

A numerical tool for the planning of container ship fleets

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ABSTRACT

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.

1. INTRODUCTION

1.1. Context

Every year ten thousand millions of tons of goods are transported by sea. 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.

As a market, container shipping is heavily characterized by economic cycles, which strongly influence the level of freight rates (i.e. the price of shipping services. Of key importance are the short cycles.

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. 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. The ship is a multi-parcel equation centred on the vessel 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 and its 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.

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 issue is mostly computational, and is handled by a process called the 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 issue is, in its essence, a problem of programming and relies on logic and a small number of simple mathematical relations. The second issue is much less of programming and much more of modelling. This requires the extensive use of physical formulas and of empirical relations as to produce a mathematical relation between the outputs and the input data and the size of the vessel. The tool which solves these two issues must be flexible enough to allow 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.

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

1.3. Structure

The thesis is divided in chapters. The first chapter is the present Introduction. The second chapter is the State of the Art, where other works, projects, or academic and scientific research on the relevant topics are reviewed.

The third chapter is the Methodology. This chapter explains in detail the methods implemented in the tool. It explains the desired outputs and discusses the used variables and how they relate to the inputs, to the outputs, and to other variables. It also goes into detail on the algorithmic procedures which process the user inputs into the outputs.

The fourth chapter is entitled ‘Numerical Results’. This chapter contains the random input trials used to guarantee the validity of the tool. This chapter also contains the three case studies, including the inputs used, the outputs obtained, and the discussion of those outputs.

The fifth and final chapter is the ‘Conclusions and Further Works’. The goal there is to both present the major conclusions of this thesis and 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. The first aim is to give a sense of the state of the collective knowledge on the subject of liner shipping, by exploring existing models which describe liner shipping and its components. The second goal is to place this thesis’ work within the context of other current projects and of modern research on the topic.

2.1. Containers and Container Ships

Containers is a term referring to the intermodal container used to transport small parcels of dry goods. In this thesis containerships are either twenty feet long (a TEU container) or forty feet long (a FEU), either empty or full, and either regular or refrigerated (reefer). Containership vessel will be defined by their capacity in TEUs (twenty feet equivalent units) and the tool is designed for capacities from five hundred TEUs 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. Each region has many ports and shipping companies operating in-between regions 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. 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. Although a round voyage can connect ports in any combination the company wishes, they tend to take certain configurations.

Ducruet and Notteboom wrote on the configurations of liner service networks (Ducruet & Notteboom, 2012), including the line bundling service and the circular line service.

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.

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 and of port calling, and the costs that depend on the cargo handled.

As do Santos (2016), Murray (2015), and Merk et al. (2015), the tool uses empirical relations between these costs and the ship size.

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. The thesis considers eight publications (Fagerholt, 2004, Hsu and Hsieh, 2007, Martins et al, 2010, Polat, et al., 2014, Plum, et al., 2014, Agarwal and Ergun, 2008, Koza, 2017, and Ye, et al, 2007) on the topic and how the authors solved the round voyage design problem, usually making use of network optimization methods and fixing the fleet size

3. METHODOLOGY

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.

Summarily, 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. The Fleet Sizing Process

This section explains the computational process by which the tool finds the required ship size of the fleet's ships, in TEUs. It is explained both with examples and with each step of the algorithm

3.3. Estimation of the 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 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 [m^3], the ballast capacity [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).

The operating speeds are given a particular focus. The tool estimates the possible vessel speeds from published data on both design speeds and lowest operating speeds and then proceeds to verify which of these allow for the completion of the voyages within the user specified duration of the round voyage.

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. The resulting operating cost are in Figure 1.

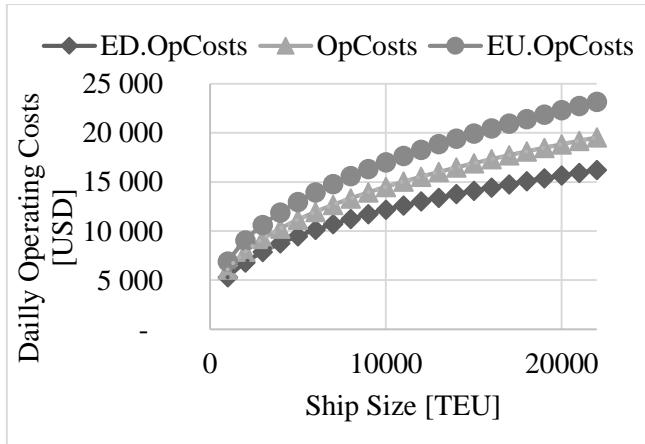


Figure 1 – Daily Operating Costs [USD] over the Ship Size [TEU], for the three cost scenarios

The operating costs for the maximum, expected, and minimum cost scenarios respectively, are in Equations 1, 2, and 3.

$$EU.OpCosts = 464.56 \cdot (\text{Ship Size})^{0.391} \cdot 365 \quad (1)$$

$$OpCosts = 449.08 \cdot (\text{Ship Size})^{0.3773} \cdot 365 \quad (2)$$

$$ED.OpCosts = 434.55 \cdot (\text{Ship Size})^{0.362} \cdot 365 \quad (3)$$

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 scrapped (also known as shipbreaking) at the end of their lives. This expense is calculated by equalling the present value (*NPV*) of the capital costs to that of the separate payments (Equation 4). To do so, the code uses the discount rate of the investment, which is a user input.

$$\sum_{N=1}^{\text{Term.of.the.loan}} \frac{(Interest_i + Instalment_i)}{(1+DRate)^N} - \frac{\text{Scrap.Value}}{(1+DRate)^{\text{Ship.Life}}} + \\ Sb.Cost \cdot (1 - \text{Loan.Value}) = \sum_{N=1}^{\text{Ship.Life}} \frac{\text{CapCosts}}{(1+DRate)^N} \quad (4)$$

Where *Sb.Cost* ($1 - \text{Loan.Value}$) is the initial investment in the ship [USD], and *DRate* is the discount rate.

Assuming a fixed principal payment loan, the annual instalment and the annual interest are in Equations 5 to 8. The value of scrapping the vessel is given in Equation 9.

$$Instalment_i = \frac{\text{Loan.Value}}{\text{Term of the loan}} \quad (5)$$

$$RDebt_0 = \text{Loan.Value} \cdot SbCost \quad (6)$$

$$RDebt_i = \begin{cases} RDebt_{i-1} - Instalment_i, & \text{if } i \leq \text{Term.of.Loan} \\ 0, & \text{if } i > \text{Term.of.Loan} \end{cases} \quad (7)$$

$$Interest_i = RoI \cdot Remaining.Debt_{i-1} \quad (8)$$

$$Scrap.Value = Lightweight \cdot Price.Scrap \quad (9)$$

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.

3.4.3. Port Costs

An analysis of the pricing schemes of several ports shows that port charges usually depend on the same ships characteristics, chiefly the gross tonnage. From this result the tool uses the port charges as in Equations 10 and 11.

$$Port.Costs = \sum_i (Call.Costs_i \cdot \frac{(365 - Off.Hire)}{TFRV}) \quad (10)$$

$$Call.Costs_i = Fixed_i + Size_i \cdot Ship.Size + Tonn_i \cdot GT + Time_i \cdot Time.in.Berth_i + Cargo_i \cdot Nr.Cont.Handled_i \quad (11)$$

Where, *Port.Costs* are the total port charges of a vessel in a year [USD]; *Call.Costs_i* is the costs of calling once at the *ith* port of call of the round voyage; *TFRV* is the time for a round voyage; *Off.Hire* is the annual off-hire, taken as fifteen days; *Fixed_i* is a fixed charge for calling in the *ith* port of call of the round voyage, *Size_i* is a fee per [TEU] of the ships capacity the *ith* port of call of the round voyage, *Tonn_i* is a fee levied per unit of ship gross tonnage in the *ith* port of call of the round voyage, *Time_i* is a fee levied per hour of berth usage in the *ith* port of call of the round voyage, *Cargo_i* is an expense per container handled in the *ith* port of call of the round voyage, and *Nr.Cont.Handled_i* is the number of containers handled in the *ith* port of call of the round voyage.

Since *Fixed_i*, *Size_i*, *Tonn_i*, *Time_i*, *Cargo_i*, and *Nr.Cont.Handled_i* are input values, there is flexibility to set the parameters as to fit each of the ports in the round voyage.

3.4.4. Fuel Costs

The cost of fuel in a vessel is given by Equation 12. 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.

$$Fuel.Costs = Price.IFO \cdot Consumption.IFO \cdot \left(\frac{365 - Off.Hire}{TFRV} \cdot \frac{STRV}{24} \right) + Price.MDO \cdot Consumption.MDO \cdot (365 - Off.Hire) \quad (12)$$

Where: *Price.IFO* is the price of IFO [UDS / t]; *Consumption.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]; *Consumption.MDO* is the daily consumption of MDO [t / day]; and *Off.Hire* is the annual off-hire, taken as fifteen days. Note: $(365 - Off.Hire) / TFRV$ is the number of round voyages in a year.

It is possible to derive the IFO consumptions for the expected, maximum, and minimum cost scenarios (Equations 13, 14, and 15).

$$EU.IFO.Cons = (1.2710 \cdot 10^{-11} \cdot x^3 - 6.94582 \cdot 10^{-7} \cdot x^2 + 0.0289068 \cdot x + 44.969) \cdot \left(\frac{\text{Operating.Speed}(x)}{23} \right)^3 \quad (13)$$

$$IFO.Cons = (9.77757 \cdot 10^{-12} \cdot x^3 - 5.34294 \cdot 10^{-7} \cdot x^2 + 0.022236 \cdot x + 33.9207) \cdot \left(\frac{\text{Operating.Speed}(x)}{23} \right)^3 \quad (14)$$

$$ED.IFO.Cons = (6.84430 \cdot 10^{-12} \cdot x^3 - 3.74006 \cdot 10^{-7} \cdot x^2 + 0.0155652 \cdot x + 23.7445) \cdot \left(\frac{\text{Operating.Speed}(x)}{23} \right)^3 \quad (15)$$

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 [knots].

The MDO consumption is modelled as a function of the electric requirements of the: the ship systems, the refer containers, and the cranes (Equations 16 to 22).

$$Consumption.MDO = Base.Cons.MDO + Reefer.Cons.MDO + Crane.Cons.MDO \quad (16)$$

$$Base.Cons.MDO = 24 \cdot Gen.Sp.Cons \cdot Base.Electric.Power \quad (17)$$

$$Base.Electric.Power(x) = Av.Gen.Power(x) \cdot (Nr.Gen - 1) \cdot 0.5 \quad (18)$$

$$Av.Gen.Power(x) = \frac{EIP}{Nr.Gen} \quad (19)$$

$$Reefer.Cons.MDO = CCpM \cdot Nr.Cont.Handled \quad (20)$$

$$Reefer.Cons.MDO(x) = 24 \cdot Gen.Sp.Cons \cdot Total.Reefer.Power \quad (21)$$

$$Total.Reefer.Power = \sum_{i=1}^{Ncalls-1} \left((Power.RET \cdot Nr.RET_i + Power.REF \cdot Nr.REF_i) \cdot \left(\frac{LDist_i}{Operating.Speed} + 0.5 \cdot (TPRV_i + TPRV_{i+1}) \right) \right) \quad (22)$$

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], 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], *Av.Gen.Power* is the average power of a generator [kW], *EIP* 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, *CCpM* is the average crane consumption per container handled [t], and *Nr.Cont.Handled* is the number of containers handled, *Total.Reefer.Power* is the power required for reefer containers over the round voyage [kWh], *Power.RET* is the power consumed by a reefer TEU container [kW], *Nr.RET_i* is the number of TEU reefer container in the voyage leg from the *i*th and the (*i*+1)th calls of the round voyage, *Nr.REF_i* is the number of FEU reefer container in that leg of the voyage, *LDist_i* is the sailing distance in that leg, *TPRV_i* is the time spent in the *i*th call, and *LDist_i / Operating.Speed + 0.5 (TPRV_i + TPRV_{i+1})* is the time the containers consume

energy during that leg [h] (which includes the sailing time and half the time in both ports).

3.4.5. Canal Costs

The costs of canals are given by Equation 23. The number of crossings is estimated from the round voyage and the cost per crossing is an input.

$$\frac{Total.Costs.Canals}{(365 - Off.Hire)} = (Costs.Canal_i \cdot Nr.Crossings_i) \cdot TFRV \quad (23)$$

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

3.4.6. Revenues

The revenues are calculated with Equation 24.

$$YRevenues = \sum_i FR_i \cdot NCont_i \quad (24)$$

Where, *FR_i* is the freight rate of containers of the type *i*, *NCont_i* 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.

3.5. Performance Indicators

The Net Profit, which is the annual profit of the fleet [USD], is given by Equation 25.

$$NP = TRev - TExp \quad (25)$$

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 Equation 26.

$$NPM = \frac{NP}{TRev} \quad (26)$$

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

Equations 27 and 28 are the formulas for the annual cost per TEU (*CpTEU*) and for the annual cost per mile (*CpMile*), respectively.

$$CpTEU = \frac{TExp}{Nr.TEU.H} \quad (27)$$

$$CpMile = \frac{TExp}{TDist} \quad (28)$$

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 Equations 29 and 30.

$$BufferT = TFRV - TRV \quad (29)$$

$$BufferR = \frac{BufferT}{TFRV} \quad (30)$$

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

This section explains the various subroutines, which are called by the code during the running of the tool.

4. NUMERICAL RESULTS

4.1 Tests of the tool

This section is dedicated to an essential step in the development of the tool: the trials. Each of them 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 well defined rules which randomly generate each input.

When compared, the handmade outputs and the tool outputs match perfectly in the vast majority of values match. 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.

4.2.1 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 2). This route is a feeder route with the hub in Singapore, meaning all cargo is either originated in or destined to Singapore.

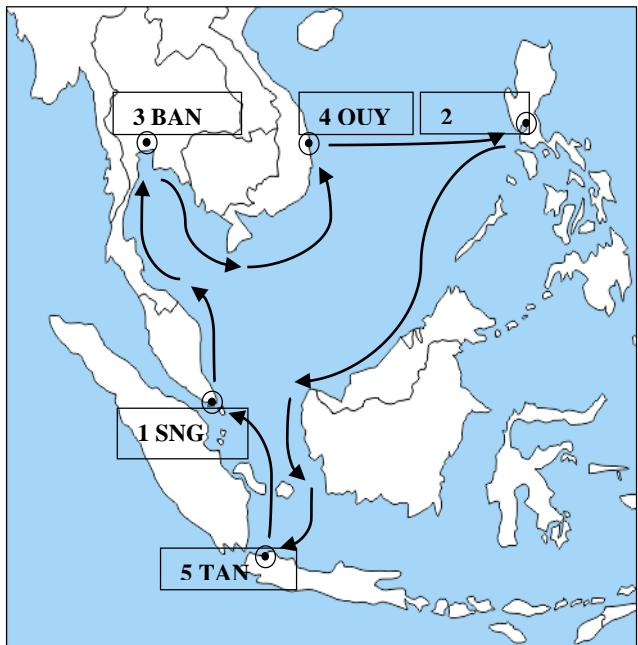


Figure 2 – Representation of the geographic location of the ports and of the voyage in the intra-Asian route. Base map from www.outline-world-map.com. Key: 1 – Singapore; 2 – Manila; 3 – Bangkok; 4 – Quy Nhon; 5 – Jakarta.

All inputs were set according to the publicly available information. These inputs include the port's data, each port's pricing scheme, the distances between ports, the cargo flows, and the freight rates. In this case study, there is only one circular service round voyage with

different durations, see Table 1. In short services, the schedules tend to be weekly, biweekly or monthly.

Figure 3 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.

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 1 – Round Voyages for the Intra-Asian Route.

Fleet Size 1 Ships with 9300.00 TEUs					
For this cruise speed 17.0000 [kn]					
For these cost scenarios			Maximum		
Performance Indicators			Expected		
For the whole fleet every year			Minimum		
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	[%]			
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 3 – Main results for the Intra-Asian route in the forty five days long circular voyage, with one vessel with 9300 TEUs of capacity, at 17 knots.

Figure 4 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.

Figure 5 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.

Figure 6 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.

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

Fleet Size	1 Ships with 6200.00 TEUs
For this cruise speed	17.0000 [kn]
For these cost scenarios	
Performance Indicators	Maximum
For the whole fleet every year	Expected
Net Profit	-5375000
Net Profit Margin [%]	-19
Cost per TEU Handled	608
Cost per Mile Sailed	1039
Net Profit (without ship purchase)	2797000
Net Profit Margin (without ship purchase) [%]	11
Cost per TEU Handled (without ship purchase)	457
Cost per Mile Sailed (without ship purchase)	781
Buffer Time (per vessel, per RV)	370
Buffer Ratio	50.7520
Ship Costs	[h]
For one ship every year	[%]
Operating Costs	5155000
Capital Costs	8172000
Port Costs	12110000
Fuel Costs	7509000
Canal Costs	0
Total Costs	32945000
Voyage Costs	19619000
Revenue	27570000
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 4 – Main results for the Intra-Asian route in the thirty day long circular voyage, with one vessel with 6200 TEUs of capacity, at 17 knots.

Fleet Size	1 Ships with 3100.00 TEUs
For this cruise speed	16.0000 [kn]
For these cost scenarios	
Performance Indicators	Maximum
For the whole fleet every year	Expected
Net Profit	1633000
Net Profit Margin [%]	6
Cost per TEU Handled	477
Cost per Mile Sailed	409
Net Profit (without ship purchase)	6658000
Net Profit Margin (without ship purchase) [%]	25
Cost per TEU Handled (without ship purchase)	385
Cost per Mile Sailed (without ship purchase)	330
Buffer Time (per vessel, per RV)	90
Buffer Ratio	22.3900
Ship Costs	[h]
For one ship every year	[%]
Operating Costs	3931000
Capital Costs	5025000
Port Costs	10875000
Fuel Costs	6107000
Canal Costs	0
Total Costs	25937000
Voyage Costs	16982000
Revenue	27570000
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 5 – Main results for the Intra-Asian route in the fifteen day long circular voyage, with one vessel with 3100 TEUs of capacity, at 17 knots.

For the round voyage number	4
1	3
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 consider other solutions with more ships

Figure 6 – Main results for the Intra-Asian route in the seven day long circular voyage.

4.2.2 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 7). Note: the port of Jeddah is a blank call.

All inputs were set according to the publicly available information. These inputs include the port's data, each port's pricing scheme, the distances between ports, the cargo flows, the freight rates, and the Suez Canal costs.

The one round voyage which is considered, shown in Table 2, is to last ninety days. This value is due to some of the freight rate calculators used stating that the transit time for a container from Europe to Shanghai is around forty to fifty days.

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

Table 2 – Round Voyage for the Northern Europe to East Asia Route.

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 8 with the minimum buffer ratio being ten percent.

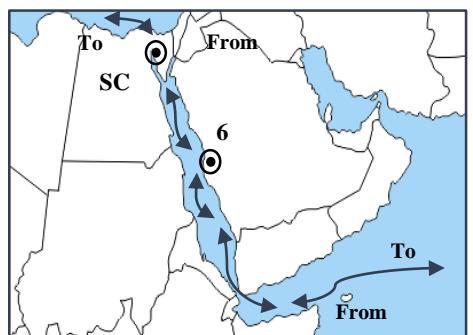
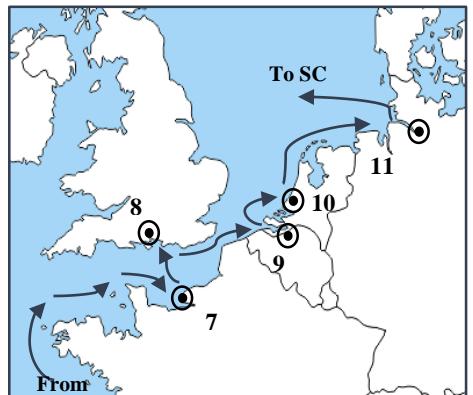
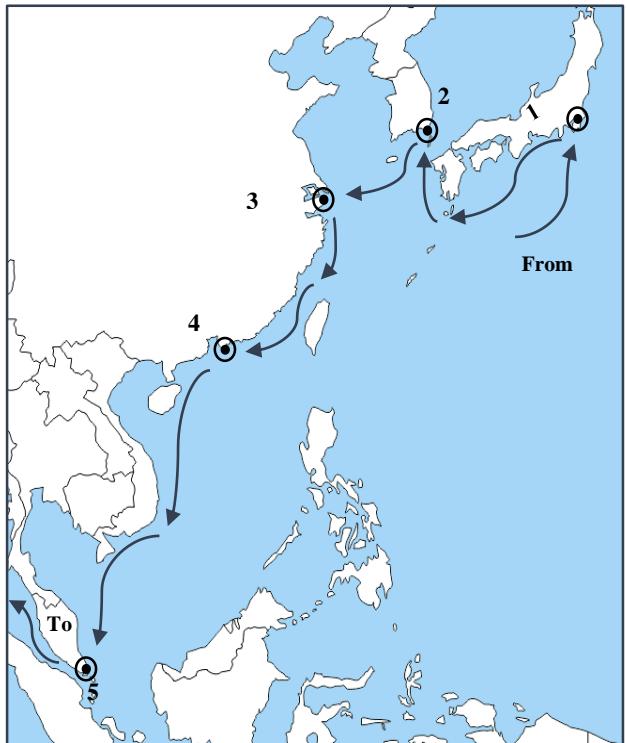


Figure 7 – Representation of the geographic location of the ports and of the voyage in the East Asia to Northern Europe route. Key: 1 – Tokyo; 2 – Busan; 3 – Shanghai; 4 – Hong Kong; 5 – Singapore; 6 – Jeddah; 7 – Le Havre; 8 – Southampton; 9 – Antwerp; 10 – Rotterdam; 11 – Hamburg; and SC – Suez Canal.

Fleet Size 2 Ships with 12100.0 TEUs

For this cruise speed	17.0000	[kn]
For these cost scenarios	Maximum	Expected
Performance Indicators		
For the whole fleet every year		
Net Profit	-21787000	-4731000
Net Profit Margin [%]	-22	-4
Cost per TEU Handled	1500	1282
Cost per Mile Sailed	1257	1075
Net Profit (without ship purchase)	-8963000	3603000
Net Profit Margin (without ship purchase) [%]	-9	4
Cost per TEU Handled (without ship purchase)	1336	1176
Cost per Mile Sailed (without ship purchase)	1120	986
Buffer Time (per vessel, per RV)	390	16
Buffer Ratio	17.6110	[%]
Ship Costs		
For one ship every year		
Operating Costs	6695000	5690000
Capital Costs	12824000	8334000
Port Costs	18349000	18349000
Fuel Costs	19132000	16100000
Canal Costs	1881000	1881000
Total Costs	58880000	50352000
Voyage Costs	39362000	36329000
Revenue	47986000	[USD]
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	[%]

	Nominal Costs		
	Maximum	Expected	Minimum
Operating	6.695	5.69	4.768
Capital	12.824	8.334	4.66
Port	18.349	18.349	18.349
Fuel	19.132	16.1	13.103
Canal	1.881	1.881	1.881
Total	58.88	50.352	42.759

	Deviations	
	Maximum	Minimum
Operating	17.7%	-16.2%
Capital	53.9%	-44.1%
Port	0.0%	0.0%
Fuel	18.8%	-18.6%
Canal	0.0%	0.0%
Total	16.9%	-15.1%

	Cost splits		
	Maximum	Expected	Minimum
Operating	11%	11%	11%
Capital	22%	17%	11%
Port	31%	36%	43%
Fuel	32%	32%	31%
Canal	3%	4%	4%
Revenues		47.986	

Figure 8 – 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 3 contains the annual vessel costs for both voyages, the deviations of the costs scenarios, and the cost splits.

From Table 3 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.

Table 3 – 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.

4.2.3 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 9) which suits a fleet of three small ships which is currently serving this route using three separate round voyages. The capacities of these vessels are around 600-650 TEU. Thus the goal is to find a round voyage which lasts fifteen days and where a four 600-650 TEU vessel fleet is optimal.

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).

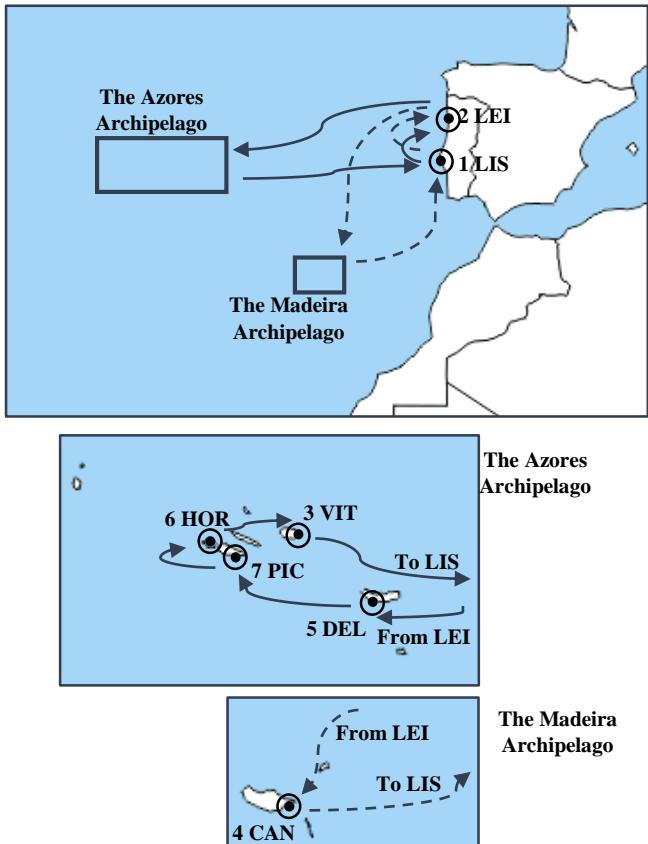


Figure 9 – Representation of the geographic location of the ports and of the circular with pendulum voyage in the Portuguese case study. Key: 1 – Lisbon; 2 – Leixões; 3 – Praia da Vitória; 4 – Caniçal; 5 – Ponta Delgada; 6 – Horta; and 7 – Pico.

To test the various possibilities, combinations of four round voyages and three durations of round voyages are used (Table 4). 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 4 – Voyages of the Portuguese route.

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 5) is the net profit margin.

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

Table 5 – Main results for the voyages of the Portuguese Condition. ‘n.p.’ stands for ‘not possible’.

From Table 5, 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 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.

Thus, 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

5. CONCLUSIONS AND FURTHER WORKS

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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