x) = \frac{9.00 \cdot 10^{-6} \cdot x^2 - 0.10 \cdot x - 18}{1.00 \cdot 10^{-8} \cdot x^3 - 1.00 \cdot 10^{-8} \cdot x^2 + 0.015 \cdot x + 1} + 26 \text{ [kn]} \quad (1)$$

$$LOSpeed(x) = \frac{1.00 \cdot 10^{-8} \cdot x^2 - 0.05 \cdot x - 8}{1.00 \cdot 10^{-8} \cdot x^3 + 1 \cdot 10^{-8} \cdot x^2 + 0.008 \cdot x + 1} + 17 \text{ [kn]} \quad (2)$$

Where  $x$  is the Ship Size [TEU],  $DSpeed$  is the design speed [kn], and  $LOSpeed$  is the lowest operating speed.

### 3.3.2. ROUND VOYAGE TIMES AND VALID OPERATING SPEEDS

However, not all operating speeds at which the vessels can sail can comply with the user inputted time of the round voyage, and as such the tool runs a verification of which, if any, operating speeds comply with this requirement. In a round voyage, there are six categories of time:

$$TFRV = BufferT + TRV \quad (3)$$

$$TRV = PTRV + STRV + TCH + TCRV \quad (4)$$

Where  $BufferT$  is the buffer time,  $TFRV$  is the time of the round voyage, as set by the user,  $TRV$  is the minimum time a vessel requires to complete the round voyage,  $PTRV$  is the time for port calling (not including cargo handling),  $STRV$  is the time for sailing in a round voyage,  $TCH$  is the time spent handling cargo in the ports, and  $TCRV$  is the time for crossing canals. All variables in [h].

The key time variable is the  $TRV$ , which is the time for the vessel to sail all the distances, handle all the cargo, call on all ports, and cross all canals. In order for the vessel to comply with the voyage,  $TRV$  must be smaller than  $TFRV$ . To validate the possible operating speeds, the tool uses a scalar  $\alpha$  (Equation 5 to 9). This scalar is calculated for the lowest operating speed and measures how much the speed can change and still comply with the time of a round voyage.

$$TRV \leq TFRV \quad (5)$$

$$TRV = TCH + STRV + PTRV + TCRV = const. + STRV \quad (6)$$

$$STRV = \sum_{i,j} \left( \frac{LDist(i,j)}{OSpeed} \right) \quad (7)$$

$$\exists \alpha : OSpeed' = \alpha \cdot LOSpeed \wedge TRV' = TFRV \quad (8)$$

$$\alpha = \frac{STRV}{(TFRV - (TCH + PTRV + TCRV))} \quad (9)$$

Where,  $OSpeed$  is an operating speed [kn].

The tool calculates the  $\alpha$  and then uses it as the criteria to validate operating speeds. There are three possibilities for the value of  $\alpha$ : either it is smaller than zero, between zero and one, or larger than one. If it is below zero, it means that the time for the round voyage is insufficient to call on the ports,

handle the cargo, and cross the canals (Equation 9). In this case no operating speed can ever satisfy the round voyage duration, and the code considers a fleet with more ships. *alpha* is smaller than one means that the lowest operating speed is sufficient to complete the round voyage, and thus all operating speeds are valid. However, if *alpha* is larger than one, then the lowest operating speed is not sufficient to comply with the round voyage, and-consequently, a higher operating speed must be considered. There is, of course, the possibility that the required speed to complete the voyage within the *TFRV* (which is  $\alpha \cdot LOSpeed$ ) is larger than the design speed, meaning that the vessel cannot comply with the stipulated duration of the round voyage.

Note: the ship referred in the section above is an individual ship of one of the many fleets the tool considers. If that ship cannot comply with the round voyage requirements, the tool states so in the outputs and moves to a more numerous fleet, whose ships, in virtue of having less cargo to carry, may comply with the duration of the round voyage.

### 3.3.3. MAXIMUM LENGTH OVERALL, MAXIMUM BREADTH, AND MAXIMUM DRAFT

These three values are particularly important due to ports and canals having restrictions for them. Santos contains the characteristics of 482 containerships, but these are restrictive measures and thus the tool does not use the expected values of this characteristics, but rather the maximum values, which ensure that most ships fall below that maximum (Santos, 2018). The curve in Equation 10 and in Figure 12 ensures that 95% of the vessels have a length lower than the one predicted. For the breadth see Equation 11 and Figure 13, and for the maximum draft, Equation 12 and Figure 14:

$$Max. Loa = \frac{2 \cdot 10^{-6} \cdot x^2 - 0.05 \cdot x - 300}{1 \cdot 10^{-11} \cdot x^3 + 5.5 \cdot 10^{-4} \cdot x + 1} + 400 [m] \quad (10)$$

$$Max. B = \frac{2 \cdot 10^{-6} \cdot x^2 - 0.071 \cdot x - 43}{8 \cdot 10^{-11} \cdot x^3 + 2 \cdot 10^{-7} \cdot x^2 - 0.002 \cdot x + 1} + 60 [m] \quad (11)$$

$$Max. D = \frac{1 \cdot 10^{-5} \cdot x^2 - 0.6 \cdot x - 11}{1 \cdot 10^{-9} \cdot x^3 + 2.7 \cdot 10^{-5} \cdot x^2 + 0.05 \cdot x + 1} + 17 [m] \quad (12)$$

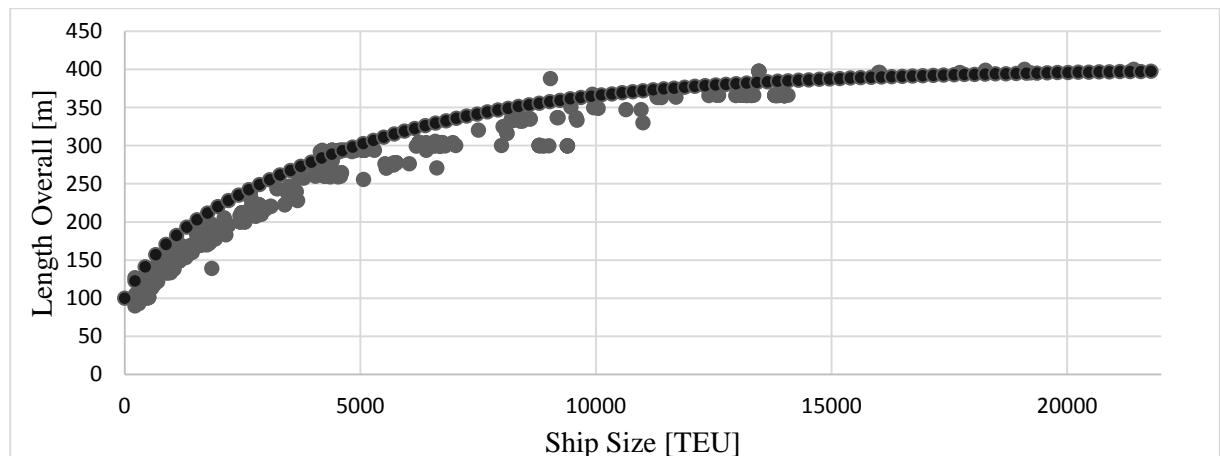


Figure 12 – Length Overall [m] over Ship Size [TEU] and the maximum length overall line, which ensures 0.95 of the vessels are below the curve (Santos, 2018).

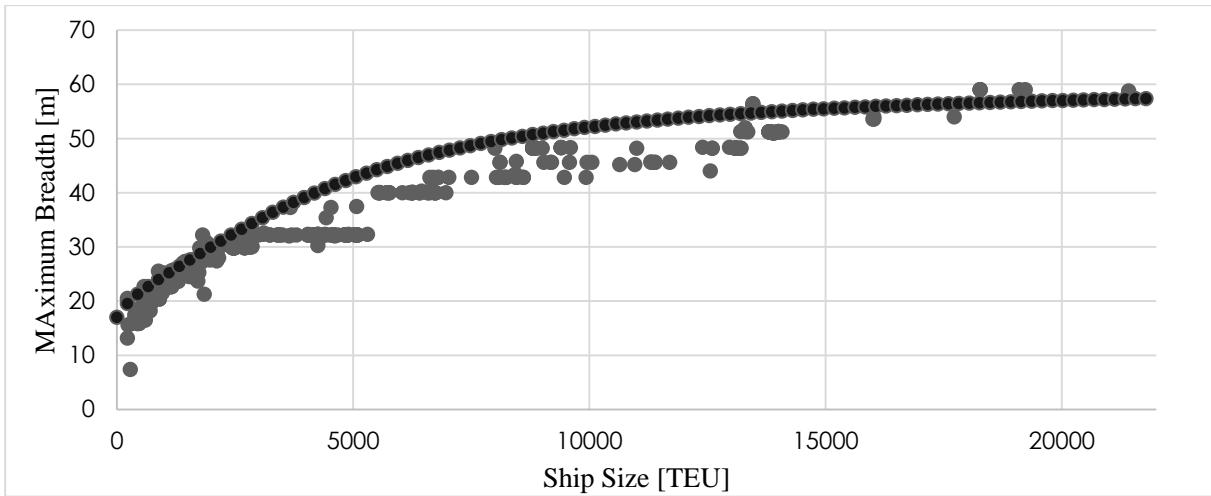


Figure 13 – Maximum Breadth [m] over Ship Size [TEU] and the maximum breadth line, which ensures 0.95 of the vessels are below the curve (Santos, 2018).

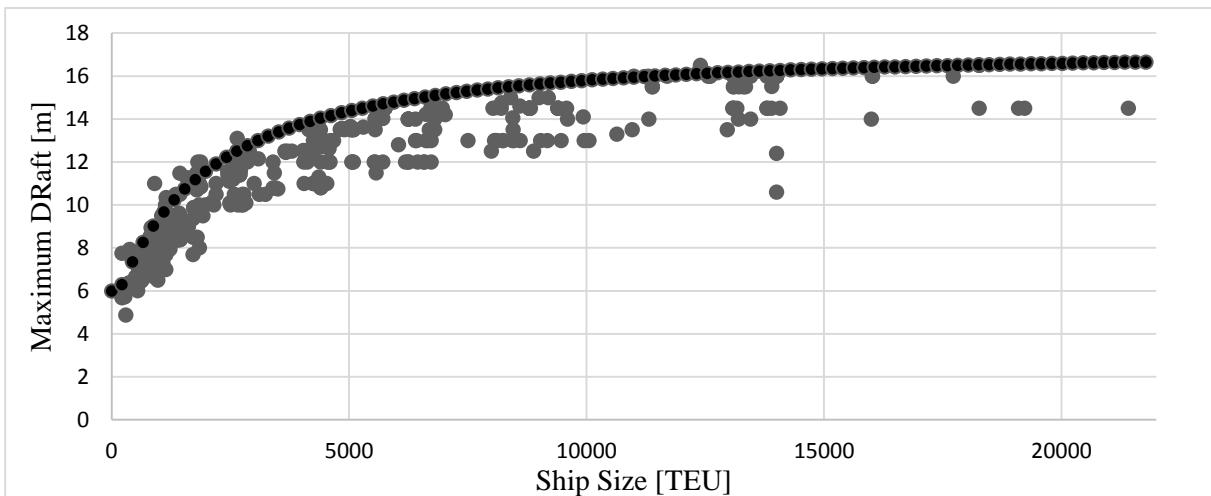


Figure 14 – Maximum Draft [m] over Ship Size [TEU] and the maximum draft line, which ensures 0.95 of the vessels are below the curve (Santos, 2018).

### 3.3.4. RATIO OF 14 TONS CONTAINERS TO THE NOMINAL CAPACITY

$R14tSS$  is the ratio between the ship's capacity in 14 tons containers (the usually taken value for a full container) and the ship's nominal capacity. Note that the ships capacity in 14 tons containers is restricted by stability. Figure 15 shows  $R14tSS$  over the ship capacity in TEUs. From this figure there is little dependence on ship size, and so the ratio is taken as of 0.8. This measure is important for it constitutes a stability restriction: while a vessel may carry in volume the number of containers stated in its capacity, the number of full containers it can actually carry may be different. The tool uses this value to ensure that the ship is not carrying more full containers than it should.

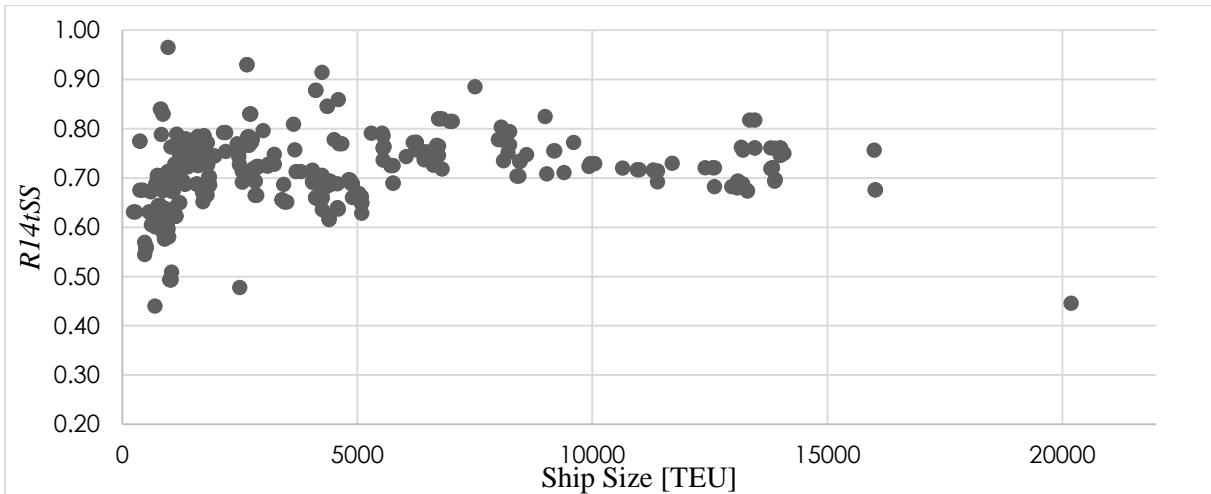


Figure 15 – Ratio of 14 ton containers to Ship Size over Ship Size (Santos, 2018)).

### 3.3.5. SHIPBUILDING COST

Two estimates of the shipbuilding cost are utilized: that of Murray and that of Santos.

Murray used a database of containerships (Murray, 2015) to make a regression of the Construction Cost per TEU against the Ship Capacity (Figure 16). Again, one can extrapolate a number of points from the plot to reproduce the regression line (Figure 17).

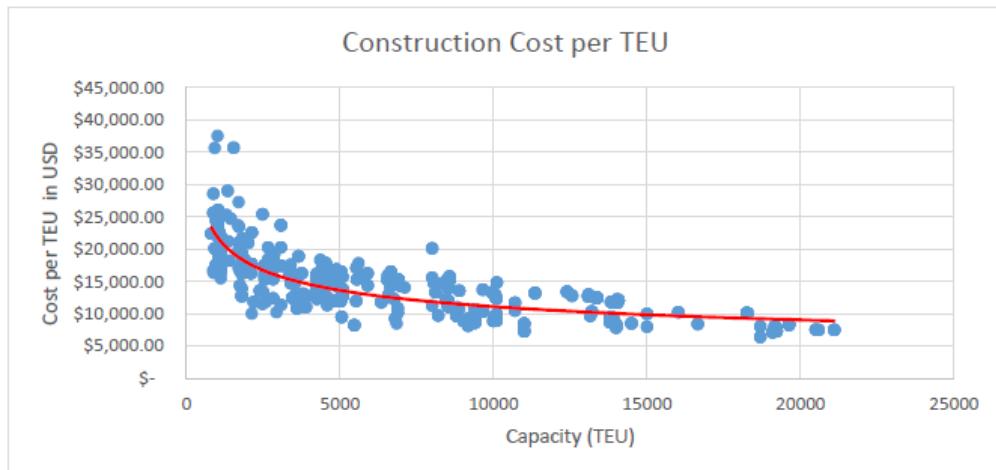


Figure 16 – Construction Cost per TEU [USD] over the Ship Size [TEU] Murray (2015)

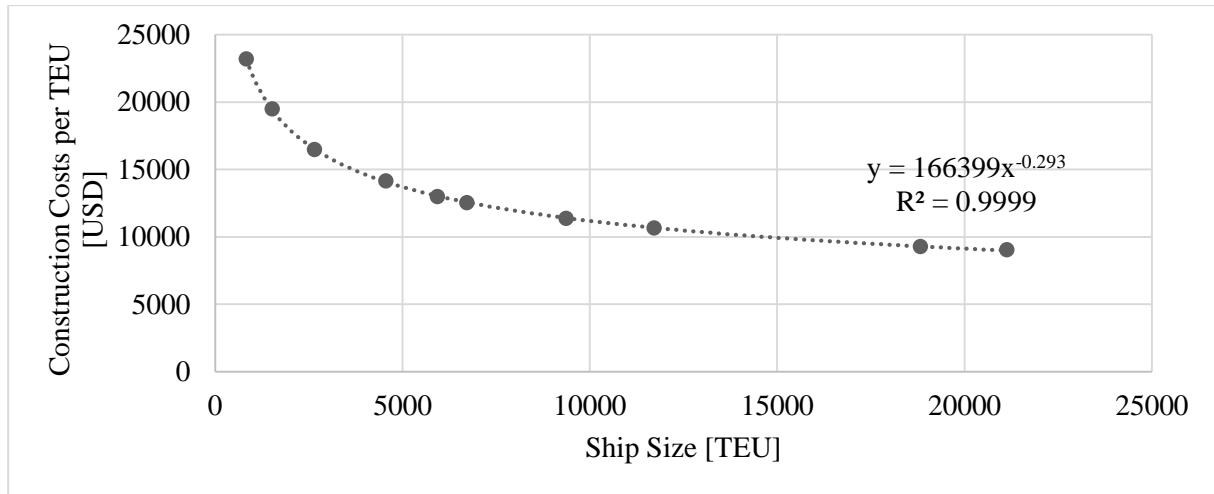


Figure 17 – Extrapolated construction Cost per TEU [USD] over the Ship Size [TEU] (Murray, 2015).

Santos provides, from an extensive collection of containerships' data (Santos, 2018), the evolution of the shipbuilding prices of ships discriminated by ship size (Figure 18), from which one can infer the relation between the price and the size (Figures 19 and 20).

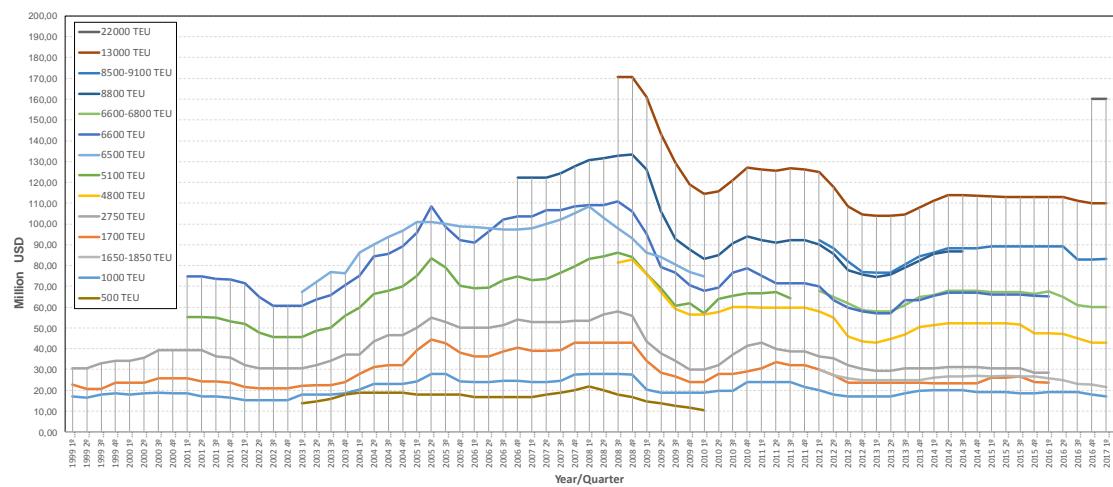


Figure 18 – Shipbuilding price [USD] over the years and quarters, over the ship size. (Santos, 2018)

Both approaches have high margins of error. In Murray (Figure 16), a ship with a capacity of two and a half thousands TEU can cost between ten million and twenty three million USD, but it is not known from which year are the prices. In Santos (Figure 18) the shipbuilding costs is shown as fluctuating over time. To account for these deviations, an error margin of error of thirty percent is used, estimated from Murray's data. The comparison between Santos' and Murray's data is in Figure 21 and, as expected the shapes are similar but the values diverge, which is the expected.

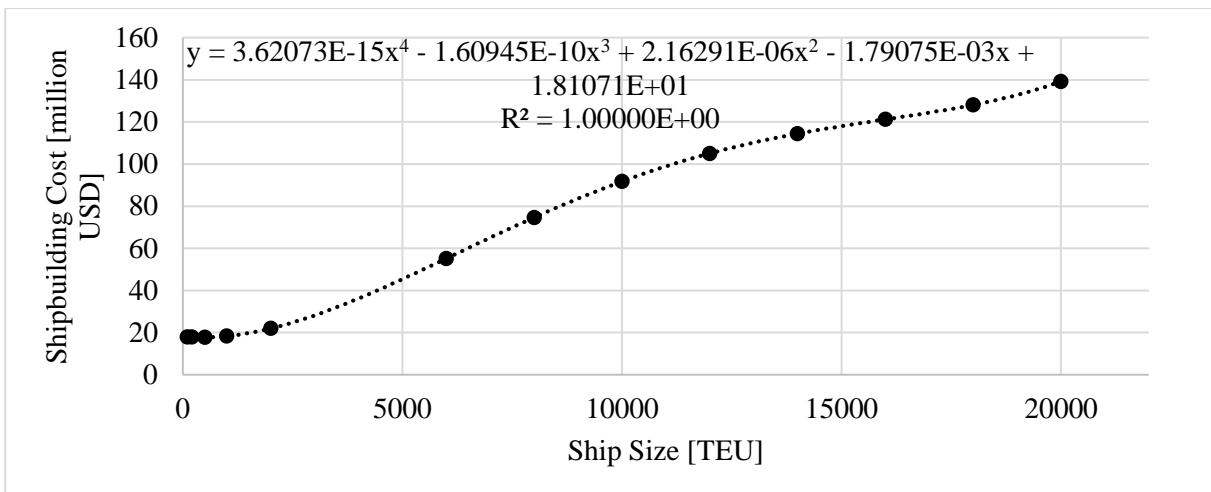


Figure 19 – Shipbuilding Cost [million USD] over Ship Size [TEU] (Santos, 2018).

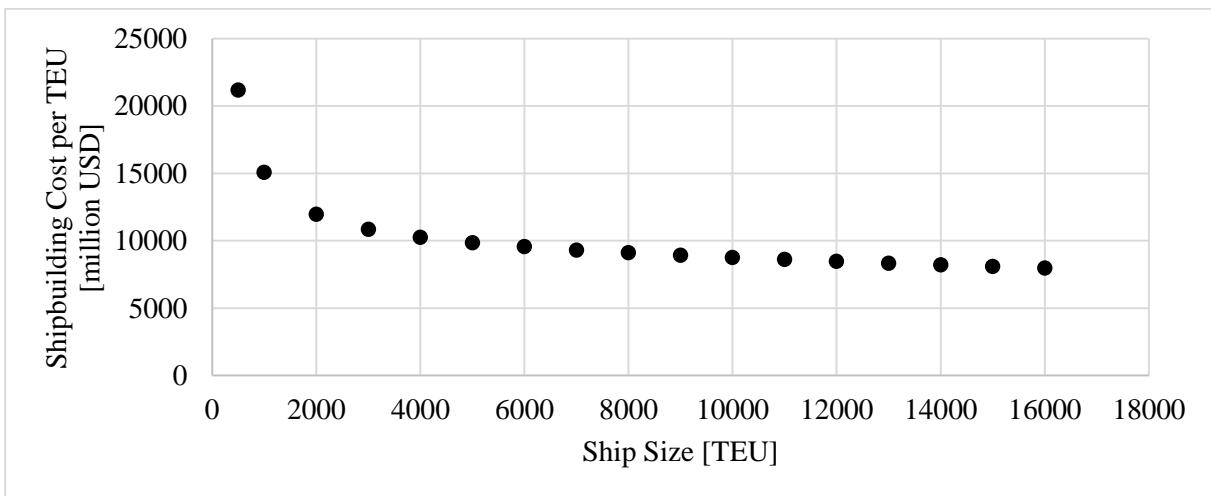


Figure 20 – Shipbuilding Cost per TEU [million USD] over Ship Size [TEU] (Santos, 2018).

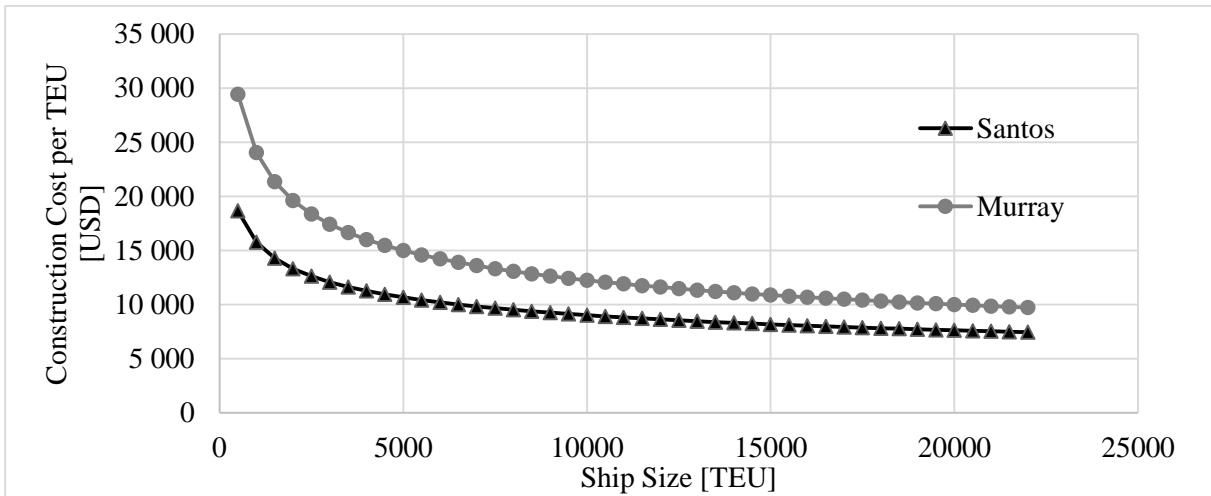


Figure 21 – Shipbuilding Cost per TEU [USD] over Ship Size [TEU]. Comparison of Santos with Murray.

To adjust the shipbuilding prices from previous years to the current year, a two percent inflation rate is used (International Monetary Fund, 2018). The final ship construction cost relations are in Figure 22 and in Equations 13, 14, and 15.

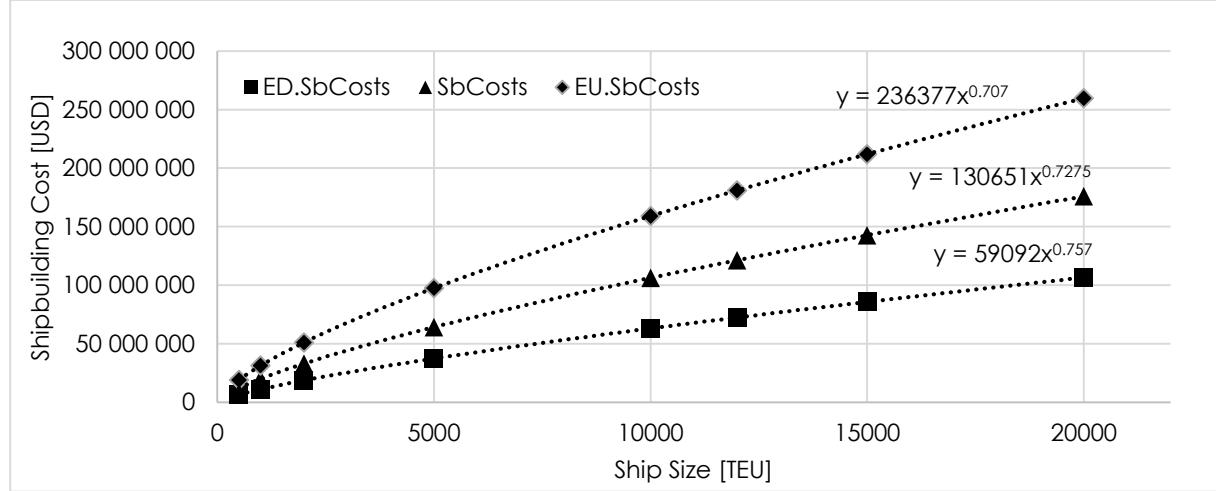


Figure 22 – Shipbuilding Costs [USD] over the Ship Size [TEU].

$$EU.SbCosts = 236\,377 \cdot (\text{Ship Size})^{0.707} \quad (13)$$

$$SbCosts = 130\,615 \cdot (\text{Ship Size})^{0.7275} \quad (14)$$

$$ED.SbCosts = 59\,092 \cdot (\text{Ship Size})^{0.757} \quad (15)$$

Where  $SbCosts$  is the cost of shipbuilding [USD] in the expected costs scenario,  $EU.SbCosts$  in the higher cost scenario and  $ED.SbCosts$  in the lower cost scenario.

### 3.3.6. OTHER SHIP CHARACTERISTICS

Figures 23 to 35 contain the data points from Santos and the regressions for: the average length between perpendiculars [m], the average breadth [m], the average depth [m], the main engine power [kW], the generators' powers [kW], the number of generators, the displacement [t], the lightship weight [t], the fuel capacity [ $m^3$ ], the ballast capacity [ $m^3$ ], the gross tonnage, the net tonnage, and the number of cranes.

$$Nr.Cranes = \begin{cases} 3, & \text{Ship.Size} < 3700 \\ 0, & \text{Ship.Size} \geq 3700 \end{cases} \quad (16)$$

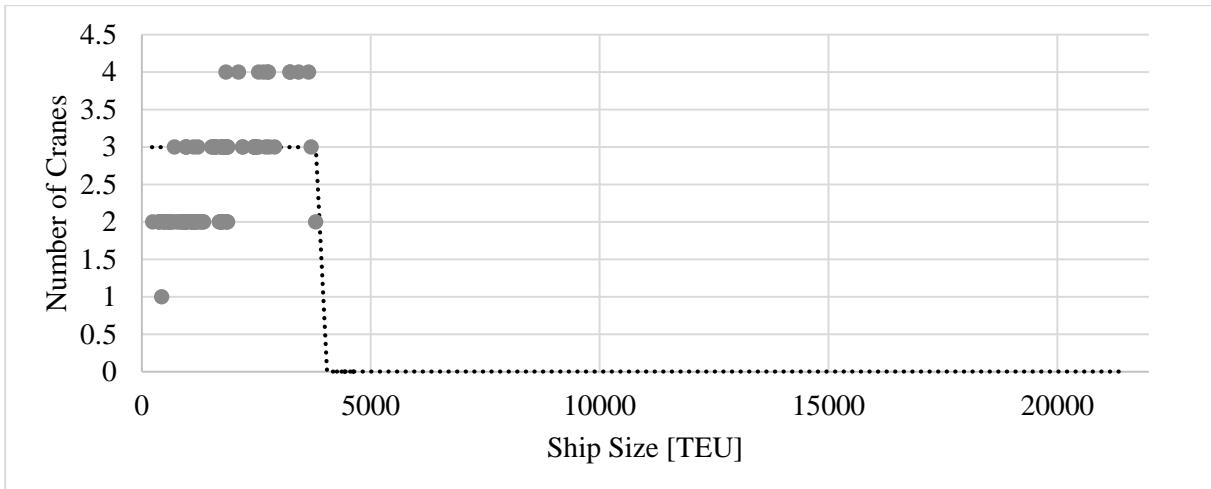


Figure 23 – Number of Cranes over Ship Size [TEU] (Santos, 2018). The trend line is the step function in Equation 16.

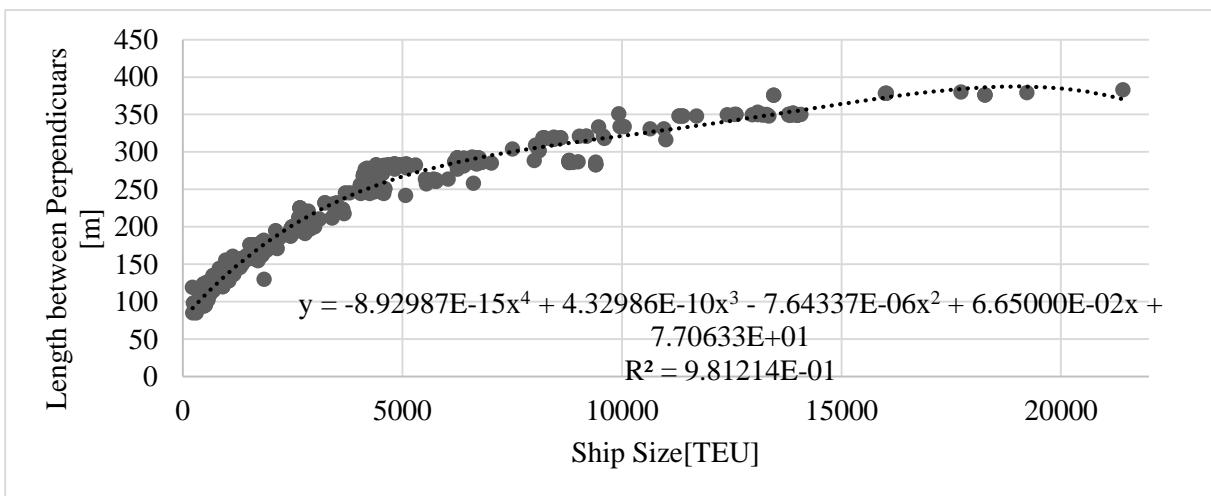


Figure 24 – Length between Perpendiculars [m] over Ship Size [TEU], data and trend (Santos, 2018)

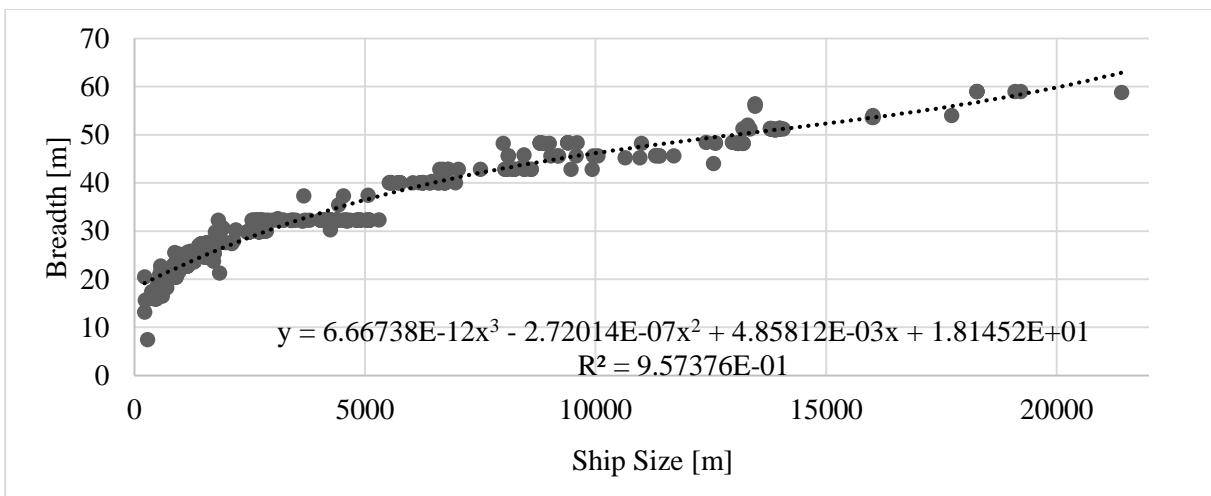


Figure 25 – Breadth [m] over Ship Size [TEU], data and trend (Santos, 2018).

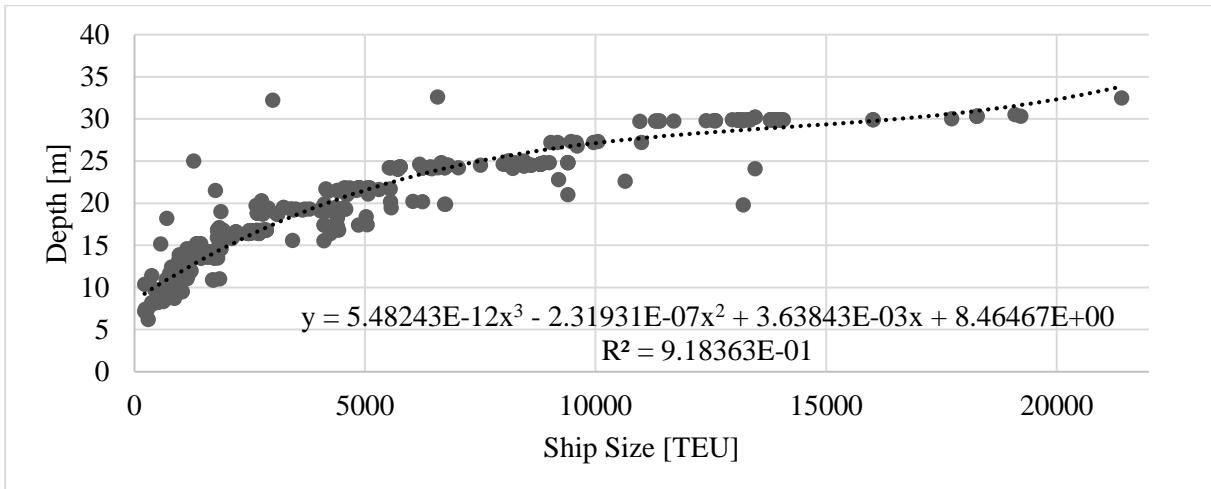


Figure 26 – Depth [m] over Ship Size [TEU], data and trend (Santos, 2018).

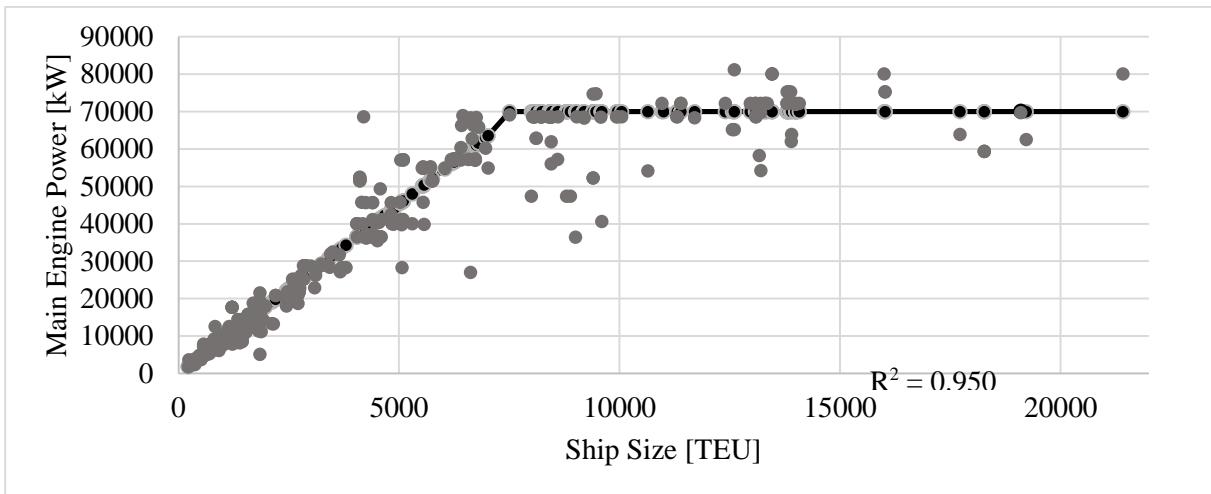


Figure 27 – Main Engine Power [kW] over Ship Size [TEU] (Santos, 2018). The trend line is in Equation 17.

$$MPP = \begin{cases} 9.0454 \cdot \text{Ship.Size} - 62.072, & \text{Ship.Size} < 7500 \\ 70\,000, & \text{Ship.Size} \geq 7500 \end{cases} \quad (17)$$

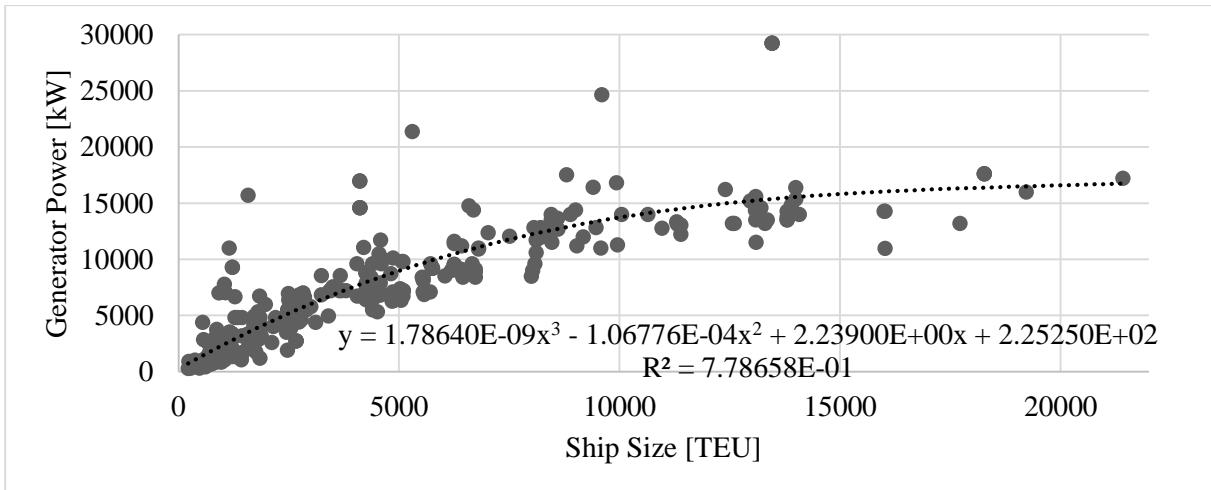


Figure 28 – Generator Power [kW] over Ship Size [TEU] (Santos, 2018).

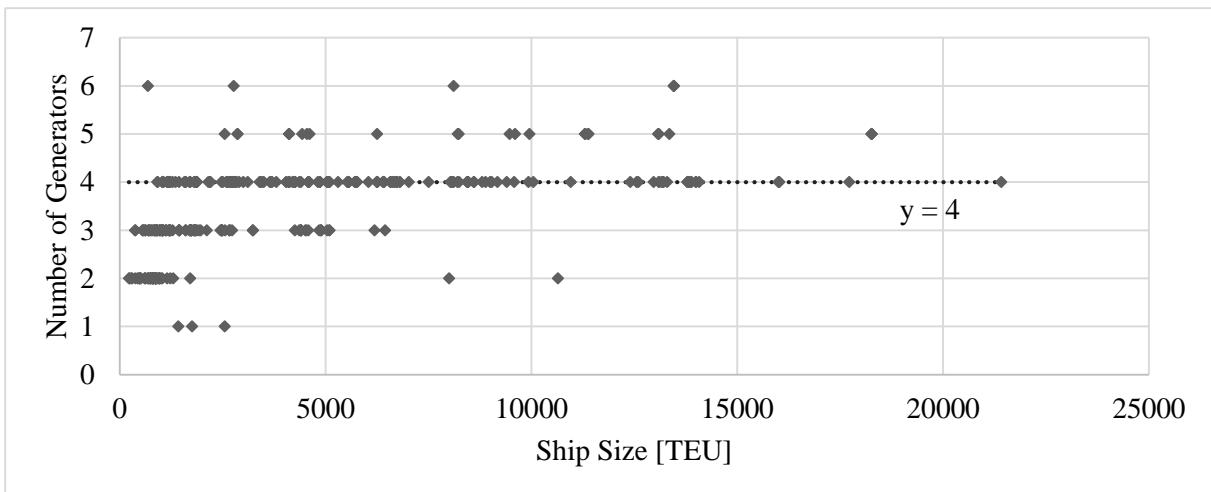


Figure 29 – Number of Generators over Ship Size [TEU] (Santos, 2018).

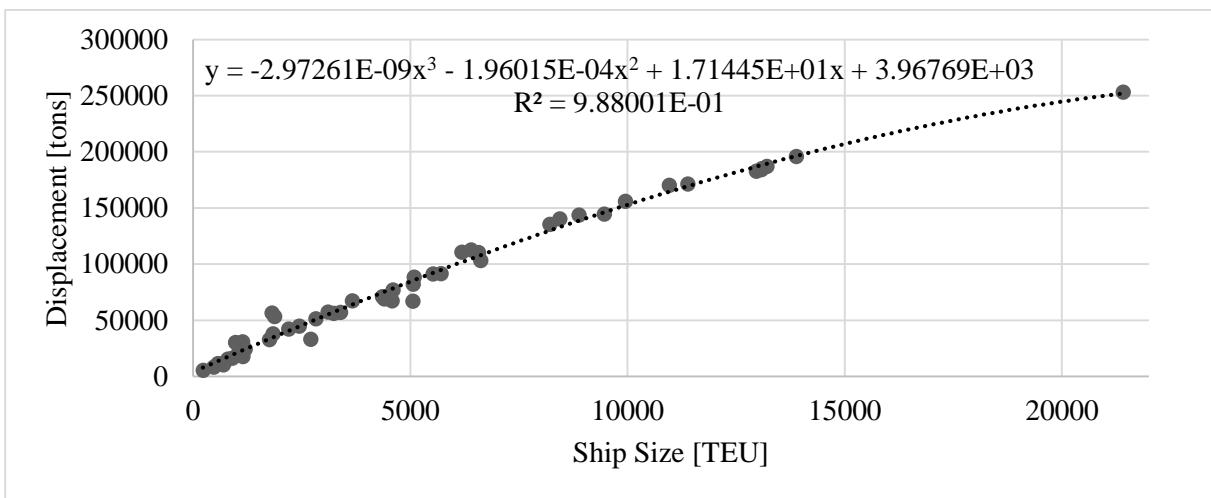


Figure 30 – Displacement [t] over Ship Size [TEU] (Santos, 2018).

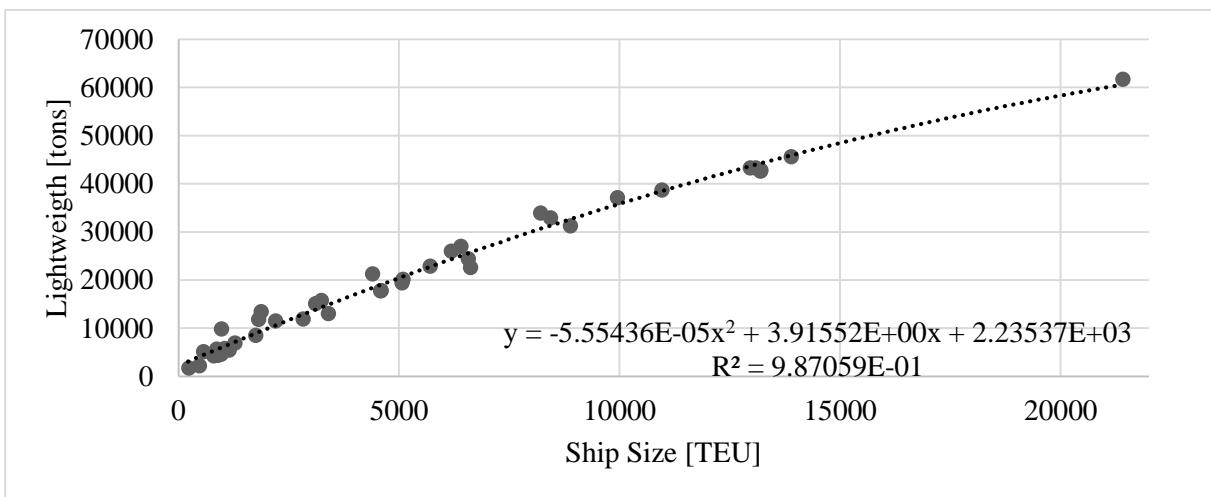


Figure 31 – Lightweight [t] over Ship Size [TEU] (Santos, 2018).

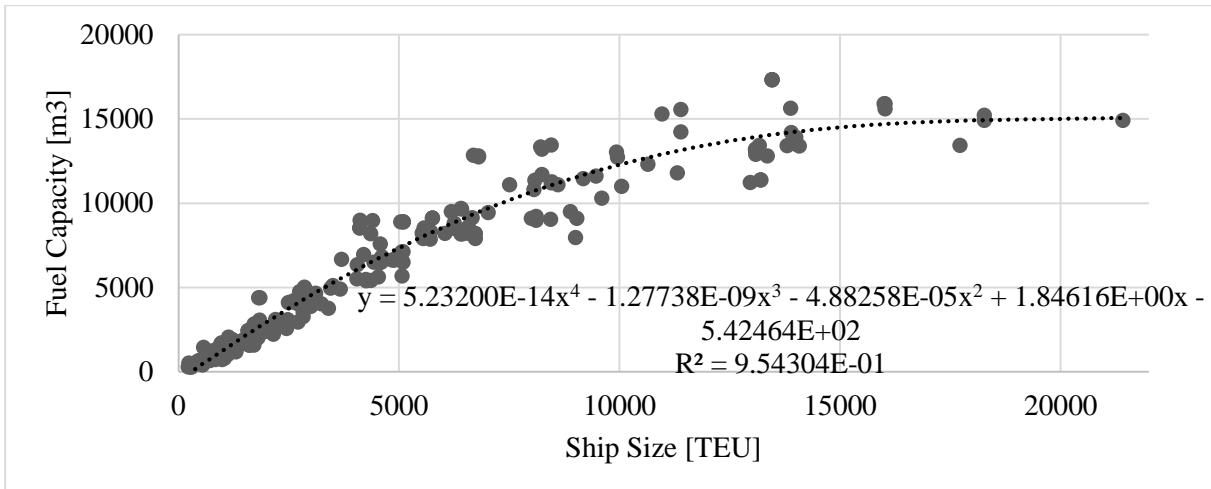


Figure 32 – Fuel Capacity [ $m^3$ ] over Ship Size [TEU] (Santos, 2018).

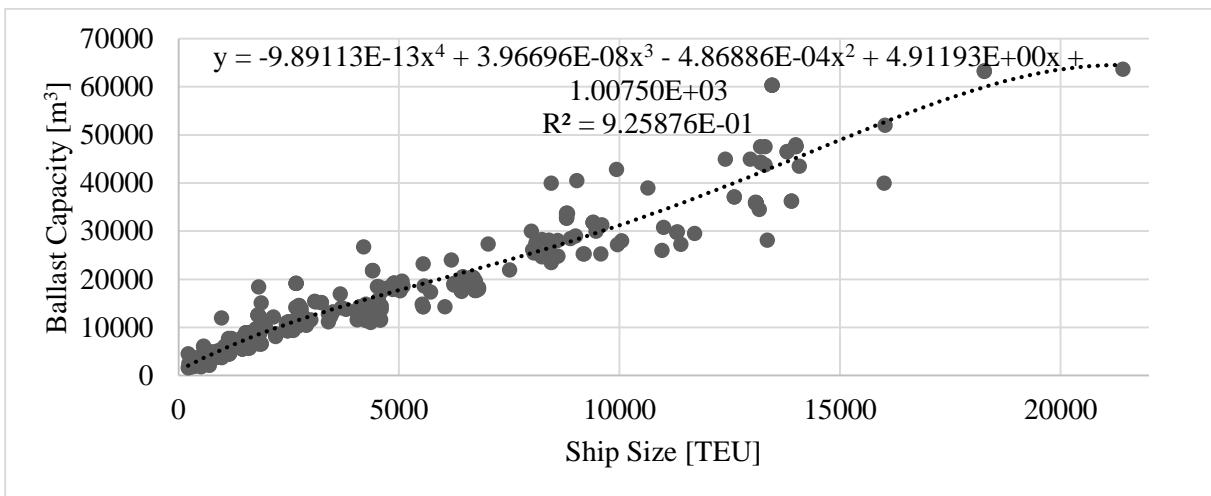


Figure 33 – Ballast Capacity [ $m^3$ ] over Ship Size [TEU] (Santos, 2018).

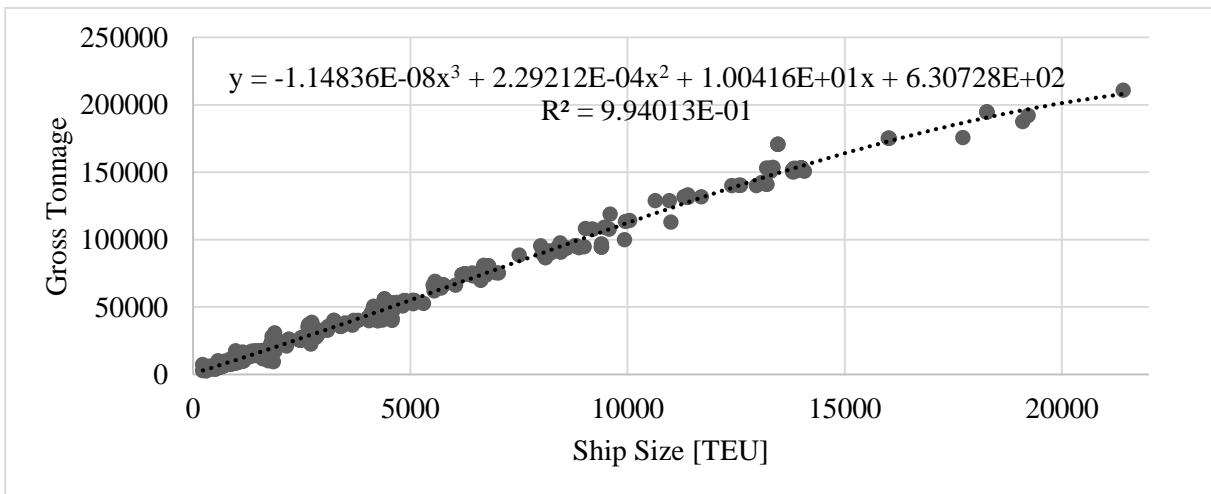


Figure 34 – Gross Tonnage over Ship Size [TEU] (Santos, 2018).

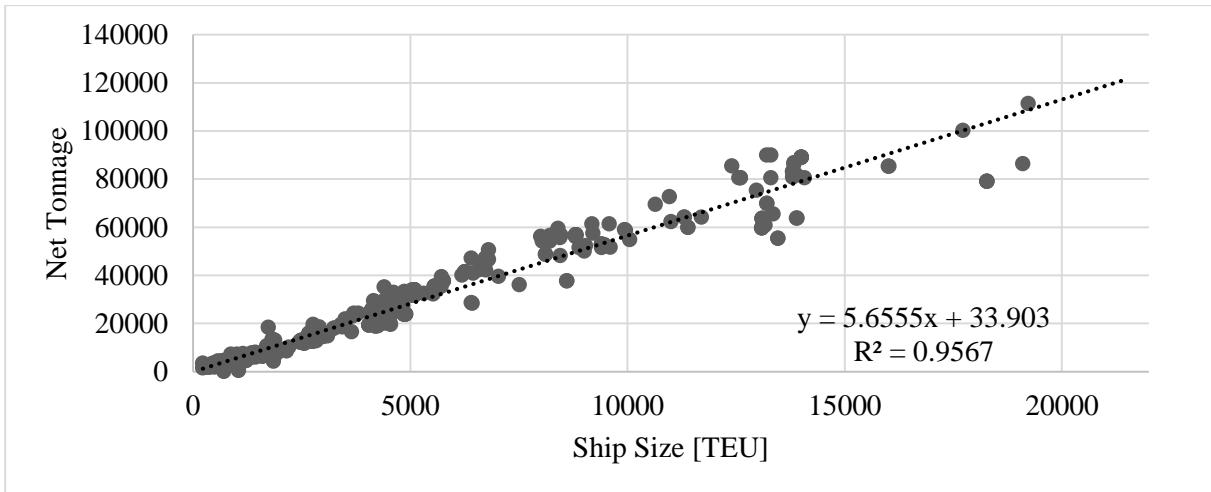


Figure 35 – Net Tonnage over Ship Size [TEU] (Santos, 2018).

### 3.4. SHIP COSTS AND REVENUES

The ship costs are divided in the operational costs, the capital costs, the port costs, the fuel costs, and the canal costs.

#### 3.4.1. OPERATING COSTS

The operating costs include all the expenses of keeping the ship operational (e.g., crew wages, stores, and maintenance). Lacking the data to directly estimate each of the components, empirical relations are used. As stated in the previous section, to present the error involved, there are three variables for the operational costs: *OpCosts*, for the scenario where costs are as expected; then *EU.OpCosts*, for the scenario where costs are maximum, and *ED.OpCost*, where they are minimum.

Here, two models of the operating costs are considered: that of Murray and that of Merk et al.. Murray displays the ‘Daily Operating Cost per TEU’ as a function of the ‘Vessel Capacity in TEUs’ in Figure 36 (Murray, 2015), from which one can extrapolate the underlying equation, by procuring points in that plot and using an Excel™ spreadsheet to find a fitting exponential regression (Figure 37).

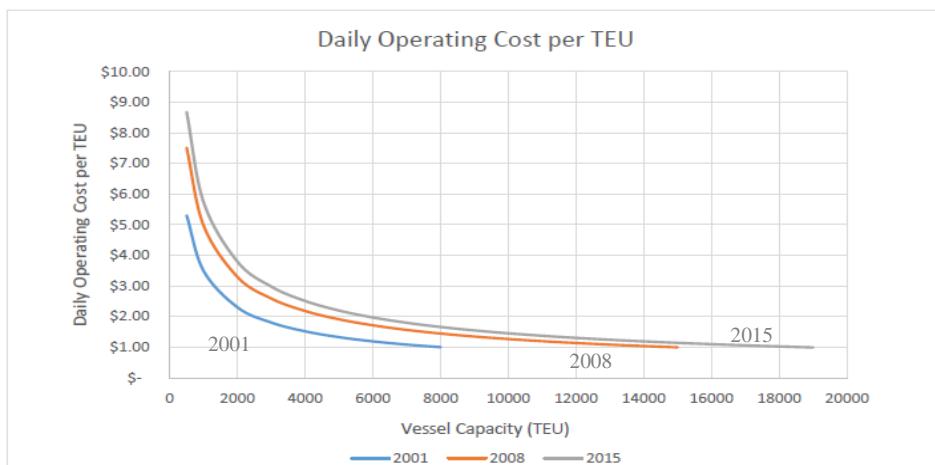


Figure 36 – Daily Operating Cost per TEU [USD] over the Ship Size [TEU] (Murray, 2015).

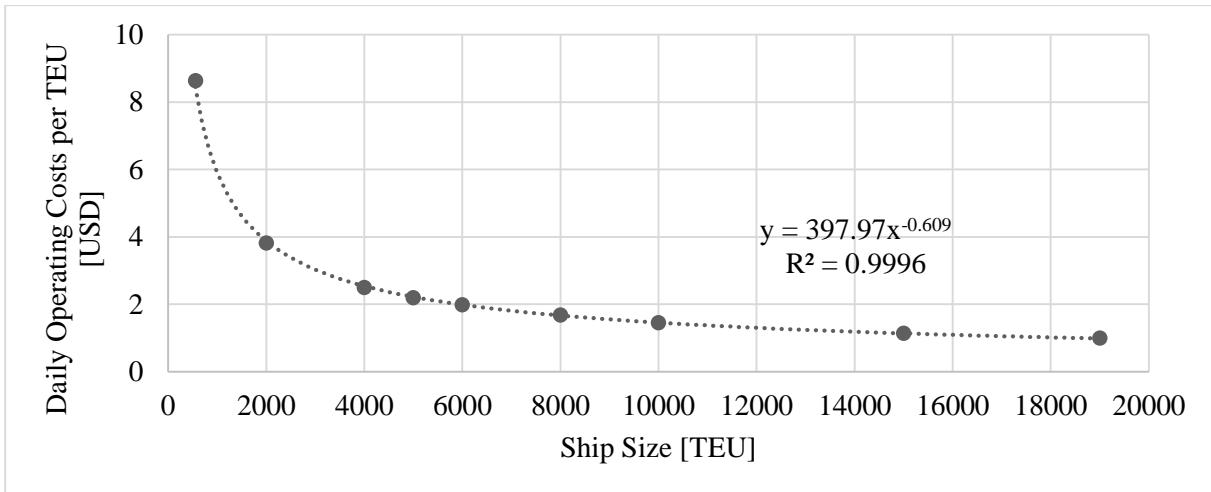


Figure 37 – Extrapolated daily Operating Costs per TEU [USD], over Ship Size [TEU] (Murray, 2015).

Thus, Murray's annual operating costs are given by:

$$OpCost_{Murray} = 397.97 \cdot (Ship.Size)^{-0.609} \cdot 365 \quad (18)$$

Where *Ship.Size* is the ship capacity [TEU].

Merk et al. considers operating costs in a very similar manner (Merk, et al., 2015) by presenting a plot with the values for the 'Annual Operating Costs per TEU' as function of the 'Nominal TEU Size' of the vessel (Figure 38). Again, one can extrapolate the values and use Excel™ to find a suiting regression (Figure 39).

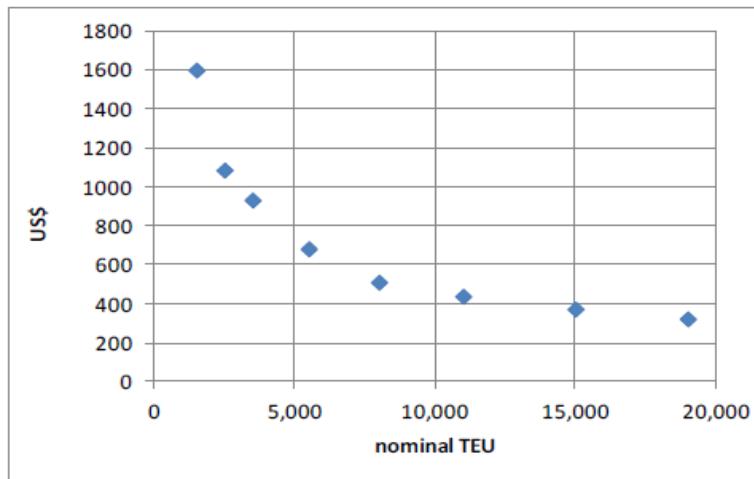


Figure 38 – Daily Operational Costs per TEU [USD] over Ship Size [TEU] (Merk, et al., 2015).

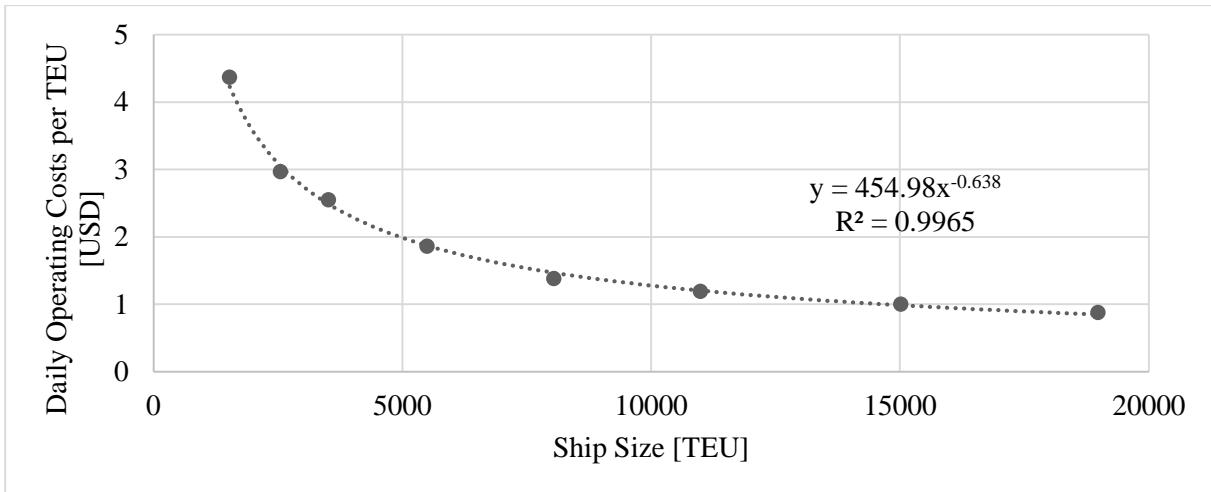


Figure 39 – Extrapolated daily Operating Costs per TEU [USD], over Ship Size [TEU] (Merk, et al., 2015).

Thus, Merk et al.'s operating costs are given by:

$$OpCosts_{Merk} = 454.98 \cdot (Ship.Size)^{-0.638} \cdot 365 \quad (19)$$

Combining these two approximations, and noting that Murray's estimate is higher than Merk et al.'s (Figure 40), the value of the expected operating costs is taken as the mean, the maximum cost scenario value as Murray's plus ten percent, and the minimum costs scenario value as Merk's minus ten percent. After adjusting for inflation, the operating costs are as in Figure 41. The inflation takes the value recommended by the IMF, which is of 2% (International Monetary Fund, 2018)

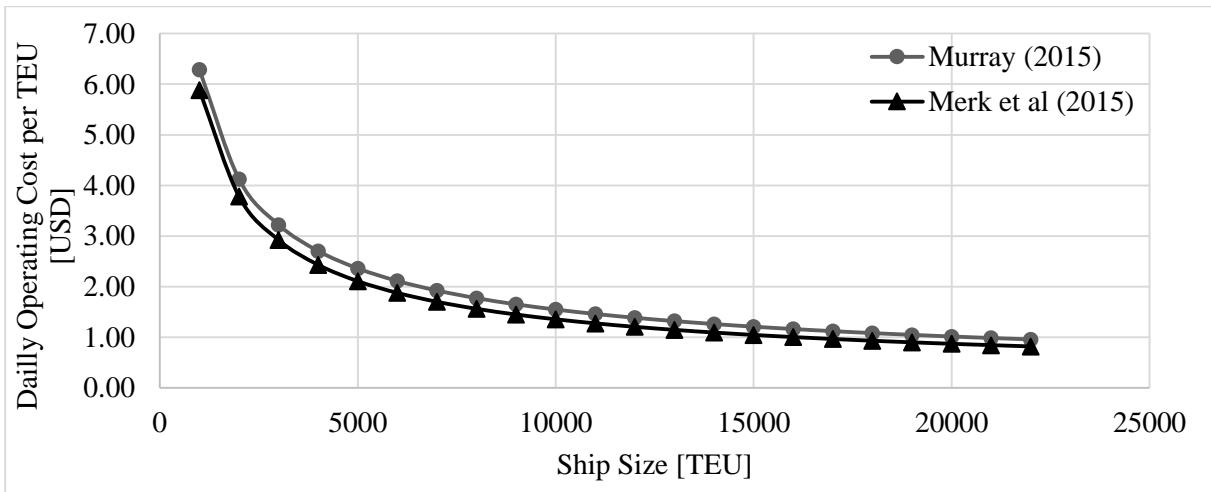


Figure 40 – Daily Operating Costs per TEU [USD] over Ship Size [TEU]. Comparison of Murray's and Merk et al.'s data, corrected for inflation.

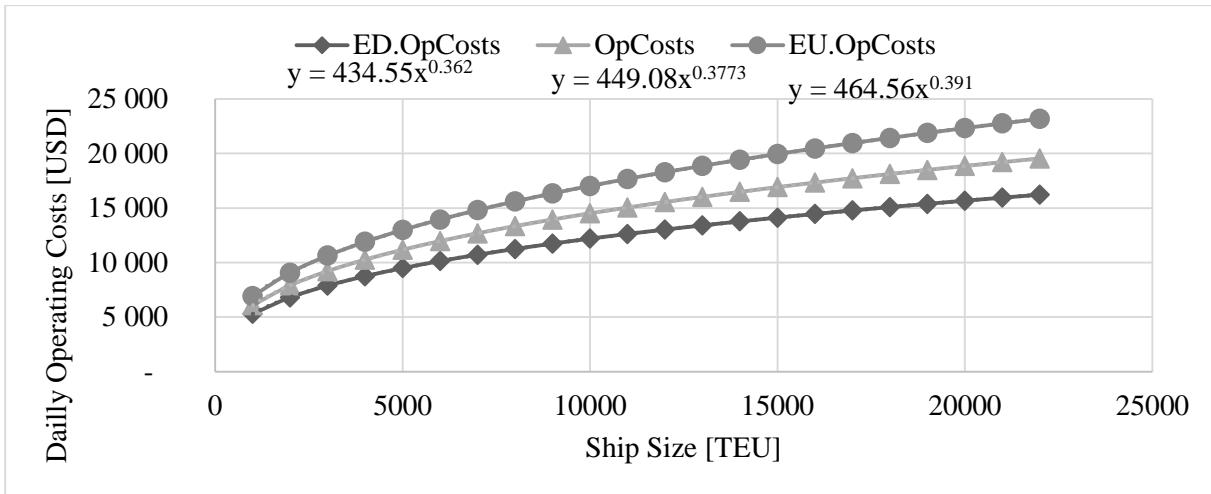


Figure 41 – Daily Operating Costs [USD] over the Ship Size [TEU], for the three cost scenarios

The operating costs for the maximum, expected, and minimum cost scenarios respectively, are in the following equations:

$$EU.OpCosts = 464.56 \cdot (Ship Size)^{0.391} \cdot 365 \quad (20)$$

$$OpCosts = 449.08 \cdot (Ship Size)^{0.3773} \cdot 365 \quad (21)$$

$$ED.OpCosts = 434.55 \cdot (Ship Size)^{0.362} \cdot 365 \quad (22)$$

### 3.4.2. CAPITAL COSTS

The capital costs are the costs of purchasing a ship, annualized over the ship's lifespan. These are not the same as the construction cost, since most shipbuilding is financed with loans which are then repaid over time and most ships are scraped (a process also known as shipbreaking) at the end of their lives. Both Oblakova and the Organization for Economic Cooperation and Development write on the common structure of ship loans and on the various intermediary payments at the key stages of the shipbuilding (Oblakova, 2011) and (OECD, 2017). Here, these details are discarded and the loan is simply seen as a series of annual cash flows. Since the ships operating life is usually superior to the term of the loan (i.e., the number of years to the total payment of the debt), the loan repayment costs are only present in the first years of operation and may not be constant over those years. The tool is general and thus accounts for the loan repayment costs, for the initial investment in the ship, and for the scraping revenue by annualizing all them into some equivalent annual cash flows which are constant over the twenty years that the ship is estimated to live. That is, there is a constant expense (here called the capital costs) that, if paid over twenty years, is equivalent to investing in the ship in the beginning, in paying the loan in the first years, and in scraping the vessel at the end of its life. This normalized annual expense is calculated by equalling the present value (*NPV*) of the capital costs to that of the separate payments (Equation 23). To do so, the code uses the discount rate of the investment, which is a user input.

$$Sb.Cost \cdot (1 - Loan.Value) + \sum_{N=1}^{Term.of.the.loan} \frac{(Interest_i + Instalment_i)}{(1+DRate)^N} - \frac{Scrap.Value}{(1+DRate)^{Ship.Life}} = \sum_{N=1}^{Ship.Life} \frac{CapCosts}{(1+DRate)^N} \quad (23)$$

Where  $Sb.Cost (1 - Loan.Value)$  is the initial investment in the ship [USD],  $Interest_i$  is the amount paid in interest in year  $i$  [USD],  $Instalment_i$  is the principal payment of the loan in the year  $i$ ,  $Scrap.Value$  is the revenue from scrapping [USD],  $CapCosts$  are the annual capital costs of the vessel [USD], and  $DRate$  is the discount rate. Note: The parcel of the  $Scrap.Value$  is negative, because it is for a revenue, while all other parcels are expenses.

Assuming a fixed principal payment loan, the annual instalment and the annual interest are in the following equations:

$$Instalment_i = \frac{Loan.Value}{Term.of.the.loan} \quad (24)$$

$$RDebt_0 = \text{Loan.Value} \cdot SbCost \quad (25)$$

$$RDebt_i = \begin{cases} RDebt_{i-1} - Instalment_i, & \text{if } i \leq \text{Term.of.Loan} \\ 0, & \text{if } i > \text{Term.of.Loan} \end{cases} \quad (26)$$

$$Interest_i = RoI \cdot Remaining.Debt_{i-1} \quad (27)$$

The value of scrapping the vessel is given by:

$$Scrap.Value = Lightweight \cdot Price.Scrap \quad (28)$$

Where the  $Price.Scrap$  is the price paid for each ton of scrap in the vessel, and  $RDebt_i$  is the remaining debt in year  $i$  [USD], and  $RoI$  is the interest rate.. In the current, the price of scrap is four hundred U.S. dollars per ton of lightweight (Go Shipping, 2018), which in twenty years would be around six hundred and twenty five [USD / t].

Thus, the problem is reduced to determining the shipbuilding cost, since the loan conditions ( $Loan.Value$ , the  $Interest.Rate$ , and  $Term.of.the.Loan$ ) and the  $Scrap.Price$  are a user input.

### 3.4.3. VOYAGE COSTS

#### 3.4.3.1. PORT COSTS

The port costs are a component of the voyage costs. Quoting Meersman et al: “The complexity of current port pricing schemes is striking. [...]The result is an opaque price structure that complicates ship operators’ and cargo owners’ port choice and therefore softens port competition (and competition among container lines)“ (Meersman, et al., 2014).

This is an issue, albeit a solvable one, since the code can handle any number of pricing formulas. The next paragraph takes a brief look into the pricing schemes of some ports as to find trends in the ports pricing schemes.

In the port of Rotterdam charges ships by each gross ton and by the amount of transhipped cargo (Rotterdam, 2018). It requires pilots, but these fees are not publicly available. The same happens for services of towage and of mooring. In the port of Gdansk, the port authority charges for the gross tonnage of vessels and for the time in berth (Port of Gdańsk Authority, 2017). The port requires pilotage services ("GDAŃSK-PILOT"Sp.zo.o., 2015), which are charged in function of the ships volume (calculated as length times maximum breadth times depth). The same goes for towing services (Port and Maritime Services, 2018). As for terminal fees, the Deepwater Container Terminal of Gdansk (DCT Gdansk, 2018) charges for each handled container (discriminating between TEU and FEU, between full and empty container, and between regular and reefer containers) and details the surcharges for operations on weekends and Holidays, as well as the fees for storing container in the terminal depending on the number of days. The port of Busan (Busan Agency Co. Ltd, 2013) calculates its port dues using the gross tonnage, the number of containers on the vessels, and the time in berth. The pilotage charges are levied depending on the area of the port the vessel navigates (Korea Maritime Pilots' Association, 2009). The port of Singapore charges per every hundred gross tons (MPA, 2018) with pilotage and towing fees levied by the duration of the services (PSA Marine (PTE), 2018). In the port of Hong Kong, the fees are set by the state (H. K. Marine Department, 2018). Some are fixed (mostly permits) and most are charged by the tonnage, with the use of port structures paid by the duration of usage. In the port of Tanjung Priok, in the city of Jakarta, the Jakarta International Container Terminal only charges per handled containers (Jakarta International Container Terminal, 2018).

From these port pricing structures, a problem emerges: there is not a port for which where all fees are estimated. Many information on fees is just the service provider's contact and e-mail. Nonetheless, these ports show that ports charges usually depend on the same ships characteristics, chiefly the gross tonnage. From these insights one can establish the formulas for the port costs as in the following equations:

$$Port. Costs = \sum_i (Call. Costs_i \cdot \frac{(365 - Off.Hire)}{TRV}) \quad (29)$$

$$Call. Costs_i = Fixed_i + Size_i \cdot Ship.Size + Tonn_i \cdot GT + Time_i \cdot Time.in.Berth_i + \\ Cargo_i \cdot Nr.Cont.Handled_i \quad (30)$$

Where, *Port.Costs* are the total port charges of a vessel in a year [USD]; *Call.Costs<sub>i</sub>* is the costs of calling once at the *i<sup>th</sup>* port of call of the round voyage; *TRV* is the time for a round voyage; *Off.Hire* is the annual off-hire, taken as fifteen days; *Fixed<sub>i</sub>* is a fixed charge for calling in the *i<sup>th</sup>* port of call of the round voyage, *Size<sub>i</sub>* is a fee per [TEU] of the ships capacity the *i<sup>th</sup>* port of call of the round voyage, *Tonn<sub>i</sub>* is a fee levied per unit of ship gross tonnage in the *i<sup>th</sup>* port of call of the round voyage, *Time<sub>i</sub>* is a fee levied per hour of berth usage in the *i<sup>th</sup>* port of call of the round voyage, *Cargo<sub>i</sub>* is an expense per container handled in the *i<sup>th</sup>* port of call of the round voyage , and *Nr.Cont.Handled<sub>i</sub>* is the number of containers

handled in the  $i^{th}$  port of call of the round voyage. Through this formula the user has the flexibility to set the parameters to fit each of the ports his fleet will call.

### 3.4.3.2. FUEL COSTS

Before beginning the modelling of fuel costs, one can state a number of premises on marine fuels. First, ships need fuel to power the main engine and the electrical generators, which usually use different fuels. Second, the absolute majority of container vessels use diesel engines, since steam turbines are less efficient economically, see (Murray, 2015), and electrical alternatives are still under testing, see (Ship Technology, 2017). Third, one assumes that these ships consume Intermediate Fuel Oil (IFO) in the main engines and Marine Diesel Oil (MDO) in the generators. Fourth, the main engine's fuel consumption depends on the type and on the number of propellers (the universal prime mover for containerships), on the shape of the hull, amongst others. These are ignored due to a lack of data to properly model them, and fuel consumption is assumed as only depending on the operating speed. Fifth, if a ship crosses a Controlled Emissions Area, it must use a low polluting fuel, which usually involves switching fuel mid voyage. As with Murray, these controlled areas are ignored by the tool. Sixth, the tool assumes that the ships sails at a constant speed through each leg of the journey.

That said, the cost of fuel in a vessel is given by Equation 31. The fuel costs are divided in two parcels: the side of the IFO is used when the ship is sailing, and the side of MDO is used whenever the ship is operating:

$$\text{Fuel.Costs} = \text{Price.IFO} \cdot \text{Consumption.IFO} \cdot \left( \frac{365 - \text{Off.Hire}}{\text{TFRV}} \cdot \frac{\text{STRV}}{24} \right) + \text{Price.MDO} \cdot \text{Consumption.MDO} \cdot (365 - \text{Off.Hire}) \quad (31)$$

Where: *Price.IFO* is the price of IFO [USD / t]; *Comsumption.IFO* is the daily consumption of IFO [t / day]; *TFRV* is the duration of a round voyage [days]; *STRV* is the sailing time in a round voyage [h]; *Price.MDO* is the price of MDO [USD / t]; *Comsumption.MDO* is the daily consumption of MDO [t / day]; and *Off.Hire* is the annual off-hire, taken as fifteen days. Note:  $(365 - \text{Off.Hire}) / \text{TFRV}$  is the number of round voyages in a year.

Concerning the consumption of IFO, which is used in the main engine, there is a distinction to make. The current speed of the vessel in a leg is called the service speed, which is different from the design speed, which in turn is different from the lowest service speed. The design speed is the speed for which the vessel is originally designed to sail at. The lowest service speed is the lowest speed the ship can physically reach.

These speeds are discussed in a later subsection. For now, the important is that the service speed has an effect on the fuel costs: the fuel consumption and the service speed are related by third degree polynomial, as shown in Equation 32. This relation is used by both Santos (Santos, 2016) and Murray (Murray, 2015):

$$\text{Consumption.IFO} = \text{Base.Consumption.IFO} \cdot \left( \frac{\text{Operating Speed}}{\text{Base Speed}} \right)^3 \quad (32)$$

Where *Base.Consumption.IFO* is the IFO consumption at a base speed and *Consumption.IFO* is the IFO consumption at the operating speed, both [t / day].

Estimate the base fuel consumption it is an issue, because the tool needs it related to the ship size [TEU] but there is no direct physical correlation between the two variable. However one can use empirical relations in these cases. Murray does, so when he displays the relation between IFO consumption per TEU [t / day] and the vessel's capacity (Figure 42).

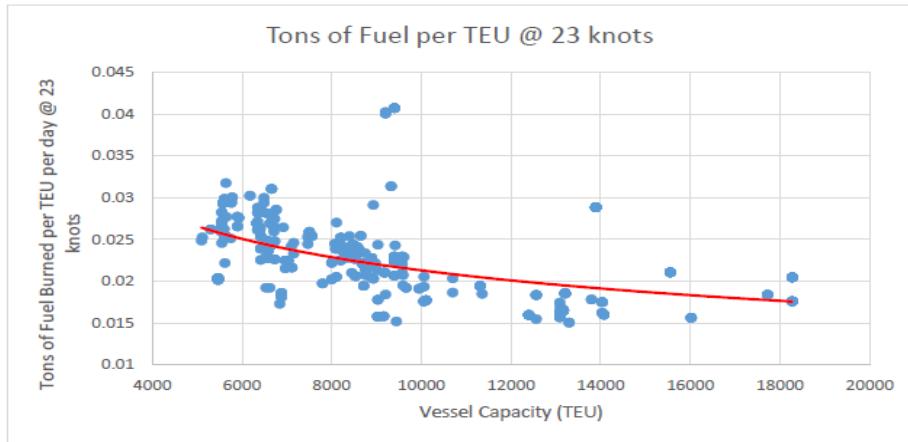


Figure 42 – HF Consumption at 23 knots [t per day per TEU] over The Ship Size [TEU] (Murray, 2015).

Extrapolating the data trend from Figure 42, one arrives at the daily fuel consumption at 23 knots as a function of the ship size, shown in Figure 43.

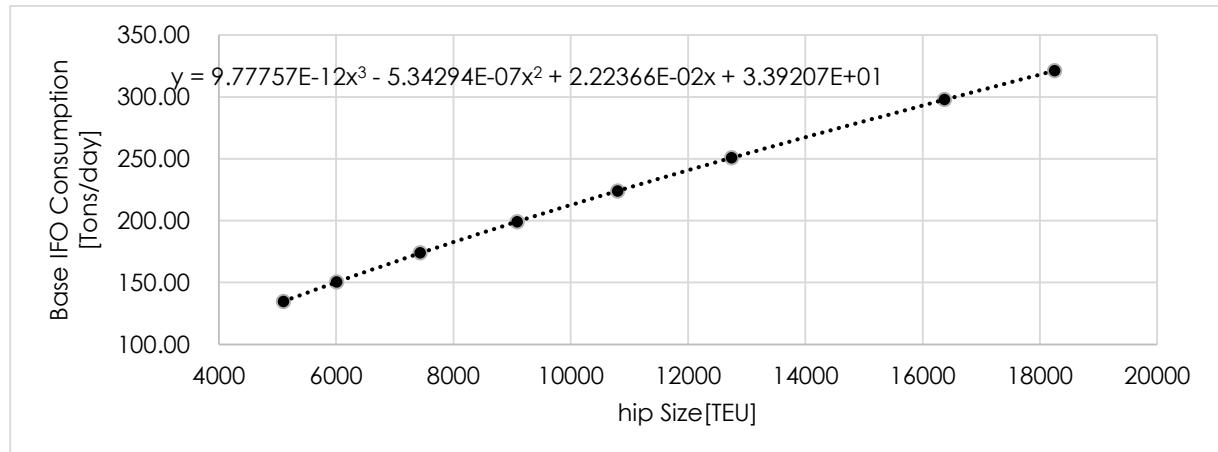


Figure 43 – Extrapolated Base IFO Consumption (at 23 knots) [t/day] over the Ship Size [TEU] (Murray, 2015)

Setting the base speed at 23 knots and with the base consumption to that speed, it is possible to derive the following equations, which are the formulas for the fuel consumption:

$$\text{Consumption.IFO} = \text{Base.IFO.Consumption}(x) \cdot \left( \frac{\text{Operating.Speed}(x)}{23} \right)^3 \quad (33)$$

$$\begin{aligned} \text{Base.IFO.Consumption}(x) = & 9.77757 \cdot 10^{-12} \cdot x^3 - 5.34294 \cdot 10^{-7} \cdot x^2 + 0.022236 \cdot x + \\ & 33.9207 \end{aligned} \quad (34)$$

Where  $x$  is the *Ship.Size* [TEU].

Combining Equations 33 and 34 and adding a thirty percent margin of error (estimated from the data in Figure 42) returns the IFO consumptions for the expected, maximum, and minimum cost scenarios:

$$\begin{aligned} \text{EU.IFO.Cons} = & (1.2710 \cdot 10^{-11} \cdot x^3 - 6.94582 \cdot 10^{-7} \cdot x^2 + 0.0289068 \cdot x + 44.969) \cdot \\ & \left( \frac{\text{Operating.Speed}(x)}{23} \right)^3 \end{aligned} \quad (35)$$

$$\begin{aligned} \text{IFO.Cons} = & (9.77757 \cdot 10^{-12} \cdot x^3 - 5.34294 \cdot 10^{-7} \cdot x^2 + 0.022236 \cdot x + 33.9207) \cdot \\ & \left( \frac{\text{Operating.Speed}(x)}{23} \right)^3 \end{aligned} \quad (36)$$

$$\begin{aligned} \text{ED.IFO.Cons} = & (6.84430 \cdot 10^{-12} \cdot x^3 - 3.74006 \cdot 10^{-7} \cdot x^2 + 0.0155652 \cdot x + 23.7445) \cdot \\ & \left( \frac{\text{Operating.Speed}(x)}{23} \right)^3 \end{aligned} \quad (37)$$

Where *IFO.Cons* is the expected value for the IFO consumption [t/day], *U.IFO.Cons* is the upper value, *L.IFO.Cons* the lowest,  $x$  is the *Ship.Size* [TEU], and *Service.Speed* is the current service speed of the vessel [kn].

Since the aim of the generators is to produce the electric power required by the vessel, the MDO consumption is modelled as a function of the electric requirements of the vessel. Chiefly, there are three consumers of power: the ship, the reefer containers, and the cranes:

$$\text{Consumption.MDO} = \text{Base.Cons.MDO} + \text{Reefer.Cons.MDO} + \text{Crane.Cons.MDO} \quad (38)$$

Where, *Consumption.MDO* is the total MDO consumed by a vessel in a day [t], *Base.Cons.MDO* is the daily consumption for the base electrical needs of the ship [t], *Reefer.Cons.MDO* is the daily consumption for the electrical needs of the transported reefer containers [t], and *Crane.Cons.MDO* is the daily consumption for the electrical usage of the cranes [t].

Concerning the *Base.Cons.MDO*, the ship has a base requirement of energy which is used to power most of the systems (e.g., navigation, communications, ballast, fuel). These system are vital to the ship and must be active whenever the vessel is operating. This consumption of energy is thus fixed throughout the whole round voyage, as given by the following equation:

$$\text{Base.Cons.MDO} = 24 \cdot \text{Gen.Sp.Cons} \cdot \text{Base.Electric.Power} \quad (39)$$

Where, *Base.Cons.MDO* is a daily consumption [t], the value 24 is in hours, *Base.Electric.Power* is the base electrical power for the ships systems [kW], *Gen.Sp.Cons* is the specific consumption of the generators [t / kWh].

To estimate the *Base.Electric.Power*, the tool makes one assumes the base electric powers of the vessel are as in Equations 40 and 41. This assumption comes from Santos, where it is stated that vessels, in normal operation, usually have one of its generators on standby (this is not the additional emergency generator required by safety regulations) and that work on half the capacity of the remaining (Santos, 2016).

$$\text{Base.Electric.Power}(x) = \text{Av.Gen.Power}(x) \cdot (\text{Nr.Gen} - 1) \cdot 0.5 \quad (40)$$

$$\text{Av.Gen.Power}(x) = \frac{\text{ElP}}{\text{Nr.Gen}} \quad (41)$$

Where, *Av.Gen.Power* is the average power of a generator [kW], *ElP* is the combined electrical power of all generators [kW], and *Nr.Gen* is the number of generators on board. The latter two are ship characteristics estimated in previous sections.

Concerning the consumption of the cranes, Santos (2018) contains both the values for the number of cranes on board and for the consumption of cranes in specific vessels (Table 3).

Ship Size [TEU]	Nr Cranes	Total Crane Consumption [t / day]	Average moves per hour	Crane Consumption per movement [t]
2 550	4	2.4	15	0.001 667
1 700	3	1.2	15	0.001 111

Table 3 – MDO Consumption of cranes.

Thus, the consumption from cranes is calculated with Equation 42.

$$\text{Reefer.Cons.MDO} = \text{CCpM} \cdot \text{Nr.Cont.Handled} \quad (42)$$

Where, *CCpM* is the average crane consumption per container handled [t], and *Nr.Cont.Handled* is the number of containers handled.

The consumption from the reefer containers is given by:

$$\text{Reefer.Cons.MDO}(x) = 24 \cdot \text{Gen.Sp.Cons} \cdot \text{Total.Reefer.Power} \quad (43)$$

Where, *Total.Reefer.Power* is the power required for reefer containers over the round voyage [kWh].

The *Total.Reefer.Power* is estimated as the average power required by the reefer containers in each hour transported voyage (Equation 44):

$$\text{Total.Reefer.Power} = \sum_{i=1}^{NCalls-1} \left( (\text{Power.RET} \cdot \text{Nr.RET}_i + \text{Power.REF} \cdot \text{Nr.REF}_i) \cdot \left( \frac{\text{LDist}_i}{\text{Operating.Speed}} + 0.5 \cdot (\text{TPRV}_i + \text{TPRV}_{i+1}) \right) \right) \quad (44)$$

Where, *Power.RET* is the power consumed by a reefer TEU container [kW], *Power.REF* is the power consumed by a reefer FEU container [kW], *Nr.RET<sub>i</sub>* is the number of TEU reefer container in the voyage leg from the *i*<sup>th</sup> and the (*i*+1)<sup>th</sup> calls of the round voyage, *Nr.REF<sub>i</sub>* is the number of FEU reefer container in that leg of the voyage, *LDist<sub>i</sub>* is the sailing distance in that leg, *TPRV<sub>i</sub>* is the time spent in the *i*<sup>th</sup> call, and *LDist<sub>i</sub>/Operating.Speed + 0.5 (TPRV<sub>i</sub> + TPRV<sub>i+1</sub>)* is the time the containers consume energy during that leg [h] (which includes the sailing time and half the time in both ports).

As for the price of a ton of MDO and of IFO, these are a user inputs. Notteboom and Vernimmen note on the irregularity of the bunker indexes which render any predictions unreliable (Notteboom & Vernimmen, 2009). Further complicating the matter, bunker prices vary from port to port, and so it is best to let the user input the prices he sees fit. According to Bunker Index in August 2018, IFO380 costs 485 [USD / t], IFO180 costs 502 [USD / t], with an average of 494 [USD / t], and MDO costs 667 [USD / t] (Bunker Index, 2018).

### 3.4.3.3. Canal Costs

The costs of canals are given by Equation 45. The number of crossings is estimated from the round voyage and the cost per crossing is an input.

$$\text{Total.Costs.Canals} = (\text{Costs.Canal}_i \cdot \text{Nr.Crossings}_i) \cdot \frac{(365 - \text{Off.Hire})}{\text{TFRV}} \quad (45)$$

Where, *Total.Costs.Canals* is the annual costs with canals [USD], *Costs.Canal<sub>i</sub>* is the crossing price for the canal *i* [USD], *Nr.Crossings<sub>i</sub>* is the number of times a vessel crosses the canal in a round voyage, and *TFRV* is the duration of the round voyage [day].

### 3.4.4. Revenues

The revenues are calculated with the following equation:

$$YRevenues = \sum_i FR_i \cdot NCont_i \quad (46)$$

Where, *FR<sub>i</sub>* is the freight rate of containers of the type *i*, *NCont<sub>i</sub>* is the number of containers of type *i* carried in a year, and *YRevenue* is the yearly revenue [USD]. Note that type *i* refers to both the kind of container (TEU or FEU, regular or reefer, and empty or full) and to pair the destination and origin of the cargo. These are all user inputs.

Note that the freight rates, as charged in the real market, may not include cargo handling costs. Those that do are called all-inclusive freight rates. If the inputs of the data in ports include the cargo handling charges in the ports, then the freight rates must be all inclusive, else they must not.

### 3.5. PERFORMANCE INDICATORS

The Net Profit, which is the annual profit of the fleet [USD], is given by the following equation:

$$NP = TRev - TExp \quad (47)$$

Where,  $NP$  is the net profit,  $TRev$  is the annual revenues, and  $TExp$  is the total annual expenses. All in [USD].

The net Profit Margin, which is the ratio of profit over revenues, is in the following equation:

$$NPM = \frac{NP}{TRev} \quad (48)$$

Where, the  $NPM$  is the net profit margin,  $NP$  is the net profit [USD], and  $TRev$  is the total income [USD].

Equations 49 and 50 are the formulas for the annual cost per TEU ( $CpTEU$ ) and for the annual cost per mile ( $CpMile$ ), respectively.

$$CpTEU = \frac{TExp}{Nr.TEU.H} \quad (49)$$

$$CpMile = \frac{TExp}{TDist} \quad (50)$$

Where,  $Nr.TEU.H$  is the number of TEUs carried by a vessel in a year, and  $TDist$  is the total distance sailed in miles.

The buffer time and the buffer ratio are given by:

$$BufferT = TFRV - TRV \quad (51)$$

$$BufferR = \frac{BufferT}{TFRV} \quad (52)$$

Where,  $BufferT$  is the buffer time [h],  $TFRV$  is the time of the round voyage, as set by the user [h];  $TRV$  is the minimum time a vessel requires to complete the round voyage (includes sailing time, port time, cargo handling time, and canal time), and  $BufferR$  is the buffer ratio.

### 3.6. ALGORITHM

The algorithm is implemented in FORTRAN95, which allows for subroutines, which are just functions which are called by the main script and allows for reading and writing in text files. The input files are explained in the User Manual (Appendix I) and the subroutines are not detailed in the dissertation (the exception being the cargo distribution algorithm). Therefore, the aim of this subsection is to expose the broad strokes of the code: the main script, the subroutines, the input files, and how each is used in the tool (see Figure 44 for a schematic summary).

The main script of the tool is the ‘Main\_Code’. This section of the code does not calculate any values, it simply reads the voyages’ data and uses it in the other subroutines. It runs the ‘Input\_Verifier’ once, and then the ‘Fleet\_Designer’ and the ‘Restriction\_Verifier’ for an inputted number of vessels in the fleet for all the inputted round voyages.

The ‘Input\_Verifier’ is a subroutine which verifies the inputs. A wrongly inputted input may cause the code to either break or just yield a wrong output. To safeguard this, the subroutine opens all the input files and checks every input. There are two kinds of errors in inputting: those which cause the tool to stop, and those who do not. In the event, there is a crashing error, the subroutine continually displays messages, so that the user can know which input the code was checking when the error occurred (e.g., if a cargo flow is negative or the term of the loan is not an integer). An inputting error which doesn’t cause the code to break prompts the tool to display a warning, informing the user that some input is not as expected, but the tool keeps running. For example, if the price of calling at a port is negative a warning appear, since ports do not usually pay for ship calls, but it could well be a part of some odd pricing scheme the user may have and thus this subroutine allows them.

The heart of the code is in the ‘Fleet\_Designer’ subroutine. It receives the round voyage and the number of ships in the fleet from ‘Main\_Code’ and the input files from the user and calculates the required ship size, the ship characteristics, the annual costs, the performance indicators, and the cargoes in each leg of the round voyage. This subroutine writes two output files: the principal is the ‘Output\_File.txt’, and the secondary is the ‘Output\_File\_2.txt’. The purpose of the secondary output file is to store the cargo in legs matrices, which are later read and written in the primary output file in the order that is desired.

The subroutine ‘Restriction\_Verifier’ is responsible for reading, from the input files, the size (length, breadth, and draft) restrictions in every port and canal. Then, it compares them with the maximum length overall, the maximum breadth, and the maximum draft. Since the latter are the maximum value of those characteristics that a vessel can take, it is very likely that the real vessel has a smaller length overall, breadth, and draft than the maximums. Thus, if maximum draft calculated is superior to the maximum draft allowed in a certain port, the only thing one can conclude is that there is a risk that the ship may not dock at that port. Since it is only a possibility the ‘Restriction\_Verifier’ does not break the calculations, instead informing the user of these situations and displaying the possibly problematic port or canal along the maximum dimension it allows. The user is then advised to consider these restriction on a case by case basis.

For more details on the input files and on the interpretation of the outputs, please consult the User manual in Appendix I.

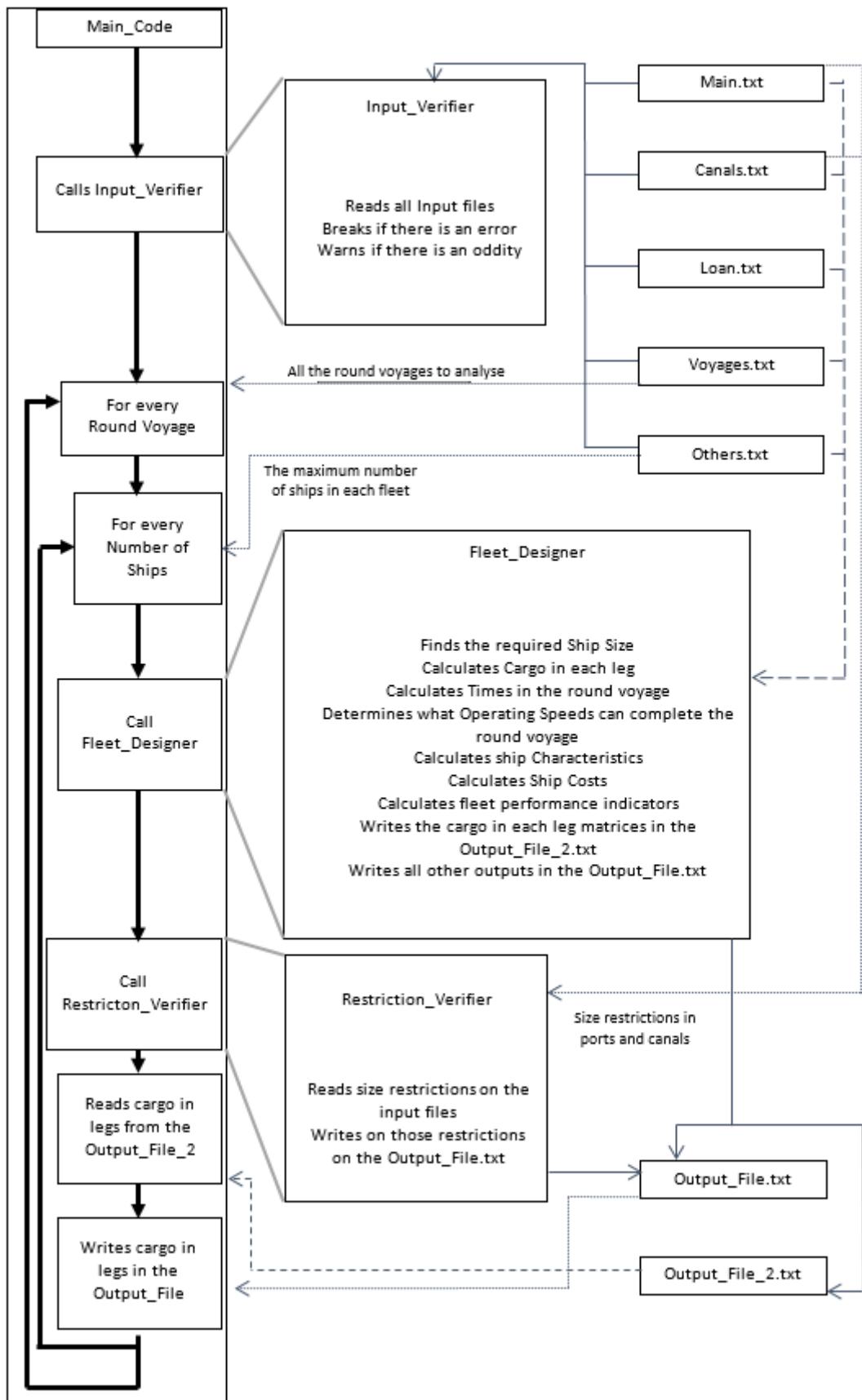


Figure 44 – Conceptual diagram of the tool's algorithm.

## 4. NUMERICAL RESULTS

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### 4.1. TESTS OF THE TOOL

This section is dedicated to an essential step in the development of the tool: the trials. Within the context of this dissertation, the aim of these tests is to prove that the tool produces the correct output. In the development of the code, the aim of testing is to identify faulty results, so that one knows what needs to be corrected.

When verifying a model it is common practice to compare the results of that model with some known results. That approach taken by means of handmade trials. This section presents the three random trials used to validate the tool.

Each of the trials consists of four steps. First, the inputs are set by means of a spreadsheet and a random number generator. Second, the inputs are manually processed, as described in the methodology, to generate the handmade results. Thirdly, the inputs are processed by the tool to obtain the tool outputs. Finally, the handmade outputs are compared to the tool outputs to verify the results. This comparison is done with the smallest number of vessels and at the top operating speed at which the voyage may be completed.

The inputs of the trial are defined according to these rules. The trials use only full Reefer TEU containers, since the algorithmic procedures of cargo distribution for full Reefer TEUs are exactly the same for all other container types and with reefer containers allows to verify the MDO consumption. The round voyages are in-between five ports, which are designated by three letters and identified by an integer: TPA is port 1 (TPA means Trial Port A), TPB is port 2, TPC is port 3, TPD is port 4, and TPE is port 5. The round voyages are set by using the random number generator to generate strings of twenty ports and then removing repeating consecutive ports. The duration of the round voyage is set to one year.

The entries of cargo flow matrices are randomized in the following manner: if the entry is in the diagonal (i.e., from port n to that same port n) it takes the value of 0; if not, then the entry has a 0.2 chance of taking the value of 1000, a 0.2 chance of being 600, a 0.4 chance of being 300, and 0.2 chance of being 0.

The port characteristics (see Chapter III. Methodology for the full description of the variables) are randomized integers:  $DNavp_i$  ( $i$  is the port identifier in the code) is between 0 and 50 nautical miles;  $SpNavp_i$  is between 5 and ten;  $MNGant_i$  is between 0 and 3;  $GantProd_i$  is between 15 and 25;  $Tep$  is between 5 and 20;  $Tfp$  is between 1 and 4;  $Fixed_i$  is between 1000 and 5000;  $Size_i$  is between 2 and 5;  $Tonn_i$  is between 2 and 5;  $Time_i$  is between 50 and 200;  $Cargo_i$  is between 20 and 120;  $Lr_i$  is between 200 and 400;  $Br_i$  is between 10 and 25; and  $Tr_i$  is between 12 and 16. The distances in-between ports are random integer between 100 and 2000 nautical miles. The freight rates in-between ports are random integers between 100 and 500 USD per container. The loan values are random integers:

*Loan\_Value* is between 0.5 and 0.9; the *Term\_of\_Loan* is between 5 and 15 years; *Inflation* is between 1% and 5%; *Interest* is between 2% and 10 %, and the *DRate* between 3% and 10%. The port characteristics are: the distance of navigation within the port (*DNavp*), the speed of navigation within the port (*SpNavp*), the number of gantry cranes which will be available in the port (*MNGant*), average crane productivity in moves per hour (*GantProd*), waiting time in port (*Tep*), the time for formal procedures (*Tfp*), the fee per call in that port (*Fixed\_i*), the fee per ship capacity (*Size\_i*), the fee per vessel tonnage (*Tonn\_i*), the fee per hour in berth (*Time\_i*), the fee per TEU handled (*Cargo\_i*), the length restriction at port (*LR*), the breadth restriction (*BR*), the draft restriction (*TR*), and the distance to every other port. The canals characteristics are: the crossing time (*Canal.Time*), the crossing cost coefficients ( $a, b, c, d$ , and  $e$ ), the length restriction (*LR*), the breadth restriction (*BR*), the draft restriction (*TR*), and in which legs it will be crossed.

There are two canals: one between port 3 and port 4, and another between ports 1 and 2 on one side and ports 3, 4, and 5 on the other. In both canals the price of crossing is a fixed random integer between 10 000 and 20 000, the time of crossing is a random integer between 10 and 30 hours, and size restriction are set as those in the ports.

Tables 4 to 10 contain the input data for the three trials.

	0	600	0	300	300		0	1000	0	0	300
1st trial	300	0	0	1000	600		600	0	300	300	600
	0	300	0	1000	600		0	300	0	1000	1000
	0	600	0	0	300		300	1000	600	0	600
	0	600	300	600	0		0	600	300	300	0
2nd trial	0	300	300	1000	0		0	0	600	300	300
	0	0	0	600	300		300	600	0	1000	300
	300	600	0	1000	300		300	1000	600	0	600
	300	1000	0	0	300		300	300	600	0	300
	300	300	300	600	0		300	300	600	0	300

Table 4 – Cargo flow matrices for the trials.

1st trial	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
2nd trial	2	3	5	3	4	3	2	4	3	1	1	5	3	2	4	2
3rd trial	5	3	1	2	4	3	4	2	1	3	2	5	3	1	4	3

Table 5 – Round voyages for the trials.

	Loan value	Term of the Loan [years]	Interest rate [%]	Inflation [%]	Discount Rate [%]
1st Trial	0.86	6	10.00	4.00	8.00
2nd Trial	0.80	6	7.00	4.00	5.00
3rd Trial	0.86	6	8.00	3.00	7.00

Table 6 – Loan data for the three trials.

	<i>DNavp_i</i>	<i>SpNavp_i</i>	<i>MNGant_i</i>	<i>GantProd_i</i>	<i>Tep_i</i>	<i>Tfp_i</i>	<i>Fixed_i</i>	<i>Size_i</i>	<i>Ton_i</i>	<i>Time_i</i>	<i>Cargo_i</i>	<i>Lr_i</i>	<i>Br_i</i>	<i>Tr_i</i>
1 <sup>st</sup> Trial	16	10	1	23	18	5	4562	4	3	149	43	392	14	13
	33	10	3	22	18	5	2164	4	5	15	90	326	25	15
	41	7	3	20	9	5	1806	3	5	6	100	306	18	16
	11	6	2	16	6	5	4791	4	5	139	107	350	25	16
	36	6	3	25	14	5	2952	4	3	68	70	317	23	14
2 <sup>nd</sup> Trial	33	6	2	16	9	5	1350	3	4	116	26	361	12	14
	8	6	3	16	13	5	1213	5	4	130	61	314	14	13
	10	6	2	18	18	5	1812	4	3	40	92	312	16	16
	4	6	1	25	14	5	3639	5	5	19	106	277	24	15
	19	10	2	21	10	5	2316	5	3	128	25	348	18	13
3 <sup>rd</sup> Trial	36	7	1	25	19	3	1280	3	5	25	69	281	20	14
	6	9	2	21	20	3	3485	5	4	106	69	221	24	15
	48	6	1	17	14	3	4146	4	4	122	119	251	18	15
	40	7	2	16	10	5	1297	5	5	99	81	294	16	13
	38	6	2	17	18	5	2170	4	5	152	49	313	12	14

Table 7 – Port Characteristics for the trials.

1 <sup>st</sup> Trial	0	1920	602	764	133	3 <sup>rd</sup> Trial	0	621	907	303	1029
	943	0	531	639	264		954	0	1616	975	799
	1800	1722	0	1294	926		1570	1261	0	1390	1855
	1848	490	944	0	1905		1052	1985	1102	0	171
	1249	1596	156	813	0		1574	1593	472	984	0
2 <sup>nd</sup> Trial	0	124	250	1871	953						
	572	0	883	1868	967						
	164	1472	0	444	223						
	479	530	1741	0	1518						
	212	1901	631	1639	0						

Table 8 – Leg Distances [nautical miles] for the trials.

1 <sup>st</sup> Trial	0	781	1771	754	1501	3 <sup>rd</sup> Trial	0	1880	1419	1833	878
	1795	0	1137	1340	1649		960	0	1037	875	841
	1611	980	0	1905	572		1543	732	0	1881	1748
	606	1818	1302	0	1557		800	1051	876	0	1992
	1187	1687	1679	1077	0		903	1629	739	1940	0
2 <sup>nd</sup> Trial	0	587	1404	1828	828						
	1235	0	1244	553	714						
	1051	950	0	837	939						
	986	1566	1724	0	1191						
	1218	1376	1891	706	0						

Table 9 – Freight Rates for the trials.

1 <sup>st</sup> Trial	Time	Costs	Lr	Br	Tr
1 <sup>st</sup> Canal	21	17679	243	11	16
2 <sup>nd</sup> Canal	12	12917	300	12	15
2 <sup>nd</sup> Trial	Time	Costs	Lr	Br	Tr
1 <sup>st</sup> Canal	18	12704	268	19	14
2 <sup>nd</sup> Canal	22	16043	398	11	14
3 <sup>rd</sup> Trial	Time	Costs	Lr	Br	Tr
1 <sup>st</sup> Canal	28	16017	395	14	13
2 <sup>nd</sup> Canal	22	10525	211	17	13

Table 10 – Canal Data for the trials.

The results of the three trials are below, Tables 11 to 13 contain the handmade outputs and Figures 45 to 47 the results of the tool. For each trial the CiL matrix was produce by hand and compared with the tool’s cargo distribution. In Appendix II is the step by step production of the CiL matrix of the first trial.

Ship Size	1900	Speed	24	
Performance Indicators	Maximum	Expected	Minimum	Costs [10 <sup>6</sup> USD]
Net Profit [million USD]	-6.144	-3.486	-1.259	Operational 3.246 2.829 2.439
Net Profit Margin [%]	-62	-35	-12	Capital 5.126 3.260 1.787
Cost per Handled TEU	2346	1955	1627	Port 3.301 3.301 3.301
Cost per Mile	929	774	645	Canal 0.165 0.165 0.165
With No Purchase				Fuel 4.114 3.737 3.375
Net Profit [million USD]	-1.018	-0.225	0.526	Total 15.950 13.293 11.066
Net Profit Margin [%]	-10	-2	5	Voyage 7.579 7.203 6.841
Cost per Handled TEU	1592	1475	1365	Revenues 9.806
Cost per Mile	631	584	541	
Buffer Time [h]	6870	Buffer Ratio [%]	81.77	
Shipbuilding Costs [million USD]	49.168	31.716	17.928	
Length between perpendiculars [m]	180	Lightweight [t]	9500	Warnings on Restrictions:
Average Breadth [m]	27			Breadth restrictions in both canals
Average Depth [m]	15	Displacement [t]	36000	Breadth restrictions in all ports
Draft [m]	12			
Gross Tonnage	20500	Number of Generators	4	Time of Round Voyage [days] 350
Net Tonnage	10800			Time in ports (no cargo) [%] 4.19
Main Engine Power [kW]	17200	Number of Cranes	3	Time for cargo handling [%] 3.60
Generator Power [kW]	4200			Time in Canals [%] 1.93
Fuel Capacity [m <sup>3</sup> ]	2800			Time Sailing [%] 8.51
Ballast Capacity [m <sup>3</sup> ]	8900			Buffer Ratio [%] 81.92

Table 11 – Handmade Outputs of the first trial.

Ship Size	2900	Speed	25	
Performance Indicators	Maximum	Expected	Minimum	Costs [10 <sup>6</sup> USD]
Net Profit [10 <sup>6</sup> USD]	-12.78	-9.659	-7.036	Operational 3.829 3.319 2.843
Net Profit Margin [%]	-232	-1759	-1281	Capital 6.119 3.895 2.123
Cost per Handled TEU	3888	3224	2666	Port 3.545 3.545 3.545
Cost per Mile	1416	1174	971	Canal 0.211 0.211 0.211
With No Purchase				Fuel 4.567 4.181 3.806
Net Profit [10 <sup>6</sup> USD]	-6.660	-5.764	-4.913	Total 18.27 15.15 12.53
Net Profit Margin [%]	-121	-105	-89	Voyage 8.323 7.937 7.562
Cost per Handled TEU	2586	2395	2214	Revenues 5.492
Cost per Mile	941.6	872.1	806	
Buffer Time [h]	7009	Buffer Ratio [%]	83.44	
Shipbuilding Costs [10 <sup>6</sup> USD]	66.30	43.14	24.69	Warnings on Restrictions
Length between perpendiculars [m]	220	Lightweight [t]	13200	Breadth restrictions in both canals
Average Breadth [m]	31			Breadth restrictions in all ports
Average Depth [m]	18	Displacement [t]	52000	Draft restrictions TPB and TPE
Draft [m]	13			
Gross Tonnage	31400	Number of Generators	4	Time of Round Voyage [days] 350
Net Tonnage	16500			Time in ports (no cargo) [%] 4.45
Main Engine Power [kW]	26200	Number of Cranes	3	Time for cargo handling [%] 2.49
Generator Power [kW]	5900			Time in Canals [%] 3.48
Fuel Capacity [m <sup>3</sup> ]	4400			Time Sailing [%] 6.15
Ballast Capacity [m <sup>3</sup> ]	12100			Buffer Ratio [%] 83.44

Table 12 – Handmade Outputs of the second trial.

Ship Size	2500	Speed	24	
Performance Indicators	Maximum	Expected	Minimum	Costs [10 <sup>6</sup> USD]
Net Profit [10 <sup>6</sup> USD]	-7.126	-4.338	-1.974	Operational 3.614 3.138 2.694
Net Profit Margin [%]	-66	-40	-19	Capital 5.042 3.208 1.752
Cost per Handled TEU	2142	1810	1528	Port 3.886 3.889 3.886
Cost per Mile	952	804	679	Canal 0.116 0.116 0.116
With No Purchase				Fuel 5.332 4.853 4.389
Net Profit [10 <sup>6</sup> USD]	-2.084	-1.130	-0.222	Total 17.99 15.20 12.84
Net Profit Margin [%]	-20	-11	-2	Voyage 9.334 8.855 8.391
Cost per Handled TEU	1541	1428	1320	Revenues 10.86
Cost per Mile	685	634	586	
Buffer Time [h]	6654	Buffer Ratio [%]	79.22	Warnings on Restrictions
Shipbuilding Costs [10 <sup>6</sup> USD]	59.70	38.73	22.07	Breadth restrictions in both canals
Length between perpendiculars [m]	210	Lightweight [t]	11700	Breadth restrictions in all ports
Average Breadth [m]	29	Lightweight [t]	11700	Draft restrictions at port TPB
Average Depth [m]	17	Displacement [t]	45600	Length restrictions at port TPB
Maximum Draft [m]	13			Length restrictions in the second canal
Gross Tonnage	27000	Number of Generators	4	Draft restriction on both canals
Net Tonnage	14200	Number of Generators	4	
Main Engine Power [kW]	22600	Number of Cranes	3	Time of Round Voyage [h] 350
Generator Power [kW]	5200			Time in ports (no cargo) [%] 4.20
Fuel Capacity [m <sup>3</sup> ]	3800			Time for cargo handling [%] 4.44
Ballast Capacity [m <sup>3</sup> ]	10900			Time in Canals [%] 2.76
				Time Sailing [%] 9.38
				Buffer Ratio [%] 79.22

Table 13 – Handmade Outputs of the third trial.

Fleet Size	1 Ships with	1900.00	TEUs	
	For this cruise speed	24.0000	[kn]	
	For these cost scenarios	Maximum	Expected	Minimum
	Performance Indicators			
	For the whole fleet every year			
	Net Profit	-6144000	-3486000	-1259000 [USD]
	Net Profit Margin [%]	-62	-35	-12 [ ]
	Cost per TEU Handled	2346	1955	1628 [USD]
	Cost per Mile Sailed	930	775	645 [USD]
	Net Profit (without ship purchase)	-1018000	-225000	527000 [USD]
	Net Profit Margin (without ship purchase) [%]	-10	-2	6 [ ]
	Cost per TEU Handled (without ship purchase)	1592	1476	1365 [USD]
	Cost per Mile Sailed (without ship purchase)	631	585	541 [USD]
	Buffer Time (per vessel, per RV)	6870	[h]	
	Buffer Ratio	81.7730	[%]	
	Ship Costs			
	For one ship every year			
	Operating Costs	3246000	2830000	2440000 [USD]
	Capital Costs	5126000	3261000	1787000 [USD]
	Port Costs	3302000	3302000	3302000 [USD]
	Fuel Costs	4114000	3738000	3376000 [USD]
	Canal Costs	165000	165000	165000 [USD]
	Total Costs	15951000	13293000	11067000 [USD]
	Voyage Costs	7580000	7203000	6841000 [USD]
	Revenue	9807000	[USD]	
	Other Characteristics			
	Shipbuilding Cost	49169000	31717000	17929000 [USD]
Length Between Perpendiculars	180 [m]		Average Breadth	27 [m]
Average Depth	15 [m]		Maximum Draft	12 [m]
Gross Tonnage	20500 [ ]		Net Tonnage	10800 [ ]
Number of Cranes	3 [ ]		Number of Generators	4 [ ]
Main engine power	17200 [kW]		Generator Power	4200 [kW]
Lightship weight	9500 [tons]		Displacement	36000 [tons]
Fuel Capacity	2800 [cub. m]		Balast Capacity	8900 [cub. m]
	Time of a round voyage	350.000	[days]	
Time in ports (not including cargo handling)	4.18700	[ % ]		
Time handling cargo	3.59800	[ % ]		
Time in Canals	1.92900	[ % ]		
Sailing Time	8.51500	[ % ]		
Buffer Time	81.7730	[ % ]		

Attention: The ships might not comply with the breadth restrictions of the following ports:

TPA	14
TPB	25
TPC	18
TPD	25
TPE	23

Attention: The ships might not comply with the breadth restrictions of the following Canals:

1st Canal	11
2nd Canal	12

Figure 45 – Tool Outputs of the first trial.

Main results

Fleet Size	1 Ships with	2900.00	TEUs	
	For this cruise speed	25.0000	[kn]	
	For these cost scenarios	Maximum	Expected	Minimum
	Performance Indicators			
	For the whole fleet every year			
	Net Profit	-12779000	-9658000	-7036000 [USD]
	Net Profit Margin [%]	-232	-175	-128 [ ]
	Cost per TEU Handled	3888	3224	2666 [USD]
	Cost per Mile Sailed	1416	1174	971 [USD]
	Net Profit (without ship purchase)	-6660000	-5763000	-4913000 [USD]
	Net Profit Margin (without ship purchase) [%]	-121	-104	-89 [ ]
	Cost per TEU Handled (without ship purchase)	2586	2395	2214 [USD]
	Cost per Mile Sailed (without ship purchase)	942	873	807 [USD]
	Buffer Time (per vessel, per RV)	7010	[h]	
	Buffer Ratio	83.4370	[%]	
	Ship Costs			
	For one ship every year			
	Operating Costs	3830000	3319000	2843000 [USD]
	Capital Costs	6120000	3896000	2124000 [USD]
	Port Costs	3545000	3545000	3545000 [USD]
	Fuel Costs	4568000	4181000	3807000 [USD]
	Canal Costs	212000	212000	212000 [USD]
	Total Costs	18272000	15151000	12529000 [USD]
	Voyage Costs	8323000	7937000	7563000 [USD]
	Revenue	5492000	[USD]	
	other Characteristics			
	Shipbuilding Cost	66302000	43141000	24693000 [USD]
Length Between Perpendiculars	220 [m]		Average Breadth	31 [m]
Average Depth	18 [m]		Maximum Draft	13 [m]
Gross Tonnage	31400 [ ]		Net Tonnage	16500 [ ]
Number of Cranes	3 [ ]		Number of Generators	4 [ ]
Main engine power	26200 [kW]		Generator Power	5900 [kW]
Lightship weight	13200 [tons]		Displacement	52000 [tons]
Fuel Capacity	4400 [cub. m]		Balast Capacity	12100 [cub. m]
	Time of a round voyage	350.000	[days]	
Time in ports (not including cargo handling)	4.45500	[ % ]		
Time handling cargo	2.48700	[ % ]		
Time in Canals	3.47700	[ % ]		
Sailling Time	6.14600	[ % ]		
Buffer Time	83.4370	[ % ]		

Attention: The ships might not comply with the breadth restrictions of the following ports:

TPA 12  
TPB 14  
TPC 16  
TPD 24  
TPE 18

Attention: The ships might not comply with the draft restrictions of the following ports:

TPB 13  
TPE 13

Attention: The ships might not comply with the breadth restrictions of the following Canals:

1st Canal 11  
2nd Canal 19

Figure 46 – Tool Outputs of the second trial.

Fleet Size	1 Ships with	2500.00	TEUS	
	For this cruise speed	24.0000	[kn]	
	For these cost scenarios	Maximum	Expected	Minimum
	Performance Indicators			
	For the whole fleet every year			
	Net Profit	-7124000	-4336000	-1971000 [USD]
	Net Profit Margin [%]	-65	-39	-18 [ ]
	Cost per TEU Handled	2142	1810	1528 [USD]
	Cost per Mile Sailed	952	804	679 [USD]
	Net Profit (without ship purchase)	-2082000	-1127000	-220000 [USD]
	Net Profit Margin (without ship purchase) [%]	-19	-10	-2 [ ]
	Cost per TEU Handled (without ship purchase)	1541	1428	1320 [USD]
	Cost per Mile Sailed (without ship purchase)	685	635	587 [USD]
	Buffer Time (per vessel, per RV)	6660	[h]	
	Buffer Ratio	79.2200	[%]	
	Ship Costs			
	For one ship every year			
	Operating Costs	3614000	3139000	2694000 [USD]
	Capital Costs	5042000	3209000	1752000 [USD]
	Port Costs	3886000	3886000	3886000 [USD]
	Fuel Costs	5330000	4851000	4387000 [USD]
	Canal Costs	117000	117000	117000 [USD]
	Total Costs	17988000	15199000	12835000 [USD]
	Voyage Costs	9332000	8853000	8389000 [USD]
	Revenue	10863000	[USD]	
	Other Characteristics			
	Shipbuilding Cost	59697000	38726000	22069000 [USD]
Length Between Perpendiculars	205 [m]		Average Breadth	29 [m]
Average Depth	17 [m]		Maximum Draft	13 [m]
Gross Tonnage	27000 [ ]		Net Tonnage	14200 [ ]
Number of Cranes	3 [ ]		Number of Generators	4 [ ]
Main engine power	22600 [kW]		Generator Power	5200 [kW]
Lighthship weight	11700 [tons]		Displacement	46000 [tons]
Fuel Capacity	3800 [cub. m]		Balast Capacity	10900 [cub. m]
Time of a round voyage	350.000	[days]		
Time in ports (not including cargo handling)	4.19700	[ % ]		
Time handling cargo	4.44500	[ % ]		
Time in Canals	2.76200	[ % ]		
Sailing Time	9.37700	[ % ]		
Buffer Time	79.2200	[ % ]		

Attention: The ships might not comply with the length restrictions of the following ports:

TPB 221

Attention: The ships might not comply with the breadth restrictions of the following ports:

TPA 20

TPB 24

TPC 18

TPD 16

TPE 12

Attention: The ships might not comply with the draft restrictions of the following ports:

TPD 13

Attention: The ships might not comply with Length Restrictions in the following Canals:

Second Canal 211

Attention: The ships might not comply with the breadth restrictions of the following Canals:

Second Canal 17

First Canal 14

Attention: The ships might not comply with the draft restrictions of the following Canals:

Second Canal 13

First Canal 13

Figure 47 – Tool Outputs of the third trial.

When comparing the handmade outputs with the tool outputs, one can see that the vast majority of values match perfectly. Those who do not, have insignificant deviations due to rounding errors, e.g., the cost per TEU (with ship purchases) in the minimum costs scenario of the first trial is 1627 in the handmade

outputs and 1628 in the tool outputs (a difference of 0.06%). The matching of the outputs in the random input trials is sufficient to validate the tool.

## **4.2. APPLICATIONS OF THE TOOL**

This section shows the application of the tool in three distinct case studies, representing three real world situations in which the tool can be useful.

The first case study is that of a company wishing to open a new feeder liner service in Asia. The company is set in on the round voyage and wishes to employ only one vessel, but has doubts on the duration of the round voyage which would be adequate.

The second case study is that of a ship operator, owning a vessel of twelve thousand TEUs and wanting to place it in the East Asia to Northern Europe route. This operator knows the ports and the duration of the round voyage which is competitive to that market and the kind of round voyage the vessel is to follow and wishes to know how profitable this vessel would be in this route.

The third case study is that of a Portuguese company wanting to redesign its liner service between mainland Portugal, the island of Madeira, and the Azores archipelago. Currently owning three small containerships, each in its individual round voyage, this company wants to bundle the three services in a single round voyage and seeks to test a number of possible round voyages as to find the most profitable.

In the following subsections alternatively define the inputs for these case studies and present the results of the tool.

### **4.2.1 INTRA-ASIAN CASE STUDY**

#### **4.2.1.1. INPUTS OF THE INTRA-ASIAN CASE STUDY**

The ports considered for this case study are the port of Singapore, the port of Manila, the port of Bangkok, Thailand, the port of Quy Nhon, Vietnam, and the port of Tanjung Priok, Indonesia (Figure 48). This route is a feeder route with the hub in Singapore, meaning all cargo is either originated in or destined to Singapore.



*Figure 48 – Representation of the geographic location of the ports and of the voyage in the intra-Asian route.*  
*Base map from [www.outline-world-map.com](http://www.outline-world-map.com). Key: 1 – Singapore; 2 – Manila; 3 – Bangkok; 4 – Quy Nhon; 5 – Jakarta.*

When finding port data there are two issues: first, many ports do not publish all their tariffs and fees; and second, it is not known in advance all the services a vessel will require in each port. Thus, it is assumed that at every port the ship pays: calling fees to the port authority, berthing fees, towing fees, pilotage fees, and cargo handling fees. When data is missing, the values are estimated from those of the other ports or the defaults are used.

Table 14 contains the data for the ports of this round voyage. For the port of Singapore, are included the fees to the port authority, which depend on the period of stay, assumed to be of one day (MPA, 2018), the terminal characteristics (MPA, 2018), the pilotage fees (PSA Marine (PTE), 2018) which depend on the GT and on the time of navigation, the latter assumed as 2 hours, the towage (PSA Marine (PTE), 2018), and the cargo handling fees (Agility Fairs & Events Logistics Pte, 2017). For the port of Manila are included the fees for the port authority (Philippines Port Authority, 2018), berthing fees, nr of cranes per berth (MICT, 2018), the size restrictions (MICT, 2018), the cargo handling fees (PPA, 2018). The port of Bangkok (Port Authority of Thailand, 2000) made available the port authority dues, the towing fees (assuming one tug during two hours), the berth fees (which are a function of both time and gross tonnage, thus assumed that the GT will be of two and a half thousands), the cargo handling fees, and the port restrictions. For their lack of publicly available information the ports of Quy Nhon, in Vietnam, and the port of Tanjung Priok, in Indonesia, have the costs of the port of Bangkok and the restrictions of the port of Manila (since Bangkok has a canal). Regarding the missing values, Singapore's berth fees are taken as those of Manila, the pilotage fees in Bangkok are assumed as the towage fees, and the pilotage

and towing fees are as those of Bangkok. The default values for the parameters: for *DNavp\_i* is 20 nautical miles; for the *SpNavp\_i* is 10 knots; for *MNGant\_i* is 2; for *GantProd\_i* is 15; for *Tep* is 3 hours (Mooney, 2017); for *Tfp* is 1 hour; and for the rest the default is 0.

Designation	Singapore SNG	Manila MAN	Bangkok BAN	Quy Nhon QUY	Tanjung Priok TAN
DNavp [NM]	20	20	40	20	20
SpNavp [kn]	10	10	10	10	10
MNGant	3	2	2	2	2
GantProd	25	15	15	15	15
Tep	3	3	3	3	3
Tfp	1	1	1	1	1
Fixed_i	492	0	0	0	0
Size_i	0	0	0	0	0
Tonn_i	0.680	0.17	0.664	0.664	0.664
Time_i	0	0	6.9	6.9	6.9
Cargo_i	125	98	41.40	41.40	41.40
LR	0	0	0	0	0
BR	0	0	0	0	0
TR	14	13.5	8	13.5	13.5

Table 14 – Data of the ports of the intra-Asian route.

Table 15 shows the distances between the ports. This data can be acquired using an online voyage planning tool (Marine Traffic, 2018).

	SNG	MAN	BAN	QUY	TAN
SNG	0	554	818	846	554
MAN	554	0	1 463	688	1 924
BAN	818	1 463	0	884	1 348
QUY	846	688	884	0	1 369
TAN	554	1 924	1 348	1 369	0

Table 15 – Distances between ports of the Northern Europe to East Asia route, in nautical miles. Columns are origins, row are destination.

The cargo flow matrix for this voyage is in Table 16. Since this is a small route the cargo matrix is defined in the following way: the number of full container is four times the number of empty containers; the amount of full containers from the hub to the feeder ports is half of all the full containers to the hub (for the empty containers is vice versa), in both full and empty containers, two thirds are TEUs, there are no reefer containers, and the total annual number of containers is 250 000 TEU (100 000 TEUf, 25 000 TEUe, 50 000 FEUf, and 12 500 FEUe).

TEUf	SNG	MAN	BAN	QUY	TAN	FEUf	SNG	MAN	BAN	QUY	TAN
SNG	0	16 664	16 664	16 664	16 664	SNG	0	8 332	8 332	8 332	8 332
MAN	8336	0	0	0	0	MAN	4 168	0	0	0	0
BAN	8336	0	0	0	0	BAN	4 168	0	0	0	0
QUY	8336	0	0	0	0	QUY	4 168	0	0	0	0
TAN	8336	0	0	0	0	TAN	4 168	0	0	0	0

TEUe						FEUe					
SNG	0	2 084	2 084	2 084	2 084	SNG	0	1 042	1 042	1 042	1 042
MAN	4 166	0	0	0	0	MAN	2 083	0	0	0	0
BAN	4 166	0	0	0	0	BAN	2 083	0	0	0	0
QUY	4 166	0	0	0	0	QUY	2 083	0	0	0	0
TAN	4 166	0	0	0	0	TAN	2 083	0	0	0	0

Table 16 – Cargo Flow matrices for the Intra-Asian route.

The freight rates were estimated using three tools: the online tool of (iContainers, 2018); the China Forwarders Freight Index, see (Shipping China, 2018) ; and the Index at (Freightos, 2018).The charges of empty containers are the loading charge of the destination port, since some ports charge to move empty containers and some do not. The input matrix with the all-inclusive freight rates is in Table 17.

TEUf	SNG	MAN	BAN	QUY	TAN	FEUf	SNG	MAN	BAN	QUY	TAN
SNG	0	244	320	320	699	SNG	0	570	450	450	1000
MAN	1054	0	0	0	0	MAN	1590	0	0	0	0
BAN	388	0	0	0	0	BAN	684	0	0	0	0
QUY	440	0	0	0	0	QUY	796	0	0	0	0
TAN	580	0	0	0	0	TAN	990	0	0	0	0

TEUe						FEUe					
SNG	125	125	125	125	125	SNG	125	125	125	125	125
MAN	98	98	98	98	98	MAN	98	98	98	98	98
BAN	41.4	41.4	41.4	41.4	41.4	BAN	41.4	41.4	41.4	41.4	41.4
QUY	41.4	41.4	41.4	41.4	41.4	QUY	41.4	41.4	41.4	41.4	41.4
TAN	41.4	41.4	41.4	41.4	41.4	TAN	41.4	41.4	41.4	41.4	41.4

Table 17 – Freight Rate matrices for the Intra-Asian route [USD / container].

In this case study, there is only one circular service round voyage with different durations, see Table 18. In short services, the schedules tend to be weekly, biweekly or monthly.

TFRV = 45 days					
SNG	BAN	QUY	MAN	TAN	SNG
			TFRV = 30 days		
SNG	BAN	QUY	MAN	TAN	SNG
			TFRV = 15 days		
SNG	BAN	QUY	MAN	TAN	SNG
			TFRV = 7 days		
SNG	BAN	QUY	MAN	TAN	SNG

Table 18 – Round Voyages for the Intra-Asian Route.

#### 4.2.1.2. RESULTS OF THE INTRA-ASIAN LINER SERVICE CASE STUDY

The results in this subsection follow two criteria: the results are for the fleet with the least possible vessels, and minimum buffer ratio of ten percent.

Figure 49 contains the results for the first voyage, the one lasting forty five days, and it is not very profitable. Without capital costs the profit margins are good, with them the fleet is quite unprofitable. In spite of this fleet being sized to the route and in slow steaming, the low profit margins can be explained by the buffer ratio, which is nearly sixty percent and by the fleet size, which is at 9 300 TEUs. This high buffer ratio is due to an excessive duration of the round voyage where the fleet spends more than half the time idle. For a voyage, feeder vessels should be used, and the vessels of this fleet are three times the size of a large feeder vessel, resulting in very costs.

Fleet Size	1 Ships with 9300.00 TEUs			
	For this cruise speed 17.0000	[kn]		
	For these cost scenarios Performance Indicators	Maximum	Expected	Minimum
	For the whole fleet every year			
	Net Profit	-10120000	-4798000	-265000 [USD]
	Net Profit Margin [%]	-36	-17	0 [ ]
	Cost per TEU Handled	695	597	513 [USD]
	Cost per Mile Sailed	1782	1530	1316 [USD]
	Net Profit (without ship purchase)	741000	2248000	3675000 [USD]
	Net Profit Margin (without ship purchase) [%]	3	9	14 [ ]
	Cost per TEU Handled (without ship purchase)	495	467	441 [USD]
	Cost per Mile Sailed (without ship purchase)	1269	1197	1130 [USD]
	Buffer Time (per vessel, per RV)	650	[h]	
	Buffer Ratio	59.6150	[%]	
	Ship Costs			
	For one ship every year			
	Operating Costs	6040000	5152000	4335000 [USD]
	Capital Costs	10862000	7047000	3940000 [USD]
	Port Costs	12447000	12447000	12447000 [USD]
	Fuel Costs	8343000	7724000	7114000 [USD]
	Canal Costs	0	0	0 [USD]
	Total Costs	37690000	32368000	27835000 [USD]
	Voyage Costs	20790000	20171000	19561000 [USD]
	Revenue	27570000	[USD]	
	Other Characteristics			
	Shipbuilding Cost	151121000	100709000	59659000 [USD]
Length Between Perpendiculars	320 [m]	Average Breadth	46 [m]	
Average Depth	27 [m]	Maximum Draft	16 [m]	
Gross Tonnage	104700 [ ]	Net Tonnage	52700 [ ]	
Number of Cranes	0 [ ]	Number of Generators	4 [ ]	
Main engine power	70000 [kW]	Generator Power	13300 [kW]	
Lightship weight	33900 [tons]	Displacement	145000 [tons]	
Fuel Capacity	11400 [cub. m]	Balast Capacity	29100 [cub. m]	
Time of a round voyage	45.0000	[days]		
Time in ports (not including cargo handling)	2.96300	[ % ]		
Time handling cargo	22.6080	[ % ]		
Time in Canals	0.00000	[ % ]		
Sailing Time	10.0750	[ % ]		
Buffer Time	64.3560	[ % ]		

Figure 49 – Main results for the Intra-Asian route in the forty five days long circular voyage, with one vessel with 9 300 TEUs of capacity, at 17 knots.

Figure 50 contains the outputs for the circular voyage lasting thirty days, and are very similar to the first voyage since both the buffer ratio and the ship size are excessive.

Fleet Size	1 Ships with	6200.00	TEUs	
	For this cruise speed	17.0000	[kn]	
	For these cost scenarios	Maximum	Expected	Minimum
	Performance Indicators			
	For the whole fleet every year			
	Net Profit	-5375000	-1022000	2703000 [USD]
	Net Profit Margin [%]	-19	-3	10 [ ]
	Cost per TEU Handled	608	528	459 [USD]
	Cost per Mile Sailed	1039	902	784 [USD]
	Net Profit (without ship purchase)	2797000	4238000	5610000 [USD]
	Net Profit Margin (without ship purchase) [%]	11	16	21 [ ]
	Cost per TEU Handled (without ship purchase)	457	431	405 [USD]
	Cost per Mile Sailed (without ship purchase)	781	736	692 [USD]
	Buffer Time (per vessel, per RV)	370	[h]	
	Buffer Ratio	50.7520	[%]	
	Ship Costs			
	For one ship every year			
	Operating Costs	5155000	4421000	3743000 [USD]
	Capital Costs	8172000	5261000	2908000 [USD]
	Port Costs	12110000	12110000	12110000 [USD]
	Fuel Costs	7509000	6802000	6107000 [USD]
	Canal Costs	0	0	0 [USD]
	Total Costs	32945000	28592000	24867000 [USD]
	Voyage Costs	19619000	18912000	18217000 [USD]
	Revenue	27570000	[USD]]	
	Other Characteristics			
	Shipbuilding Cost	113456000	74983000	43891000 [USD]
Length Between Perpendiculars	290 [m]	Average Breadth	40 [m]	
Average Depth	24 [m]	Maximum Draft	15 [m]	
Gross Tonnage	69000 [ ]	Net Tonnage	35100 [ ]	
Number of Cranes	0 [ ]	Number of Generators	4 [ ]	
Main engine power	56100 [kW]	Generator Power	10500 [kW]	
Lightship weight	24400 [tons]	Displacement	103000 [tons]	
Fuel Capacity	8700 [cub. m]	Balast Capacity	20800 [cub. m]	
Time of a round voyage	30.0000	[days]		
Time in ports (not including cargo handling)	4.44500	[ % ]		
Time handling cargo	22.5820	[ % ]		
Time in Canals	0.00000	[ % ]		
Sailing Time	15.1120	[ % ]		
Buffer Time	57.8630	[ % ]		

Figure 50 – Main results for the Intra-Asian route in the thirty day long circular voyage, with one vessel with 6 200 TEUs of capacity, at 17 knots.

Figure 51 contains the outputs for the circular voyage lasting fifteen days. This duration seems to be good, for the ship size is that of a large reefer, the profit margins are high, the buffer ratio is still over twenty percent, and the vessel is in slow steaming. This fleet is both profitable and flexible.

Fleet Size	1 Ships with For this cruise speed	3100.00 16.0000	TEUs [kn]
For these cost scenarios			
Performance Indicators	Maximum	Expected	Minimum
For the whole fleet every year			
Net Profit	1633000	4802000	7540000 [USD]
Net Profit Margin [%]	6	18	28 [ ]
Cost per TEU Handled	477	419	369 [USD]
Cost per Mile Sailed	409	359	316 [USD]
Net Profit (without ship purchase)	6658000	7994000	9270000 [USD]
Net Profit Margin (without ship purchase) [%]	25	29	34 [ ]
Cost per TEU Handled (without ship purchase)	385	360	337 [USD]
Cost per Mile Sailed (without ship purchase)	330	309	289 [USD]
Buffer Time (per vessel, per RV)	90	[h]	
Buffer Ratio	22.3090	[%]	
Ship Costs			
For one ship every year			
Operating Costs	3931000	3404000	2913000 [USD]
Capital Costs	5025000	3192000	1731000 [USD]
Port Costs	10875000	10875000	10875000 [USD]
Fuel Costs	6107000	5298000	4513000 [USD]
Canal Costs	0	0	0 [USD]
Total Costs	25937000	22768000	20030000 [USD]
Voyage Costs	16982000	16173000	15388000 [USD]
Revenue	27570000	[USD]	
Other Characteristics			
Shipbuilding Cost	69503000	45286000	25972000 [USD]
Length Between Perpendiculars	225 [m]	Average Breadth	31 [m]
Average Depth	18 [m]	Maximum Draft	14 [m]
Gross Tonnage	33700 [ ]	Net Tonnage	17600 [ ]
Number of Cranes	3 [ ]	Number of Generators	4 [ ]
Main engine power	28000 [kW]	Generator Power	6200 [kW]
Lightship weight	13900 [tons]	Displacement	56000 [tons]
Fuel Capacity	4700 [cub. m]	Balast Capacity	12700 [cub. m]
Time of a round voyage	15.0000	[days]	
Time in ports (not including cargo handling)	8.88900	[ % ]	
Time handling cargo	21.5810	[ % ]	
Time in Canals	0.00000	[ % ]	
Sailing Time	30.2230	[ % ]	
Buffer Time	39.3090	[ % ]	

Figure 51 – Main results for the Intra-Asian route in the fifteen day long circular voyage, with one vessel with 3100 TEUs of capacity, at 16 knots.

Figure 52 contains the performance indicators for the circular voyage which last only seven days, and as the tool outputs, seven days is insufficient to complete the voyage.

For the round voyage number	4			
1	3	4	2	5
For this number of ships in the fleet	5			

#### Main results

Error: the speed required for this fleet to complete the journey is beyond what the ships can do.  
Consider other solutions with more ships

Figure 52 – Main results for the Intra-Asian route in the seven day long circular voyage.

By using the tool, one concludes that a best solution is to use a vessel with three thousand and one hundred TEUs capacity in a fifteen days long round voyage.

#### **4.2.2. NORTHERN-EUROPE TO EAST ASIA SERVICE CASE STUDY**

##### **4.2.2.1. INPUTS OF THE NORTHERN-EUROPE TO EAST ASIA SERVICE CASE STUDY**

In this case study, the vessel is to connect the larger ports in the East Asia and those in Northern Europe. Large transcontinental port networks work on the hub and feeder model, and thus a fleet connecting these two regions would only call on the hub ports of these regions. Thus, the ports considered in Asia are: Singapore, Hong Kong, Shanghai, Busan, and Tokyo; and in Northern Europe: Le Havre, Southampton, Antwerp, Rotterdam, and Hamburg (Figure 53). Note: the port of Jeddah is a blank call.

As in the previous route, it is assumed that the vessels in each port require port dues, cargo handling fees, pilotage, towage, and berthing. Table 19 contains the data for the ports of this round voyage. For the port of Tokyo, the official website (Tokyo MG, 2018) sets the port dues as a function of the gross tonnage, the tug boat charge is also a function of the gross tonnage (Tokyo Kisen Co., n.d.), the Tokyo port corporation (TPC, 2018) contains data on the container terminals, including the physical restrictions and crane data, while the values for the cargo handling and the pilotage are unknown. For the port of Busan two documents provide the port dues, the berth hire, the cargo handling fees (Busan Agency Co. Ltd, 2013), and the pilotage fees (Korea Maritime Pilots' Association, 2009), leaving the tug charges unknown. These charges included some formulas with multiple dependent variables, so it is assumed that the vessel stays in the berth for one day and that the vessel has a draft of fourteen meters. The port of Shanghai does not publish most values and is taken as ^Hong Kong. For the Hong Kong port, the marine department's website states the port dues, the pilotage fees, and the berthing fees (H. K. Marine Department, 2018) and the cargo handling charges are given by OOCL's website (OOCL, 2018). It is assumed that the vessel occupies three hundred meters of quay. The port of Jeddah does no display the fees for either ships or cargo, thus assumed as the port of Manila. For the port of Le Havre, the OOCL claims the handling charges at this port for standard containers is one hundred and ninety five euro, and the official document of the port (Le Havre Port, 2017) calculate the port dues as a function of the volume (calculated as a function of the volume of the vessel, which in turn is directly proportional to the gross tonnage by a scalar), an extra charge per container, and also provide limited information on the piloting and towage fees (Haropa, 2016).

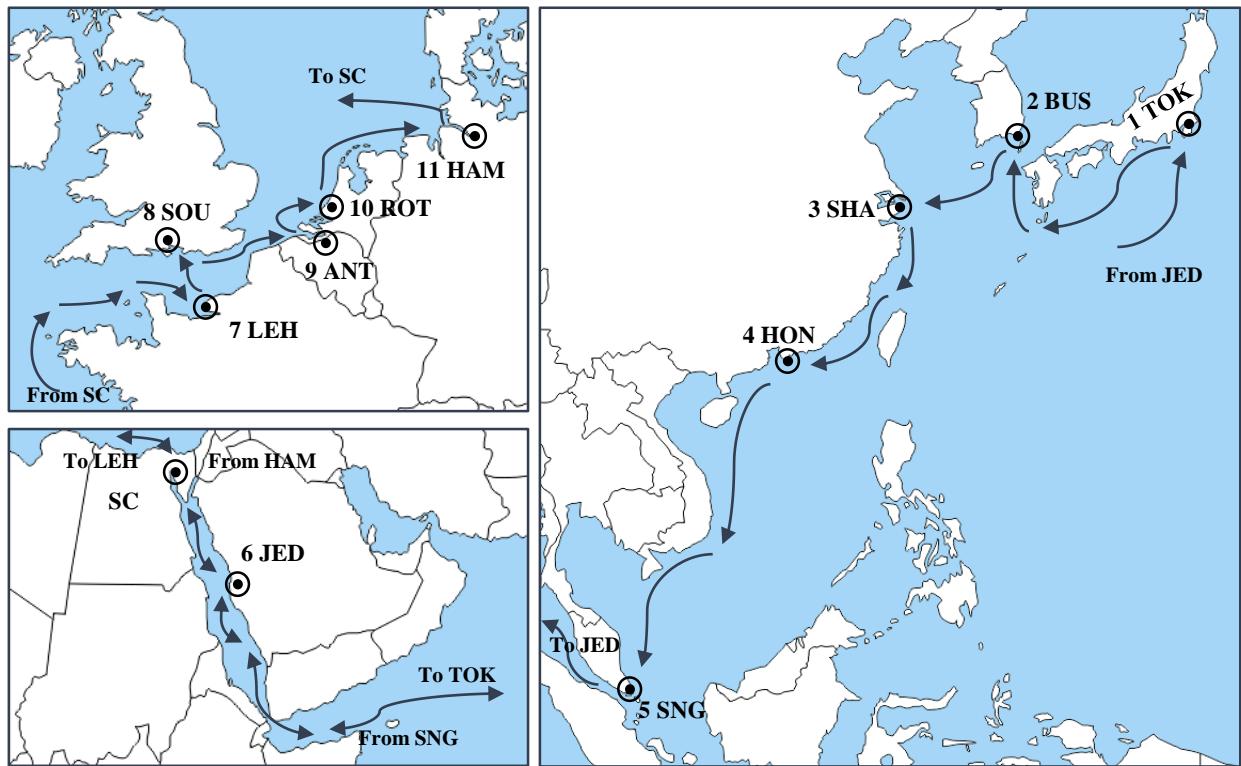


Figure 53 – Representation of the geographic location of the ports and of the voyage in the East Asia to Northern Europe route. Key: 1 – Tokyo; 2 – Busan; 3 – Shanghai; 4 – Hong Kong; 5 – Singapore; 6 – Jeddah; 7 – Le Havre; 8 – Southampton; 9 – Antwerp; 10 – Rotterdam; 11 – Hamburg; and SC – Suez Canal.

For the port of Southampton, the official documents of the port (ABP, 2018) give the port dues as a function of the gross tonnage, the pilotage fees as a function of the draft (ABP, 2018) and the cargo handling costs (DP World, 2018). For the port of Antwerp, the port authority charges the port dues and the berthing fees (Antwerp Port Authority, 2017) and the OOCL provides information on container handling charges. For the port of Rotterdam, the port dues are given by the port authority as a function of the gross tonnage (Rotterdam, 2018), the pilotage charges depend on the draft of the vessel (Loodswezen, 2015), and the cargo handling fees are charged for number of containers (Containershipsgroup, 2018). For the Hamburg port the port fees are charged on both tonnage and cargo handled (HPA, 2018). The EUROGATE Container terminal Hamburg charges both the cargo handling and the berthing (EUROGATE, 2016). Note: The default values for the parameters: for  $DNavp_i$  is 20 nautical miles; for the  $SpNavp_i$  is 10 knots; for  $MNGant_i$  is 2; for  $GantProd_i$  is 15; for  $Tep$  is 3 hours (Mooney, 2017); for  $Tfp$  is 1 hour; and for the rest the default is 0.

Designation	DNavp [NM]	SpNnavp [kn]	MNGant	GantProd	Tep	Tfp	Fixed_i	Size_i	Tonn_j	Time_j	Cargo_i	LR	BR	TR
TOK	40	10	4	20	3	1	1519	0	0.413	177.9	202.00	0	0	15
BUS	5	10	3	20	3	1	1528	0	1.246	0	207.37	0	0	14
SHA	25	10	3	20	3	1	1548	0	0.645	177.9	202.00	0	0	14
HON	10	10	3	20	3	1	1548	0	0.645	177.9	202.00	0	0	14
SNG	20	10	3	25	3	1	1561	0	0.680	0	125.00	0	0	14
JED	3	10	2	15	3	1	0	0	0.170	0	98.00	0	0	13.5
LEH	5	10	3	20	3	1	12354	0	1.635	0	235.58	0	0	14
SOU	20	10	3	20	3	1	15814	0	0.993	0	236	0	0	15
ANT	40	10	3	20	3	1	15783	0	0.263	0	253.82	0	0	15
ROT	16	10	3	20	3	1	15789	0	0.812	0	106.72	0	0	15
HAM	50	10	3	20	3	1	15823	0	1.068	0	302.27	0	0	15

Table 19 – Data of the ports of the Northern Europe to East Asia route.

Table 20 shows the distances between the ports. This data can be acquired using an online voyage planning tool (Marine Traffic, 2018).

	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	697	1 077	1 581	2 919	7 307	11 143	11 140	11 329	11 342	11 657
BUS	697	0	476	1 138	2 518	6 925	10 791	10 826	10 976	10 991	11 234
SHA	1 077	476	0	821	2 201	6 578	10 411	10 400	10 595	10 768	10 878
HON	1 581	1 138	821	0	1 455	5 847	9 688	9 675	9 867	9 912	10 142
SNG	2 919	2 518	2 201	1 455	0	4 407	8 273	8 222	8 420	8 473	12 136
JED	7 307	6 925	6 578	5 847	4 407	0	3 884	3 845	4 039	4 066	4 308
LEH	11 143	10 791	10 411	9 688	8 273	3 884	0	112	263	270	512
SOU	11 140	10 826	10 400	9 675	8 222	3 845	112	0	252	244	512
ANT	11 329	10 976	10 595	9 867	8 420	4 039	263	252	0	71	387
ROT	11 342	10 991	10 768	9 912	8 473	4 066	270	244	71	0	304
HAM	11 657	11 234	10 878	10 142	12 136	4 308	512	512	387	304	0

Table 20 – Distances between ports of the Northern Europe to East Asia route. Columns are origins, row are destination.

The cargo flow matrix for this voyage is in Table 21. As with the previous condition, real world cargo flows in-between the ports are unknown, and thus the matrix is set with the following rules: every port in Asia only has container for European ports, and European ports only have containers for Asian ports; there is no cargo to or from Jeddah; the flow of container from one port is the same for all destinations; the flow of full containers from Asia to Europe is five halves of the flow of full containers from Europe to Asia, with empty container it is the inverse; the flow of full TEUs from a port in Europe to a port in Asia is four thousand TEUs; the flow of full FEUs is a quarter of the flow of TEUs; the flow of empty TEUs from the port of origin to the port of destination is a quarter of the flow of full TEUS from the port of destination to the port of origin; it is the same with Empty FEU containers; and whenever the previous rules yield a number with decimals that number is rounded by excess.

TEUf	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	4000	4000	4000	4000	4000
BUS	0	0	0	0	0	0	4000	4000	4000	4000	4000
SHA	0	0	0	0	0	0	4000	4000	4000	4000	4000
HON	0	0	0	0	0	0	4000	4000	4000	4000	4000
SNG	0	0	0	0	0	0	4000	4000	4000	4000	4000
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	10000	10000	10000	10000	10000	0	0	0	0	0	0
SOU	10000	10000	10000	10000	10000	0	0	0	0	0	0
ANT	10000	10000	10000	10000	10000	0	0	0	0	0	0
ROT	10000	10000	10000	10000	10000	0	0	0	0	0	0
HAM	10000	10000	10000	10000	10000	0	0	0	0	0	0
FEUf	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	1000	1000	1000	1000	1000
BUS	0	0	0	0	0	0	1000	1000	1000	1000	1000
SHA	0	0	0	0	0	0	1000	1000	1000	1000	1000
HON	0	0	0	0	0	0	1000	1000	1000	1000	1000
SNG	0	0	0	0	0	0	1000	1000	1000	1000	1000
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	2500	2500	2500	2500	2500	0	0	0	0	0	0
SOU	2500	2500	2500	2500	2500	0	0	0	0	0	0
ANT	2500	2500	2500	2500	2500	0	0	0	0	0	0
ROT	2500	2500	2500	2500	2500	0	0	0	0	0	0
HAM	2500	2500	2500	2500	2500	0	0	0	0	0	0
TEUe	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	2500	2500	2500	2500	2500
BUS	0	0	0	0	0	0	2500	2500	2500	2500	2500
SHA	0	0	0	0	0	0	2500	2500	2500	2500	2500
HON	0	0	0	0	0	0	2500	2500	2500	2500	2500
SNG	0	0	0	0	0	0	2500	2500	2500	2500	2500
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	1000	1000	1000	1000	1000	0	0	0	0	0	0
SOU	1000	1000	1000	1000	1000	0	0	0	0	0	0
ANT	1000	1000	1000	1000	1000	0	0	0	0	0	0
ROT	1000	1000	1000	1000	1000	0	0	0	0	0	0
HAM	1000	1000	1000	1000	1000	0	0	0	0	0	0
FEUe	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	625	625	625	625	625
BUS	0	0	0	0	0	0	625	625	625	625	625
SHA	0	0	0	0	0	0	625	625	625	625	625
HON	0	0	0	0	0	0	625	625	625	625	625
SNG	0	0	0	0	0	0	625	625	625	625	625
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	250	250	250	250	250	0	0	0	0	0	0
SOU	250	250	250	250	250	0	0	0	0	0	0
ANT	250	250	250	250	250	0	0	0	0	0	0
ROT	250	250	250	250	250	0	0	0	0	0	0
HAM	250	250	250	250	250	0	0	0	0	0	0

Table 21 – Cargo Flow matrices for the Intra-Asian route.

The only canal in this route is the Suez Canal, for which the applicable crossing tolls can be described as a function of the gross tonnage of the vessel (Suez Canal Authority, n.d.). If calculated for different values of gross tonnage, these fees take the form of a second degree polynomial (Figure 54). The crossing time is between 16 and 12 hours and the size restrictions are given by the canal. The input values are in Table 22.

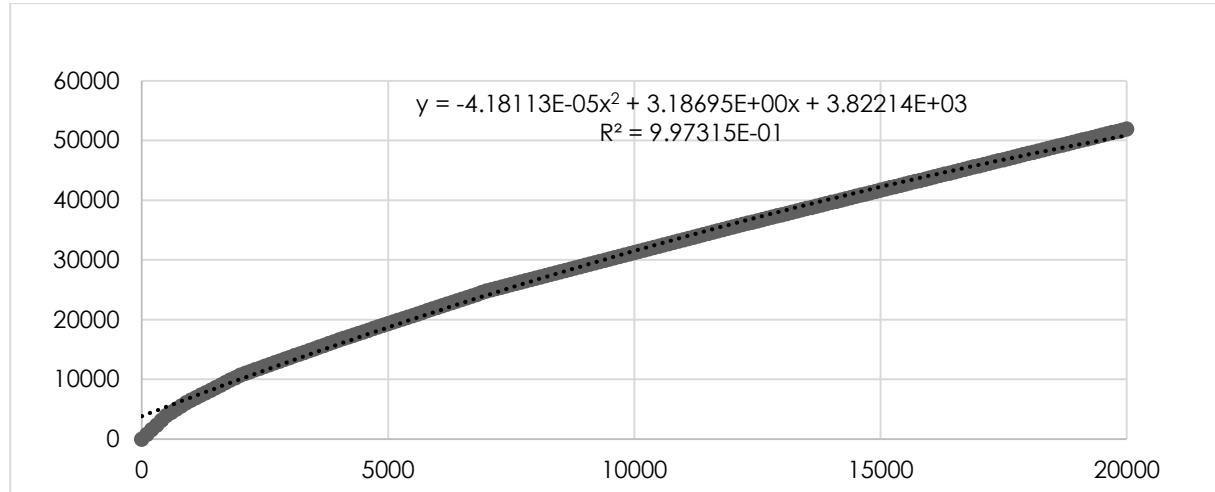


Figure 54 – Suez Canal's Crossing Fee [USD] as a function of the Gross Tonnage.

Cost coefficients		Crossing time [h]	LR [m]	BR[m]	TR [m]
-0.0000418113	3.1869	3822.14	14	0	24

Table 22 – Suez Canal input values.

The freight rates were estimated using three tools: the online tool of (iContainers, 2018); the China Forwarders Freight Index, see (Shipping China, 2018) ; and the Freightos (Freightos, 2018).The charges of empty containers are the loading charge of the destination port, since some ports charge to move empty containers and some do not. Table 23 has the all-inclusive freight rates.

TEUf	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	1759	1779	1556	1389	1579
BUS	0	0	0	0	0	0	1315	1269	1198	1074	1276
SHA	0	0	0	0	0	0	1298	1310	1185	1041	1237
HON	0	0	0	0	0	0	1400	1320	1309	1162	1401
SNG	0	0	0	0	0	0	1245	1121	1169	964	1220
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	1568	1576	1670	1633	1536	0	0	0	0	0	0
SOU	1369	1416	1464	1411	1365	0	0	0	0	0	0
ANT	1653	1795	1731	1731	1651	0	0	0	0	0	0
ROT	1506	1632	1628	1628	1579	0	0	0	0	0	0
HAM	1704	1832	1805	1807	1732	0	0	0	0	0	0
FEUf	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	2107	2161	1931	1677	1873
BUS	0	0	0	0	0	0	1506	1717	1409	1243	1500
SHA	0	0	0	0	0	0	1298	1779	1368	1221	1454
HON	0	0	0	0	0	0	1638	1690	1569	1422	1679
SNG	0	0	0	0	0	0	1430	1457	1373	1229	1473
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	2153	2573	2557	2558	2511	0	0	0	0	0	0
SOU	2074	2286	2372	2281	2322	0	0	0	0	0	0
ANT	2223	2628	2543	2523	2446	0	0	0	0	0	0
ROT	2076	2458	2453	2459	2400	0	0	0	0	0	0
HAM	2326	2680	2623	2683	2615	0	0	0	0	0	0
TEUe	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	768	630	731	579	773
BUS	0	0	0	0	0	0	661	506	645	504	701
SHA	0	0	0	0	0	0	653	512	638	492	688
HON	0	0	0	0	0	0	678	515	669	522	729
SNG	0	0	0	0	0	0	582	407	576	415	626
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	720	726	746	736	654	0	0	0	0	0	0
SOU	527	543	551	538	468	0	0	0	0	0	0
ANT	755	795	775	775	697	0	0	0	0	0	0
ROT	608	644	638	638	568	0	0	0	0	0	0
HAM	804	840	830	830	754	0	0	0	0	0	0
FEUe	TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM
TOK	0	0	0	0	0	0	855	725	825	651	847
BUS	0	0	0	0	0	0	709	618	698	546	757
SHA	0	0	0	0	0	0	653	630	684	537	742
HON	0	0	0	0	0	0	738	607	734	587	798
SNG	0	0	0	0	0	0	628	491	627	481	689
JED	0	0	0	0	0	0	0	0	0	0	0
LEH	866	975	967	968	898	0	0	0	0	0	0
SOU	703	760	778	755	708	0	0	0	0	0	0
ANT	898	1003	978	973	896	0	0	0	0	0	0
ROT	750	850	845	846	774	0	0	0	0	0	0
HAM	960	1052	1034	1049	974	0	0	0	0	0	0

Table 23 – Freight Rate matrices for the Northern Europe to East Asia route.

The one round voyage which is considered, shown in Table 24, is to last ninety days. This value is due to some freight rate calculators used stating that the transit time for a container from Europe to Shanghai is around forty days.

TFRV = 90 days												
TOK	BUS	SHA	HON	SNG	JED	LEH	SOU	ANT	ROT	HAM	JED	TOK

Table 24 – Round Voyage for the Northern Europe to East Asia Route.

#### 4.2.2.2. RESULTS OF THE NORTHERN-EUROPE TO EAST ASIA CASE STUDY

In this case study the goal is to study the profitability of a twelve thousand TEUs vessel in the Northern Europe to East Asia Route. The results are in Figure 55 with the minimum buffer ratio being ten percent.

Fleet Size	2 Ships with	12100.0	TEUs									
	For this cruise speed	17.0000	[kn]									
	For these cost scenarios		Maximum	Expected	Minimum							
	Performance Indicators											
	For the whole fleet every year											
	Net Profit	-21787000	-4731000	10455000	[USD]							
	Net Profit Margin [%]	-22	-4	11	[ ]							
	Cost per TEU Handled	1500	1282	1089	[USD]							
	Cost per Mile Sailed	1257	1075	913	[USD]							
	Net Profit (without ship purchase)	-8963000	3603000	15114000	[USD]							
	Net Profit Margin (without ship purchase) [%]	-9	4	16	[ ]							
	Cost per TEU Handled (without ship purchase)	1336	1176	1030	[USD]							
	Cost per Mile Sailed (without ship purchase)	1120	986	863	[USD]							
	Buffer Time (per vessel, per RV)	390	[h]									
	Buffer Ratio	17.6110	[%]									
	Ship Costs											
	For one ship every year											
	Operating Costs	6695000	5690000	4768000	[USD]							
	Capital Costs	12824000	8334000	4660000	[USD]							
	Port Costs	18349000	18349000	18349000	[USD]							
	Fuel Costs	19132000	16100000	13103000	[USD]							
	Canal Costs	1881000	1881000	1881000	[USD]							
	Total Costs	58880000	50352000	42759000	[USD]							
	Voyage Costs	39362000	36329000	33332000	[USD]							
	Revenue	47986000	[USD]									
	other Characteristics											
	Shipbuilding Cost	182027000	121961000	72812000	[USD]							
Length Between Perpendiculars	340 [m]		Average Breadth		49 [m]							
Average Depth	29 [m]		Maximum Draft		17 [m]							
Gross Tonnage	135400 [ ]		Net Tonnage		68500 [ ]							
Number of Cranes	0 [ ]		Number of Generators		4 [ ]							
Main engine power	70000 [kW]		Generator Power		14900 [kW]							
Lightship weight	41500 [tons]		Displacement		178000 [tons]							
Fuel Capacity	12700 [cub. m]		Balast Capacity		38300 [cub. m]							
Time of a round voyage	90.0000	[days]										
Time in ports (not including cargo handling)	3.32000	[ % ]										
Time handling cargo	12.1590	[ % ]										
Time in Canals	1.29700	[ % ]										
Sailing Time	65.6160	[ % ]										
Buffer Time	17.6110	[ % ]										

Figure 55 – Main results for the Northern Europe to East Asia route.

The figure has the values for a two vessel fleet not for one vessel, as desired. However, since the tool uses homogenous fleets, all indicators, with the exception of the net profit, are similar for the fleet and for each vessel. In this case, the net profit margin is inconclusive, for the ship can turn a large loss or a

reasonable profit. To fully understand the profitability of the vessel it is necessary to look at the ship costs in detail. Table 25 contains the annual vessel costs for both voyages, the deviations of the costs scenarios, and the cost splits.

	Nominal Costs			Deviations		Cost splits		
	Maximum	Expected	Minimum	Maximum	Minimum	Maximum	Expected	Minimum
Operating	6.695	5.69	4.768	17.7%	-16.2%	11%	11%	11%
Capital	12.824	8.334	4.66	53.9%	-44.1%	22%	17%	11%
Port	18.349	18.349	18.349	0.0%	0.0%	31%	36%	43%
Fuel	19.132	16.1	13.103	18.8%	-18.6%	32%	32%	31%
Canal	1.881	1.881	1.881	0.0%	0.0%	3%	4%	4%
Total	58.88	50.352	42.759	16.9%	-15.1%	Revenues		47.986

Table 25 – Annual ship costs [million USD], deviation in the maximum and minimum cost scenarios, and cost splits in the three scenarios in the voyage of the Northern Europe to East Asia route.

From Table 25 one can make some observations. First, the greatest cost in the ship are the port costs. This is not unusual and can be explained by the freight rates used being all-inclusive, meaning the vessel charged the cargo handling to its customers and paid it to the ports, at no loss or profit. A ship which did not charge this, would have smaller port costs. Second, fuel costs are one third of the costs, as expected. Third, the most volatile cost are the capital costs, which can either be five million or twelve millions.

From the tool the user could see that a twelve thousand TEU vessel might not be profitable and that the user could attempt to improve the profitability by reducing either the port costs or the fuel costs.

#### 4.2.3. PORTUGUESE CASE STUDY

##### 4.2.3.1. INPUTS OF THE PORTUGUESE CASE STUDY

In this case study the goal is to find a round voyage configuration for the port network between mainland Portugal and the insular Portugal (Figure 56) which suits a fleet of three small ships which is currently serving this route using three separate round voyages. According to the official website of a company engaging in such traffic (Transinsular, 2018), this company employs four containerships shipping in this route. The capacities of these vessels are around 600-650 TEUs. Thus the goal is to find a round voyage which lasts fifteen days and where a four 600-650 TEU vessel fleet is optimal.

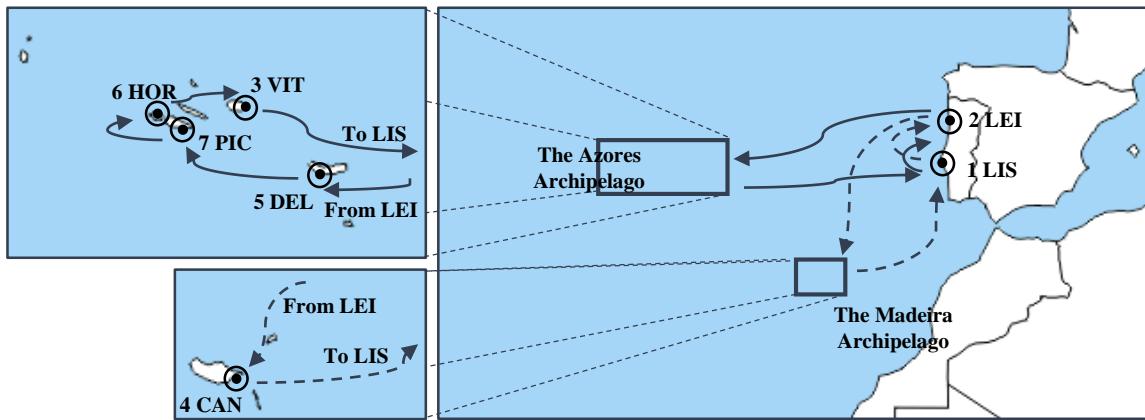


Figure 56 – Representation of the geographic location of the ports and of the circular with pendulum voyage in the Portuguese case study. Key: 1 – Lisbon; 2 – Leixões; 3 – Praia da Vitória; 4 – Caniçal; 5 – Ponta Delgada; 6 – Horta; and 7 – Pico.

The ports of call are in the continent: Lisbon (LIS) and Leixões (LEI); in Madeira archipelago: Caniçal (CAN); and in the Azores archipelago: Praia da Vitória (VIT), Ponta Delgada (DEL), Horta (HOR), and Pico (PIC). Table 26 contains the port data for these ports, as stated by the port authorities of Lisbon (APL, 2018), Leixões (APDL, 2018), and the islands (PdA, 2018). The cargo handling fees are not included, for the freight rates used are only for the transportation, leaving the container handling fees to the shipper.

	DNavp	SpNavp	MNGant	GantProd	Tep	Tfp	Fixed_i	Size_i	Tonn_i	Time_i	Cargo_i
LIS	20	10	0	15	3	1	455.3	0	9.964	0	0
LEI	20	10	0	15	3	1	455.3	0	8.726	0	0
VIT	0	10	0	15	3	1	644.96	0	5.925	0	0
CAN	0	10	0	15	3	1	644.96	0	5.591	0	0
DEL	0	10	0	15	3	1	644.96	0	5.713	0	0
HOR	0	10	0	15	3	1	644.96	0	5.591	0	0
PIC	0	10	0	15	3	1	644.96	0	5.591	0	0

Table 26 – Data of the ports of the Portuguese route.

The distances between the ports are in Table 27.

Distances	LIS	LEI	VIT	CAN	DEL	HOR	PIC
LIS	0	191	846	523	788	920	904
LEI	191	0	946	643	818	939	930
VIT	846	946	0	647	92	82	67
CAN	523	643	647	0	543	691	680
DEL	788	818	92	543	0	153	136
HOR	920	939	82	691	153	0	15
PIC	904	930	67	680	136	15	0

Table 27 – Distances between the ports of the Portuguese route

The annual cargo flows are in Table 28. These cargo flows were extracted from the official websites of the ports of Lisbon and Leixões, who publish the annual cargo flows in between these ports and other

ports, thus making these cargo flows realistic. The freight rates (Table 29) are estimated from Mutualista's freight rates for 2015 (Mutualista Açoreana, 2015)

TEUf	LIS	LEI	VIT	CAN	DEL	HOR	PIC	TEUe	LIS	LEI	VIT	CAN	DEL	HOR	PIC
LIS	0	0	1476	5036	2287	526	0	LIS	0	0	492	1679	762	175	0
LEI	0	0	471	824	746	95	9	LEI	0	0	756	1810	508	338	45
VIT	1580	930	0	0	0	0	0	VIT	527	18	0	0	0	0	0
CAN	4625	2633	0	0	0	0	0	CAN	1542	168	0	0	0	0	0
DEL	3421	1870	0	0	0	0	0	DEL	1140	88	0	0	0	0	0
HOR	238	341	0	0	0	0	0	HOR	79	7	0	0	0	0	0
PIC	0	129	0	0	0	0	0	PIC	0	1	0	0	0	0	0

FEUf	LIS	LEI	VIT	CAN	DEL	HOR	PIC	FEUe	LIS	LEI	VIT	CAN	DEL	HOR	PIC
LIS	0	0	1601	11102	6503	209	0	LIS	0	0	534	3701	2168	70	0
LEI	0	0	841	2086	1871	176	9	LEI	0	0	1353	4577	1275	625	41
VIT	1743	1916	0	0	0	0	0	VIT	581	37	0	0	0	0	0
CAN	12484	4934	0	0	0	0	0	CAN	4161	315	0	0	0	0	0
DEL	5616	5396	0	0	0	0	0	DEL	1872	253	0	0	0	0	0
HOR	526	424	0	0	0	0	0	HOR	175	9	0	0	0	0	0
PIC	0	259	0	0	0	0	0	PIC	0	3	0	0	0	0	0

Table 28 – Cargo Flows for the Portuguese route.

TEUf	LIS	LEI	VIT	CAN	DEL	HOR	PIC	FEUf	LIS	LEI	VIT	CAN	DEL	HOR
LIS	0	0	676	676	676	676	676	LIS	0	0	1082	1082	1082	1082
LEI	0	0	676	676	676	676	676	LEI	0	0	1082	1082	1082	1082
VIT	1555	1555	0	0	0	0	0	VIT	2599	2599	0	0	0	0
CAN	1555	1555	0	0	0	0	0	CAN	2599	2599	0	0	0	0
DEL	1555	1555	0	0	0	0	0	DEL	2599	2599	0	0	0	0
HOR	1555	1555	0	0	0	0	0	HOR	2599	2599	0	0	0	0
PIC	1555	1555	0	0	0	0	0	PIC	2599	2599	0	0	0	0

TEUe	LIS	LEI	VIT	CAN	DEL	HOR	PIC	FEUe	LIS	LEI	VIT	CAN	DEL	HOR
LIS	0	0	676	676	676	676	676	LIS	0	0	1082	1082	1082	1082
LEI	0	0	676	676	676	676	676	LEI	0	0	1082	1082	1082	1082
VIT	1555	1555	0	0	0	0	0	VIT	2599	2599	0	0	0	0
CAN	1555	1555	0	0	0	0	0	CAN	2599	2599	0	0	0	0
DEL	1555	1555	0	0	0	0	0	DEL	2599	2599	0	0	0	0
HOR	1555	1555	0	0	0	0	0	HOR	2599	2599	0	0	0	0
PIC	1555	1555	0	0	0	0	0	PIC	2599	2599	0	0	0	0

Table 29 – Freight rates of the Portuguese route.

So to test the various possibilities, combinations of five round voyages and three durations of round voyages are used (Table 30). Four of these round voyages include all the ports and one (the Azores voyage) will only exclude the port of Caniçal in Madeira. Since calling that port consist add a significantly long leg to the voyage it is useful to consider a voyage only between the Azores and the mainland.

Type of round voyage	Duration [days]	Configuration
Circular		LIS – LEI – VIT – HOR – PIC – DEL – CAN – LIS
Double circular	30	LIS – VIT – HOR – PIC – DEL – CAN – LIS – LEI – VIT – HOR – PIC – DEL – CAN – LEI – LIS
Circular with pendulum	15	LIS – LEI – CAN – LIS – LEI – DEL – PIC – HOR – VIT – LIS
Pendulum	7	LIS – CAN – LIS – DEL – PIC – LEI – LIS – VIT – HOR – LEI – LIS
Azores		LIS – LEI – VIT – HOR – PIC – DEL – LIS

Table 30 – Voyages of the Portuguese route.

#### 4.2.3.2. RESULTS OF THE PORTUGUESE CASE STUDY

The goal is to see in which combination of round voyage and duration of round voyage is the most profitable for four ships with capacities between six to seven hundred TEU. As such the only indicator compared here (Table 31) is the net profit margin.

Voyage	Duration [days]	Number of Ships	Ship Size [TEU]	Speed [kn]	NPM	BuffR
Circular	7		n.p.			
	15	14	700	13	4	34
	30	28	700	13	-23	67
Double circular	7		n.p.			
	15		n.p.			
	30	14	700	13	4	34
Circular with pendulum	7		n.p.			
	15	8	700	14	29	11
	30	15	700	13	20	53
Pendulum	7		n.p.			
	15		n.p.			
	30	19	700	13	-14	35
Azores	7		n.p.			
	15	7	700	13	7	42
	30	14	700	13	-22	71

Table 31 – Main results for the voyages of the Portuguese Condition. ‘n.p.’ stands for ‘not possible’ and NPM is the expected costs’ net profit margin, in percentage.

From Table 31, it is clear that the best route system is the circular with pendulum voyage in fifteen days. This voyage is equivalent to a circular with pendulum voyage to the Azores archipelago and then a pendulum trip to the Madeira island. Of the four vessels discussed in the previous section, one vessel does the Madeira-mainland line and the other three do circular voyages between Lisbon, Leixões and the Azores (Transinsular, 2018). This configuration is similar to the circular with pendulum voyage. The fact that this voyage needs eight vessels of this size to be completely served also correlates to the real route, since the cargo flow data is the annual total and there are two companies operating in this route (and one of them has four vessels).

When comparing the results for the circular, circular with pendulum, and Azores voyages some interesting effects can be observed. Comparing the circular voyage with the circular with pendulum voyage, the latter has a higher profit margin. The difference between the two is on the configuration of

the round voyage. Since Lisbon and Leixões have a large cargo flow in-between Caniçal, ships in the circular voyage must load these cargoes and carry them around the Azores before calling at Caniçal, while ships in the circular with pendulum voyage call on Lisbon and Leixões between calling on the Azores ports and calling on Caniçal, which in turn means that these vessels either carry cargo of the Azores ports or carry cargo of Caniçal. Thus the circular with pendulum voyage can be completed with a smaller number of seven hundred TEU vessels than the circular voyage in which vessels must always carry cargo of both the Azores and the Caniçal. And it is this smaller number of vessels that makes the difference in the profit margins, thus explaining why the circular with pendulum configuration is more efficient.

Comparing the circular with pendulum voyage with the Azores voyage attests to the size of the cargo flows from and to Caniçal. Though both voyages have similar number of ships, the ships of the Azores voyage are unproductive for much of the voyage (buffer time of forty two percent) and the circular with pendulum vessels sail at a higher speed (fourteen knots) and engage in the large cargo flows of Caniçal. This additional profit and lower buffer ratios explain why the Azores voyage is much less profitable.

Comparing the circular voyage with the Azores voyage, Table 31 returns that the profitability of the Azores voyage is higher, even though the buffer ratio of the Azores voyage is higher (42%) than the circular's (34%). This is due to a combination of two factors. First, as discussed before, the configuration of the circular voyage requires it to employ a large number of seven hundred TEU vessels in a way that the configuration of the Azores voyage, for not engaging in the cargo flow to Caniçal, does not. The number of vessels in the fleet is a key parameter in the cost per TEU. Second the distance between the Azores port and Caniçal and between Caniçal and Lisbon is long (1063 NM) and by not sailing it, the Azores voyage can save fuel, which is a main cost of the vessel. This effects combined overcome the additional profit from calling the port of Caniçal.

Thus, adding the call on the Caniçal to the Azores voyage can either increase the profit margin (as in the circular with pendulum voyage) or reduce it (as in the circular voyage), which emphasises the importance of the configuration of the voyage. In the Azores voyage the buffer ratio is too high, meaning that the vessels are idle (if a buffer ratio of 10% is the required for all delays, as is assumed, then these vessels are idle 32% of the time) and in these cases one seeks to add another call to the voyage. What these three voyages show is that the way this new call is inserted in the voyage is critical, else one risks a less profitable voyage.

If the company wished to bundle these three vessels into a single service, the tool would show them that a double circular voyage would be the most profitable (Figure 57).

Fleet Size	8 Ships with	700.000	TEUs	
	For this cruise speed	13.0000	[kn]	
	For these cost scenarios	Maximum	Expected	Minimum
	Performance Indicators			
For the whole fleet every year				
Net Profit	45724000	55700000	64220000	[USD]
Net Profit Margin [%]	25	30	34	[ ]
Cost per TEU Handled	697	649	607	[USD]
Cost per Mile Sailed	1795	1671	1565	[USD]
Net Profit (without ship purchase)	47445000	56754000	64756000	[USD]
Net Profit Margin (without ship purchase) [%]	25	30	35	[ ]
Cost per TEU Handled (without ship purchase)	688	643	605	[USD]
Cost per Mile Sailed (without ship purchase)	1774	1658	1558	[USD]
Buffer Time (per vessel, per RV)	30	[h]		
Buffer Ratio	5.97000	[%]		
Ship Costs				
For one ship every year				
Operating Costs	2197000	1942000	1700000	[USD]
Capital Costs	1721000	1054000	536000	[USD]
Port Costs	12044000	12044000	12044000	[USD]
Fuel Costs	2070000	1747000	1441000	[USD]
Canal Costs	0	0	0	[USD]
Total Costs	18031000	16784000	15719000	[USD]
Voyage Costs	14114000	13790000	13484000	[USD]
Revenue	23747000	[USD]		
Other Characteristics				
Shipbuilding Cost	24272000	15340000	8420000	[USD]
Length Between Perpendiculars	125 [m]	Average Breadth	22	[m]
Average Depth	11 [m]	Maximum Draft	9	[m]
Gross Tonnage	7800 [ ]	Net Tonnage	4000	[ ]
Number of Cranes	3 [ ]	Number of Generators	4	[ ]
Main engine power	6300 [kW]	Generator Power	1800	[kW]
Lightship weight	5000 [tons]	Displacement	16000	[tons]
Fuel Capacity	800 [cub. m]	Balast Capacity	4300	[cub. m]
Time of a round voyage	15.0000	[days]		
Time in ports (not including cargo handling)	12.2230	[ % ]		
Time handling cargo	8.19800	[ % ]		
Time in Canals	0.00000	[ % ]		
Sailing Time	73.6120	[ % ]		
Buffer Time	5.97000	[ % ]		

Figure 57 – Main results for the fifteen day long circular with pendulum voyage in the Portuguese route.

## **5. CONCLUSIONS AND FURTHER WORKS**

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The tool which was developed is a tool for the design of liner routes. Its main functionality is to test different round voyages and fleet sizes and present them in terms of comparable performance indicators. The code outputs many values, chief amongst them the ship size and the performance indicators. The economic performance indicators are: the net profit, the net profit margin, the cost per handled TEU and the cost per mile, then allow the user to compare fleets, and are calculated for three different cost scenarios and for many possible operating speeds. The code boasts a process which determines the feasible operating speeds for each vessel, and uses them to estimate the performance indicator which, when presented for three cost scenarios (maximum costs, costs as expected, and minimum costs), are critical to paint a complete picture of the fleet's performance. With the performance indicators, the tool also returns other relevant outputs, such as the time split for the various activities in the round voyage and the annual costs of the individual vessel discriminated in its most relevant categories. Many ship characteristics are presented, like the net tonnage or the fuel capacity. The code also considers size restrictions on ports and canals, using them to inform the user when they might be an issue. Finally the code presents the cargos carried by the vessel in each leg, discriminated by type of container, origin and destination. From this data it is also clear to see what cargoes are loaded in every call, which is useful for further schedule designing. All the values calculated are estimated with data from an extensive database of container ships and using common techniques in the industry. With these values the user of the tool has the necessary information to compare options, plan schedules, design vessels, allocate ships, and design liner services.

The principal intent of this dissertation is to present the tool, to explain the methods by which it operates, to test the tool in validating trials, and finally to show its application to three problems in different routes. The chief objective of this thesis has been achieved, for the tool is valid. The application of the tool has permitted to show the impact some variables have on the outputs. As seen in the first case study, the duration of the round voyage has a large impact on the outputs. Shorter voyages require more vessels than large voyages, which lead to larger buffer ratios and to larger vessels. Eventually, if the duration is sufficiently large, the cargo distribution algorithm will even return ships larger than twenty two thousand TEU. The problem of larger vessels is that the transported cargo (i.e., the annual revenue) is fixed in the inputs and thus does not scale with vessel size while the costs do. This can be seen in the case study, where a seven day trip required more than five small vessels to be completed, a forty day voyage used a too large ship with nine thousand TEUs, and the fifteen days voyage used a profitable three thousand TEUs vessel. In conclusion, one should want match the duration of the round voyage to the voyage and to the cargo flows as to obtain the most profitable solution.

The application of the tool to the second case study, that of the Northern Europe to East Asia service, shown that the deviations of the maximum and minimum performance indicators from the expected ones

are quite significant. Once the costs were properly analysed it emerged that the cause lies in the uncertainty of the models used. The tool allows a user to change the regressions used but these methods always carry substantial errors. In the case of the regressions used, they were based on a database of real vessels, which bundled vessels which are new and efficient with ships that are older and less profitable. In the case study the deviations were such that the maximum cost scenario predicted a loss and the minimum costs scenario a profit.

The application of the tool to the third case study, the Portuguese one, resulted that a circular with pendulum voyage is the most profitable, amongst the six possibilities under consideration. The analysis the results of these voyages shows the impact voyage the configuration (i.e. the order of the port calls) can have on the net profit margin. In the case study the most profitable with four small feeder vessels is similar to the four individual voyages similar vessels currently practice.

There are some modifications which would improve the tool. First, the development of a routine to design round voyages served by multiple line services, adapting the cargo flows for those line services and optimizing the round voyage configuration with network analysis methods. This feature would allow the tool to optimize hub and spoke voyage configurations.

Second, the modification of the tool to allow for heterogeneous fleets. With this feature the user could input the ships he intends to deploy and run the tool for that specific fleet.

Third, the improving of the regressions used, in all three scenarios. This would reduce the deviations and make the tool more accurate.

Fourth, the improvement of the cargo distribution algorithm. The current algorithm was not designed to be computational efficient. If this tool is to be used with a round voyage optimizer, which would test a very large number of round voyages per minute, improving the code as to accelerate the computations would save the user much time.

Fifth, the improving of the port data's inputting and processing. As discussed in the section 3.4.3.1. Port Costs, there are some issues with the model of the port's charges. Currently the tool accepts costs that are fixed or dependent either on time, tonnage, cargo handling, or size. An improved model of the port pricing schemes, with a wider range of pricing formulas as well as charges dependant on two variables (e.g., USD per hour per every 10 gross t), would improve the accuracy and scope of the code.

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## APPENDIX I – USER MANUAL

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### Introduction

The purpose of this manual is to explain to any users of the tool how to prepare the inputs, how to run the code, and how to read the results. To acquire the tool or question, please contact me at hugo55loureiro@gmail.com.

### Preparing the inputs

The inputs are in five input files. The paragraphs below contain a description of the variables of each file. Afterwards, templates of the files are presented Note: In this section, lines preceded by ‘!!’ are not to be altered, as they are part of the template, text preceded by a ‘!’ is a comment, and values in bold are the variables to be inputted. Note: when inputting vectors, the values of different columns must be separated by either a ‘blank space’ or a ‘tab’.

The ‘**Loan.txt**’ file contains the data for the calculation of loans, which is in four variables: **Loan\_Value**, **Term\_of\_Loan**, **RoI**, **Inflation**, **Scarp\_Price**, and **DRate**. **Loan\_Value** is the fraction of the shipbuilding cost which is paid with a loan, e.g. if a ship costs one thousand dollar and the loan’s principal is six hundred dollars, then **Loan\_Value** = 0.6. **Loan\_Value** must be between zero and one. **Term\_of\_Loan** is the number of years in which the loan is repaid. The life expectancy of a vessel is set to twenty years and that is the limit of the loan’s term. **Term\_of\_Loan** must be a natural number larger than zero and smaller than twenty. **RoI** is the loan’s interest rate, in percentage. **RoI** can be negative, but such

prompts the code to display a warning. **Inflation** is the annual rate of inflation over the ship’s life, in percentage. **Inflation** can be negative, but such prompts the code to display a warning. **Scarp\_Price** is the price paid per ton of ship scrap in twenty years’ time (the life expectancy of the vessel), in USD per ton. can be negative, but such prompts the code to display a warning **Scarp\_Price** can be negative, but such prompts the code to display a warning. **DRate** is the discount rate of the ship investment, in percentage. **DRate** must be positive.

The file ‘**Canals.txt**’ contains the data for canals. This file requires **NCC** (which is the number of canals inputted) and for each canal inputted: the name of that canal (**Name\_Canal**) the crossing time of the canal (**Time\_Crossing**), the cost coefficients \* (**c1** to **c5**), the size restrictions for that canal (**RL** for length, **RB** for breadth, and **RD** for draft) \*\*, and the sets of ports which have the canal in-between.

\* Cost in a canal are estimated by the following formula:  $\text{Canal.Costs} = \sum_{i=1}^5 (c_i \cdot GT^{i-1})$ , where **GT** is the gross tonnage of the vessel.

\*\* These restriction should be represented in meters and rounded to the unit. If one restriction

does not exist (e.g. if the canal does not restrict length) input ‘0’ (e.g. **RL** = 0).

There are two ways of inputting the journeys which cross the canal. The particular and the general. In the particular, the user must input the pairs of ports which have the canal in the leg between them. In general, one lists the ports on the one side, and then the ports on the other side (the template contains both cases).

The ‘**Main.txt**’ is contains the inputs on the ports, on the cargo flows between ports, and on the freight rates. This file requires the following variables: **NPorts**, the number of ports. **LDist**, the distance between the ports. **LDist(i,j)** is the distance between port j to port i, in nautical miles. **NamPorts**, the three letter designation of each port. The ports’ number is defined by the order here (e.g. the first port on this list will be the port number one in the rest of the code). **TEUf** is the cargo flow of full standard twenty feet containers. **TEUf(i,j)** is the annual number of full TEU containers from port j to port i. **TEUe** is the cargo flow of empty standard twenty feet containers. **TEUe(i,j)** is the annual number of empty TEU containers from port j to port i. **FEUf** is the cargo flow of full standard forty feet containers. **FEUf(i,j)** is the annual number of full FEU containers from port j to port i. **FEUe** is the cargo flow of empty standard forty feet containers. **FEUe(i,j)** is the annual number of empty FEU containers from port j to port i. **RETf** is the cargo flow of full standard twenty feet reefer containers. **RETf(i,j)** is the annual number of full TEU reefer containers from port j to port i. **RETe** is the cargo flow of empty standard twenty feet reefer containers. **RETe(i,j)** is the annual number of

empty TEU reefer containers from port j to port i. **REff** is the cargo flow of full standard forty feet reefer containers. **REff(i,j)** is the annual number of full FEU reefer containers from port j to port i. **REFe** is the cargo flow of empty standard forty feet reefer containers. **REFe(i,j)** is the annual number of full FEU reefer containers from port j to port i. **TEUffr** is the freight rate of full standard twenty feet containers. **TEUffr(i,j)** is the freight rate, in USD per container, of full TEU containers from port j to port i. **TEUefr** is the freight rate of empty standard twenty feet containers. **TEUefr(i,j)** is the freight rate, in USD per container, of empty TEU containers from port j to port i. **FEUffr** is the freight rate of full standard forty feet containers. **FEUffr(i,j)** is the freight rate, in USD per container, of full FEU containers from port j to port i. **FEUefr** is the freight rate of empty standard forty feet containers. **FEUefr(i,j)** is the freight rate, in USD per container, of empty FEU containers from port j to port i. **RETffr** is the freight rate of full standard twenty feet reefer containers. **RETffr(i,j)** is the annual number of full TEU reefer containers from port j to port i. **RETeFr** is the freight rate of empty standard twenty feet reefer containers. **RETeFr(i,j)** is the freight rate, in USD per container, of empty TEU reefer containers from port j to port i. **REfffr** is the freight rate of full standard forty feet reefer containers. **REfffr(i,j)** is the freight rate, in USD per container, of full FEU reefer containers from port j to port i. **REFeFr** is the freight rate of empty standard forty feet reefer containers. **REFeFr(i,j)** is the freight rate, in USD per container, of full FEU reefer containers from port j to port i. For each port: **DNavp**, which is the distance of

navigation within the port's boundaries; **SpNavp** is the speed at which the vessel can sail **DNavp**. **SpNavp** must be positive; **MNGant** is the average number of cranes available at that port; **GantProd** is the average crane productivity in moves per hour; **Te** is, the waiting time, in hours; **Tfp** is the time for formal proceedings, in hours; **Fixed\_i** is the fixed charge to be paid at the port in USD; **Tonn\_i** is the charge in USD to be paid for every gross tonne of the vessel; **Time\_i** is charge, in USD, per hour of berth use; **Size\_i** is charge in USD, to be paid by TEU of capacity of the vessel; **Cargo\_i** is charge, in USD, paid for every container move in port; **LR** is length restriction, in meters, in the port; **BR** is breadth restriction, in meters, in the port; and **TR** is draft restrictions, in meters, in the port.

The ‘**Others.txt**’ file contains the data for the regressions. The variables required for this file are: **Max\_NShips** which is the maximum fleet size the code considers. **Max\_NShips** must be a natural number; the **R14tSS** which is the ratio between the ship’s capacity in 14 tons containers. **R14tSS** must be a positive real number between zero and one; and the **Regression** of the number of cranes, of the number of generators, of the operating costs in the minimum cost scenario [USD], of the operating costs in the expected cost scenario [USD], of the operating costs in the maximum cost scenario [USD], of the shipbuilding price in the minimum cost scenario [USD], of the shipbuilding price in the expected cost scenario [USD], of the shipbuilding price in the maximum cost scenario [USD], of the service

speed [kn], of the lowest operating speed [kn], of the gross tonnage, of the average breadth [m], of the average depth [m], of the main propulsive power [kW], of the electrical power [kW], of the length between perpendiculars [m], of the net tonnage, of the lightship weight [t], of the displacement at summer draft [m], of the fuel capacity [ $m^3$ ], of the ballast capacity [ $m^3$ ], of the IFO consumption in the maximum cost scenario [t / day], of the IFO consumption in the expected costs scenario [t / day], of the IFO consumption in the minimum cost scenario [t / day], of the price of IFO [USD / t], of the price of MDO [USD / t], of the consumption of the geared ship’s cranes [t / container], of the power of a TEU reefer container [kW], of the power of one FEU reefer container [kW], and of the specific consumption of the generators [t / kWh].

A **Regression** of a variable is the function which calculates that variable from the ship size [TEU]. The regressions can be of five types, which are explained in the template file.

The file ‘**Voyages.txt**’ contains the round voyages and their durations which the tool uses. It contains the **NRV**, which is the number of round voyages, and the data of each round voyages, which consists on: the **NCalls** which is the number of calls in that round voyage; the **RV** which is the vector with the calls of the round voyage (use the port numbers as defined in the ‘Main.txt’ file); and the **TFRV** which is the duration of the round voyage, in days (**TFRV** must be positive).

**Example of the ‘Loan.txt’.....**

!! Loan Data  
!! Value (As fraction of the shipbuilding cost).  
**0.7** ! **Loan\_Value**  
!! Term of the loan [years]  
**14** ! **Term\_of\_Loan**  
!! Interest Rate [%]  
**5.5** ! **RoI**  
!! Inflation [%]  
**1** ! **Inflation**  
!! Scrap Price [USD / Ton]  
**5.2E2** ! **Scrap\_Price**  
!! Discount Rate [%]  
**7** ! **DRate**

---

**Example of the ‘Voyages.txt’.....**

!! Number of Round Voyages  
**2** ! **NCC**  
!! NCalls  
!! RV  
!! Maximum Time between fleet calls [days]  
**7** ! **NCalls**  
**5 3 1 2 4 3 4** ! **RV**  
**60** ! **TFRV**  
**14** ! **NCalls**  
**5 3 1 2 4 3 4 2 1 3 2 5 3 1** ! **RV**  
**35** ! **TFRV**

---

**Example of the ‘Canals.txt’.....**

!! Number of Canals Considered

**2** ! NCC

!! -----

!! Canal Nr. 1

**Bungalow** ! Name of the first canal

!! How is the canal defined? (1 for particular, 2 for general)

**2** ! 1 or 2

!! Canal Time [h]

**22** ! Time\_Crossing

!! Canal Costs [ Cost = 4th degree Polinom(Ship.Size) ]

**0 0 0 0 10525** ! Vector of [c1 c2 c3 c4 c5]

!! Canal Restrictions

!! L B T

**211 17 13** ! LR BR and TR

!! [For Canals type 2] Ports on one side (use the three letter designations)

**2** ! Number of ports on the one side of the canal

**TPA** ! Port on the one side of the canal

**TPB** ! Port on the one side of the canal

!! [For Canals type 2] Ports on the other side (use the three letter designations)

**3** ! Number of ports on the other side of the canal

**TPC** ! Port on the other side of the canal

**TPD** ! Port on the other side of the canal

**TPE** ! Port on the other side of the canal

!! -----

!! Canal Nr. 2

**Zumassa** ! Name of the second canal

!! How is the canal defined? (1 for particular, 2 for general)

**1** ! **1 or 2**  
 !! Canal Time [h]  
**28** ! **Time\_Crossing**  
 !! Canal Costs [ Cost = 4th degree Polinom(Ship.Size) ]  
**0 0 0 0 16017** ! **Vector of [c1 c2 c3 c4 c5]**  
 !! Canal Restrictions  
 !! L B T  
**395 14 13** ! **LR BR and TR**  
 !! [For Canals type 1] sets of ports which have the canal in between (use the three letter designations)  
**1** ! **Number of port pairs whose legs cross the canal**  
**TPC TPD** ! **Port pair which leg crosses the canal**

---

Note: As can be seen each canal starts with a '!! -----'. To add a new canal simply copy that line, write as above, and change the third line of the file.

#### Example of the 'Main.txt' .....

! Header 1  
 ! Header 2  
 ! Header 3  
 !!  
 !! Number of ports  
**2** ! **Number of Ports**  
 !!  
 !! Name of ports [use three letter designations]  
**TPA** ! **Name of port 1**  
**TPB** ! **Name of port 2**  
 !!  
 !! Characteristics of ports  
 !! DNavy SpNavy MNGant GantProd Tep Tfp Fixed\_i Size\_i Tonn\_i Lime\_i Cargo\_i

<b>36</b>	<b>7</b>	<b>1</b>	<b>25</b>	<b>19</b>	<b>3</b>	<b>1280</b>	<b>3</b>	<b>5</b>	<b>25</b>	<b>69</b>	<b>! For port 1</b>
<b>6</b>	<b>9</b>	<b>2</b>	<b>21</b>	<b>20</b>	<b>3</b>	<b>3485</b>	<b>5</b>	<b>4</b>	<b>106</b>	<b>69</b>	<b>! For port 2</b>
<b>!!</b>											
<b>!! Port Restrictions</b>											
<b>! LR</b>	<b>BR</b>	<b>TR</b>									
<b>281</b>	<b>20</b>	<b>14</b>	<b>! For port 1</b>								
<b>221</b>	<b>24</b>	<b>15</b>	<b>! For port 2</b>								
<b>!!</b>											
<b>!! Leg Distances [nautical miles]</b>											
<b>0</b>	<b>621</b>		<b>! Distances to port 1</b>								
<b>954</b>	<b>0</b>		<b>! Distances to port 2</b>								
<b>!!</b>											
<b>!! Supply and Demand Matrices</b>											
<b>!!</b>											
<b>!!</b>	full TEUs per year										
<b>0</b>	<b>100</b>		<b>! This is TEUf</b>								
<b>200</b>	<b>0</b>										
<b>!!</b>	empty TEUs per year										
<b>0</b>	<b>1E3</b>		<b>! This is TEUe</b>								
<b>234</b>	<b>0</b>										
<b>!!</b>	full FEUs per year										
<b>0</b>	<b>0</b>		<b>! This is FEUf</b>								
<b>0</b>	<b>0</b>										
<b>!!</b>	empty FEUs empty per year										
<b>0</b>	<b>0</b>		<b>! This is FEUe</b>								
<b>0</b>	<b>0</b>										
<b>!!</b>	full Reefers TEU per year										
<b>0</b>	<b>0</b>		<b>! This is RETf</b>								

<b>0</b>	<b>0</b>	
!!		empty Reefers TEU per year
<b>0</b>	<b>0</b>	<b>! This is RETe</b>
<b>0</b>	<b>0</b>	
!!		full Reefers FEU per year
<b>0</b>	<b>0</b>	<b>! This is REFF</b>
<b>0</b>	<b>0</b>	
!!		empty Reefers FEU per year
<b>0</b>	<b>0</b>	<b>! This is REFe</b>
<b>0</b>	<b>0</b>	
!!		
!!		Freight Rates [USD per container]
!!		
!!		full TEUs
<b>0</b>	<b>1000</b>	<b>! This is TEUffFr</b>
<b>462.34</b>	<b>0</b>	
!!		empty TEUs
<b>0</b>	<b>1000</b>	<b>! This is TEUeFr</b>
<b>462.34</b>	<b>0</b>	
!!		full FEUs
<b>0</b>	<b>0</b>	<b>! This is FEUffFr</b>
<b>0</b>	<b>0</b>	
!!		empty FEUs
<b>0</b>	<b>0</b>	<b>! This is FEUeFr</b>
<b>0</b>	<b>0</b>	
!!		full TEU Reefers
<b>0</b>	<b>0</b>	<b>! This is RETffFr</b>
<b>0</b>	<b>0</b>	

```

!!                                empty TEU Reefers

0      0                      ! This is RETeFr

0      0

!!                                full FEU Reefers

0      0                      ! This is REffFr

0      0

!!                                empty FEU Reefers

0      0                      ! This is REFeFr

0      0

```

---

#### Example of the ‘Others.txt’.....

```

!! Maximum fleet size

5                            ! Max_NShips

! Ratio of 14 tons container to Ship size

0.8                          ! R14tSS

!!

!! Types of Regressions

!! 1 -- Polynomial  $y = a + x^4 + b * x^3 + c*x^2 + d*x + e$ 

!! Input in this order:   a      b      c      d      e

!! 2 -- Rational  $y = H(x) / P(x) + Q(x)$ , where H, P, and Q are polynomials (as in type 1)

!! Input in this order:

!!      a      b      c      d      e      of the H(x)

!!      a      b      c      d      e      of the P(x) -- must not be all zeros

!!      a      b      c      d      e      of the Q(x)

!! 3 -- Exponential  $y = a * x ^ b$ 

!! Input in this order: a  b

!! 4 -- Logarithmic  $y = a * \ln(x) + b$ 

!! Input in this order: a  b

```

!! 5 -- Branches function:  $y = (P1(x), \text{ if } a1 < x \leq b1), (P2(x), \text{ if } a2 < x \leq b2),$

!! Input first the number of branches

!! Then, for each branch, input the a and b

!! Input in this order: a b

!! Then input the coefficients of  $P(x)$

!! Input in this order: a b c d e

!! Repeat for the next branch. Ensure that branches do not overlap

!!

!! Regressions

!! Number of Cranes

**5**

**! Example of a branch regression**

**2**

**! Number of branches**

**0 3700**

**! Limits of the 1<sup>st</sup> branch (e.g., if  $0 < \text{Size} < 3700$ )**

**0 0 0 0 3**

**! Polynomial coefficients for the 1<sup>st</sup> branch**

**3700 2500000**

**! Limits of the 2<sup>nd</sup> branch (e.g., if  $0 < \text{Size} < 3700$ )**

**0 0 0 0 0**

**! Polynomial coefficients for the 2<sup>nd</sup> branch**

!! Number of Generators

**4**

**! Example of a logarithmic regression**

**1 4**

**! Logarithmic coefficients**

!! Operating Costs Maximum

**3**

**! Example of an exponential regression**

**464.56 0.391**

**! Exponential coefficients**

!! Operating Costs Expected

**2**

**! Example of a rational regression**

**0 0 0.000009 -0.1 -18**

**! Polynomial coefficients of  $H(x)$**

**0 0.00000001 -1E-5 0.01 1**

**! Polynomial coefficients of  $P(x)$**

**0 0 0 0 26**

**! Polynomial coefficients of  $Q(x)$**

!! Operating Costs Minimum

**Regression**

!! Shipbuilding Cost Maximum

**1**

**! Example of a polynomial regression**

**0**

**0. 666738E-6 -2.72014E-8 0.00485812 18.1452 ! Polynomial coefficients**

!! Shipbuilding Cost Expected

**Regression**

!! Shipbuilding Cost Minimum

**Regression**

!! Design Speed [knots]

**Regression**

!! Lowest Service Speed [knots]

**Regression**

!! GT

**Regression**

!! Average Breadth

**Regression**

!! Average Depth

**Regression**

!! Main propulsive power

**Regression**

!! Electrical power

**Regression**

!! Length between Perpendiculars

**Regression**

!! Net tonnage

**Regression**

!! Lightship weight

**Regression**

!! Displacement at summer draft

**Regression**

!! Fuel capacity [m<sup>3</sup>]

**Regression**

!! Ballast capacity [m<sup>3</sup>]

**Regression**

!! IFO Consumption Maximum

**Regression**

!! IFO Consumption Expected

**Regression**

!! IFO Consumption Minimum

**Regression**

!! Length Overall

**Regression**

!! Maximum Breadth

**Regression**

!! Maximum Draft

**Regression**

!! IFO price per ton

**Regression**

!! MDO price per ton

**Regression**

!! Crane Consumption [t / movement]

**Regression**

!! Power for one TEU Reefer [kW]

**Regression**

!! Power for one FEU Reefer [kW]

**Regression**

!! Generator specific consumption [t / kWh]

## Regression

---

### Running the Tool

To run the tool, create a folder, place in it all the input files and the tool, and then run tool. A command window will appear and the tool may crash. Upon crash a new window spawns. Close this second window and see what the command window displays. The tool begins by verifying all inputs and, upon meeting an unacceptable input, shows an error message on the command window and causes the tool to crash. This message informs on the unacceptable input. If the tool finds no errors, the command window proceeds to display the rate of completion, which is updated until the 100% mark, at which point the tool finishes running and command window is closed.

### Reading the Results

While running, the tool produces two output files. Consider only the ‘OutputFile.txt’ and ignore the ‘OutputFile2.txt’.

The output file is divided by fleets. Recall that the tool will consider several fleet sizes (as defined in the ‘Others.txt’ file, in the Max\_NShips variable) for each round voyage (as defined in the ‘Voyages.txt’ file). For each set of round voyage and fleet size the code displays a header with the number of the round voyage, the duration, the calls of that round voyage, and the number of ships.

Bellow this header are the outputs for that fleet size in that voyage.

The output can be a message explaining why that fleet cannot complete that voyage or can be all the indicators, port costs, fleet times, etc, for all the valid operating speeds of the vessels. These results are in the form of tables and are properly explained in the file. Bellow the data for all the speeds are the possible size conflicts on the ports or canals and the CiL matrices (which represent the cargo aboard the vessel in each leg of the round voyage and discriminated by type of container: TEUf, TEUe, FEUf, FEUe, RETf, RETe, REFf, and REFe).

**NOTE: The output file can be quite long and scrolling from fleet to fleet is inefficient. It is highly recommended that the user uses a finder feature (in windows, press CTRL + f ) and search for ‘Fleet Size’. Doing so allow the user to jump from fleet to fleet in a quickly and efficiently.**



## APPENDIX II – 1<sup>ST</sup> TRIAL’S CiL MATRIX

The goal of this Appendix is to complement Chapter 3.2. The Fleet Sizing Process and Chapter 4.1. Tests, by explaining how the CiL matrix of the 1<sup>st</sup> Trial was produced by hand. The matrices presented in Tables 32 to 46 are several key moments on the handmade production of the CiL. The table entries in bold are the entries which changed from the previous table and the entries in blue are notes and not part of the matrices.

### Design of the NCF matrix

RV	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
NCF																
1																
2																
3																
4																
5																

Origin of cargo

Table 32 – 1<sup>st</sup> test. Empty NCF Matrix.

RV	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
NCF																
1																
2																
3																
4																
5																

Table 33 – 1<sup>st</sup> test. First step of the NCF matrix. The first call is in the port 1. The ship will call on port 1 again, so it must load the cargo for all ports until it calls again at port 1. These are the containers for ports 3 and 4, so the NCF on the first call, for entries of cargo to ports 3 and 4 turns to 1.

RV	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
NCF																
1																
2																
3																
4																
5																

Table 34 – 1<sup>st</sup> test. Second step of the NCF matrix. Again but for the second call

RV	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
NCF																
1																
2																
3																
4																
5																

Table 35 – 1<sup>st</sup> test. Next steps of the NCF matrix. Continued until the 12<sup>th</sup> call, on port 4. This port is special for the next time the vessel calls at port 4 is in the next round voyage. The code considers this.

RV	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2
NCF																
1																
2																
3																
4																
5																

Table 36 – 1<sup>st</sup> test. Final step of the NCF matrix

### Design of the CiL matrix

Origin of the leg Cargo Origin	Cargo Destin.	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs
1	1																	
1	2																	
1	3																	
1	4																	
1	5																	
2	1																	
2	2																	
2	3																	
2	4																	
2	5																	
3	1																	
3	2																	
3	3																	
3	4																	
3	5																	
4	1																	
4	2																	
4	3																	
4	4																	
4	5																	
5	1																	
5	2																	
5	3																	
5	4																	
5	5																	
Total cargo in leg																		

Table 37 – 1st test. Empty CiL matrix.

Origin of the leg Cargo Origin	Cargo Destin.	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs
1	1																	
1	2							<b>1</b>		<b>2</b>					<b>3</b>		<b>3</b>	
1	3																	
1	4																	
1	5																	
2	1																	
2	2																	
2	3																	
2	4																	
2	5																	
3	1																	
3	2																	
3	3																	
3	4																	
3	5																	
4	1																	
4	2																	
4	3																	
4	4																	
4	5																	
5	1																	
5	2																	
5	3																	
5	4																	
5	5																	
Total cargo in leg																		

Table 38 – 1st test. First step of the CiL matrix. First we must write in the matrix the legs in which each type of cargo (from now on type of cargo refers to the pair origin destination of the cargo, there are twenty five types of cargo in this matrix) is carried aboard the vessel. We start with cargo type from port 1 to port 2. From the NCF matrix we know when such cargo is loaded on the vessel three times. Each time cargo is loaded it is the beginning of a group of legs in which that cargo is carried (add to the last column)

Origin of the leg Cargo Origin	Cargo Destin.	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs
1	1																	
1	2					1		2	2						3	3		3
1	3																	
1	4																	
1	5																	
2	1																	
2	2																	
2	3																	
2	4																	
2	5																	
3	1																	
3	2																	
3	3																	
3	4																	
3	5																	
4	1																	
4	2																	
4	3																	
4	4																	
4	5																	
5	1																	
5	2																	
5	3																	
5	4																	
5	5																	
Total cargo in leg																		

Table 39 – 1st test. Second step of the CiL matrix.(Not all rows of the matrix are showed here) Now we must complete the groups of legs. The first group of leg will have only one leg, since the cargo is loaded at the 5<sup>th</sup> call and unloaded at the 6<sup>th</sup>. The second group of legs starts with the cargo loading at the 7<sup>th</sup> call and only ends in the 9<sup>th</sup> call. Similarly the third group of legs has two legs.

Origin of the leg Cargo Origin	Cargo Destin.	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs
1	1																	
1	2					1		2	2						3	3		3
1	3	1	1					2	2	2					3			3
1	4	1						2	2	2	2	2						2
1	5							1										1
2	1						1											3
2	2																	3
2	3	3	3						1		2	2	2	2		3		3
2	4	2								1								2
2	5					1	1			2	2							2
3	1			1	1					2	2	2	2			3	3	3
3	2			1	1	1				2						3		3
3	3																	
3	4	3		1						2	2					3	3	3
3	5			1	1	1	1	1		2	2	2	2					2
4	1				1								2	2				2
4	2				1	1							2	2	2	2		2
4	3		1		2	2	2	2	2				3	3	3			3
4	4																	
4	5				1	1	1	1				2						2
5	1												1					1
5	2								1				2	2	2			2
5	3								1	1			2	2				2
5	4	2							1	1	1	1		2	2	2	2	
5	5																	
Total cargo in leg																		

Table 40 – 1st test. Steps of the CiL matrix. Using the same procedure for all other cargo types, thus drawing all the groups of legs

Cargo Origin	Cargo Destin.	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs	
1	1																		
1	2					1		2	2						3	3		3	
1	3			1	1			2	2	2					3	3		3	
1	4				1			2	2	2	2				3	2		2	
1	5							0										1001	
2	1						1						2	2	2		3		3
2	2																		
2	3	3	3							1		2	2	2	2	3		3	
2	4			2								1				2		2	
2	5						1	1				2	2					2	
3	1				1	1					2	2	2	2		3	3		3
3	2				1	1	1			2					3			3	
3	3																		
3	4	3			1					2	2				3	3		3	
3	5				1	1	1	1	1	2	2	2				2			
4	1					1							2	2				2	
4	2					1	1						2	2	2	2		2	
4	3			1		2	2	2	2	2			3	3	3			3	
4	4												2						
4	5					1	1	1	1				2					2	
5	1													300				1001	
5	2									1			2	2	2			2	
5	3									1	1		2	2				2	
5	4	2								1	1	1	1		2	2	2	2	
5	5																	2	
Total cargo in leg																			
		300																	

Table 41 – 1st test. 1<sup>st</sup> cargo distribution of the CiL matrix. To distribute the cargo the code looks to the last columns and starts from bottom to top by the types which have only one group of legs and replaces the entries in the matrix by the cargo carried. In the type from 5 to 1 there are 300 containers so place it and change the number of groups of legs to 1001 (so the code never calls that type of cargo again). For the type 1 to 5, there are 0 containers, changing nothing.

From	To	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs	
1	1																		
1	2					1		2	2						3	3		3	
1	3	1	1					2	2	2					3			3	
1	4	1						2	2	2	2				2			2	
1	5							0										1001	
2	1						1						2	2	2		3		3
2	2																		
2	3	3	3						1		2	2	2	2		3		3	
2	4	2								1						2		2	
2	5					1	1				2	2						2	
3	1			1	1						2	2	2	2		3	3		3
3	2			1	1	1				2					3			3	
3	3																		
3	4	3		1						2	2				3	3		3	
3	5			1	1	1	1	1		2	2	2				2			
4	1				1								2	2				2	
4	2				1	1							2	2	2	2		2	
4	3	1		2	2	2	2	2	2				3	3	3			3	
4	4																		
4	5				1	1	1	1					2					2	
5	1													300				1001	
5	2								1				2	2	2			2	
5	3								1	1			2	2				2	
5	4	2							1	1	1	1		2	2	2	2		
5	5																	2	
Total cargo in leg																			
		300																	

Table 42 – 1st test. 2<sup>nd</sup> cargo distribution of the CiL matrix. Now the code considers types which have only two groups of legs, from bottom to top. The next step is distribute the cargo from 5 to 4. There are 300 containers and we must distribute them through the groups of legs. Attempting to balance the cargo carried by the vessel throughout the legs, we take the total cargo in leg in the legs of the first group of legs and see its maximum is 0

container. The same maximum for the second group of legs is 300. In these situations the code takes the available containers and fills the lower group of legs until its maximum total cargo in legs is the same as the other group of legs, and then splits the remaining containers (see next table).

From	To	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs
1	1																	
1	2					1		2	2						3	3		3
1	3	1	1					2	2	2					3	3		3
1	4							2	2	2	2							2
1	5							0										1001
2	1						1						2	2	2			3
2	2																	
2	3	3	3						1			2	2	2	2			3
2	4										1							2
2	5							1	1				2	2				2
3	1			1	1						2	2	2	2	3	3		3
3	2			1	1	1				2					3			3
3	3																	
3	4	3		1						2	2				3	3		3
3	5			1	1	1	1	1		2	2	2			3	3		2
4	1				1								2	2				2
4	2				1	1							2	2	2	2		2
4	3			1		2	2	2	2	2	2		3	3	3			3
4	4																	
4	5					1	1	1	1				2					2
5	1														300			1001
5	2								1					2	2	2		2
5	3								1	1				2	2			2
5	4	0							300	300	300	300		0	0	0	0	1001
5	5																	
Total cargo in leg						300	300	300	300	300	300	300	300	300				

Table 43 – 1st test. 2<sup>nd</sup> cargo distribution in the CiL matrix.

From	To	1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs	
1	1																		
1	2					1		2	2						3	3		3	
1	3	1	1					2	2	2					3			3	
1	4	0						0	0	0	0							1001	
1	5							0										1001	
2	1						1						2	2	2			3	
2	2												2	2	2	2		2	
2	3	3	3						1			2	2	2	2			3	
2	4	600										0						600	
2	5						600	600				0	0					1001	
3	1			1	1						2	2	2	2		3	3		3
3	2			1	1	1					2					3			3
3	3																		
3	4	3		1							2	2				3	3		3
3	5			0	0	0	0	0		300	300	300						1001	
4	1					150							150	150				1001	
4	2					800	800						200	200	200	200		1001	
4	3			1		2	2	2	2	2			3	3	3			3	
4	4																		
4	5					300	300	300	300				300					1001	
5	1												300					1001	
5	2								300				300	300	300			1001	
5	3								300	300			300	300				1001	
5	4	0							300	300	300	300		0	0	0	0	1001	
5	5																		
Total cargo in leg		600		1250	1100	900	900	900	600	600	600	600	950	1250	800	500	600		

Table 44 – 1st test. 3<sup>rd</sup> cargo distribution in the CiL matrix. Distribution of groups of legs with two legs

1	4	3	4	1	2	1	5	2	3	2	4	5	1	3	2	Nr group of legs		
				0		100	100					200	200				1001	
0	0					0	0	0				0					1001	
0						0	0	0	0								1001	
						0											1001	
						150			0	0	0				450		1001	
0	0						300		0	0	0	0			0		1001	
600								0		0					600		1001	
						600	600		0	0							1001	
		0	0					0	0	0	0		0	0			1001	
		0	0	0				0				0					1001	
0		0						0	0					0	0		1001	
0		0	0	0	0			300	300	300							1001	
						150					150	150						1001
		800	800							200	200	200	200					1001
1000		0	0	0	0	0				0	0	0						1001
		300	300	300	300				300									1001
						300					300	300	300					1001
0						300	300	300	300		0	0	0	0				1001
600	1000	1250	1100	1050	1000	900	900	600	600	950	1250	1000	700	1050				

Table 45 – 1st test. Final step of cargo distributions in the CiL matrix, for types with three groups of legs.

		0		100	100					200	200			1001	
0	0			0	0	0				0				1001	
0				0	0	0	0							1001	
				0										1001	
		150						0	0	0			450	3	
0	0					300		0	0	0	0		0	1001	
600								0					600	1001	
		600	600					0	0					1001	
	0	0						0	0	0	0		0	1001	
	0	0	1					0					0	1001	
0	0							0	0				0	1001	
0	0	0	0	0	0			300	300	300				1001	
		150									150	150			1001
		800	800								200	200	200	200	1001
1000		0	0	0	0	0				0	0	0			1001
		300	300	300	300				300						1001
					300						300	300	300		1001
					300						300	300	300		1001
0					300	300	300	300			0	0	0	0	1001
600	1000	1250	1100	1050	1000	900	900	600	600	950	1250	1000	700	1050	

Table 46 – 1st test. Final cargo distributions in the CiL matrix