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Petar Georgiev
Yordan Garbatov

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MULTIPURPOSE VESSEL FLEET FOR SHORT BLACK SEA SHIPPING THROUGH MULTIMODAL TRANSPORT CORRIDORS

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Summary

A study about the requirements and cargo transportation demand in the Black Sea as part of a multimodal transportation frame is performed, estimating the potential need of a ship fleet of multipurpose ships. The study performs conceptual multipurpose vessel design and fleet sizing using the long-time experience and statistics in defining main dimensions of the ship and her hull form, resistance and propulsion, weights, stability, free-board, seakeeping and manoeuvrability, capital, operational and decommissioning expenditure, where the optimal design solution is obtained based on the energy efficiency, shipbuilding, operation, and resale costs at the end of the service life. A discussion about possible applications of a different fleet of ship sizes in improving the cargo transportation efficiency considers the vessel's typical operational profile in such a way to maximise the economic impact conditional of the unsteady cargo flow and environmental impact.

Keywords: *Black Sea; fleet size; ecological impact; multimodal transport; short sea shipping; Three seas initiative*

1. Introduction

Models for short sea shipping have been intensively developed in the last two decades in connection to intermodal cargo transportation through the sea and roads, where some recent studies can be found in [1-3]. In a series of studies in [4, 5], transport chains along the motorway of the Sea of Western Europe and the impact of external costs in short sea shipping services were analysed. The "Glossary for transport statistics" [6] defines multimodal transport as the transport of goods by at least two different modes of transport. Intermodal transport is a particular type of multimodal transport using the same transport unit by successive modes without handling the goods themselves when changing modes. The intermodal transport units are container, swap body or a loaded vehicle travelling on another vehicle.

The EU Directive 92/106/EEC (December 1992) established standard rules for the specific combined transport of goods (considered multimodal transport) between the Member States. According to the Report on Combined Transport (CT) from 2020, approximately two-thirds (62%) of the units are containers, 21% semi-trailers and 17% swap bodies. The most used units among the groups are 40' containers – 43%; Standard non-craneable semi-trailers- 49% and swap bodies, Class A – 41%.

Several intergovernmental initiatives: Burgas Ministerial Declaration of 31 May 2020 towards a Common Maritime Agenda for the Black Sea[1]; the BSAM[2] (Black Sea Assistance Mechanism) project funded by EU; introducing the SRIA (Strategic Research and Innovation Agenda for the Black Sea), supported by relevant agreements and projects determine the future development of multimodal transport across the Black Sea. These latest acts are also the basis for the motivation of this study.

One of the main areas of activity of the Three Seas Initiative (3SI)[3] is developing infrastructure for transport, along the North-South axis, by supporting cross-border and transnational projects. The 3SI was established in 2015 as a platform for cooperation between three seas: the Baltic, the Adriatic, and the Black Sea. The countries taking part in the initiative are Austria, Bulgaria, Croatia, Czech Republic, Estonia, Hungary, Latvia, Lithuania, Poland, Romania, Slovakia, and Slovenia (Fig. 1). Out of the 77 priority projects which were announced, 51% are in transport. The estimated demand for transport investments in the 3SI for inland and maritime transport in the decade until 2030 is about 13 bn € (about 5% of the total necessary investments for the transport).

Fig. 1. Countries of Three-sea initiative [adopted from https://www.3seas.eu/media/news/secretariat-of-the-three-seas-was-created], (left) and South-north corridors (right)

Ruse-Varna railway line is an essential part of the transport chain across the countries of 3SI from Port of Varna on the Black Sea to Port of Gdansk on the Baltic Sea. Two transport corridors by train (left) and by truck (right) are presented in Fig. 1 (right). *EcoTransIT World*[4] (Ecological Transport Information Tool for Worldwide Transports) offers an emission calculator for greenhouse gases and exhaust emissions for different services. Table 1 evaluates two South-North corridors. The amount of cargo is 100 TEU containers (10 t/TEU).

Table 1 Greenhouse gases and exhaust emissions for two South-North corridors

Transport service	Distance, km	GHG (calc.as CO_2 equiv.), tonnes	Sulfur dioxide (SO_2), kg	Nitrogen oxides (NOx), kg	Non-methane hydrocarbon (NMHC), kg	Particulate matter (PM10), kg
Train	2,100	2	0.01	24	1	0.3
Truck	1,945	100	0.66	269	4	4.3

Note: All figures for Tank-to-Wheel (TTW) assessment

1 http://www.bsec-organization.org/areas-of-cooperation/bsec-eu-cooperation/common-maritime-agenda

2 https://blackseablueconomy.eu/

3 https://3seas.eu/

4 https://www.ecotransit.org/en/emissioncalculator/#

The benefits of transporting containers from the Black Sea through the 3SI countries by train are indisputable, and this coincides with the strategic objectives of the European Green Deal.

The objective of the study here is to perform MPV fleet sizing for the transportation flow in the Black Sea region as short shipping through multimodal transport corridors using the long-time experience and statistics in defining the optimal ship design solution obtained based on the energy efficiency, shipbuilding, operation, and resale costs at the end of the service life.

2. Transportation flow in the Black Sea region

The development of world trade influences the development of ships for the carriage of containers. Specialised container ships are the fastest-growing type of ship, and over 60 years, the container capacity has increased more than 25 times [7]. Despite that, from 2011 to 2016, the demand for container shipments was lower than the available capacity of the vessels. The World Container Index, WCI, has continually been growing with minor exceptions, as shown in Fig. 2.

In the first half of 2019, the Black Sea container terminals of Bulgaria, Georgia, Romania, Russia, and Ukraine handled 1,582,932 TEU containers, including empty containers and excluding transhipped containers (Fig. 2). The number of full containers was 1,176,621 TEU (74.33% from total). The total growth achieved from these five countries in the first half of 2019 was 8.52% compared to the same period from the previous year, 2018. There is an increase in turnover in all countries except Russia. In the first half of 2019, the highest growth was achieved by Georgia and Ukraine, 30.62% and 17.89%, respectively. 57.54% of the processed full containers were imported during this period, and 42.46% were exported.

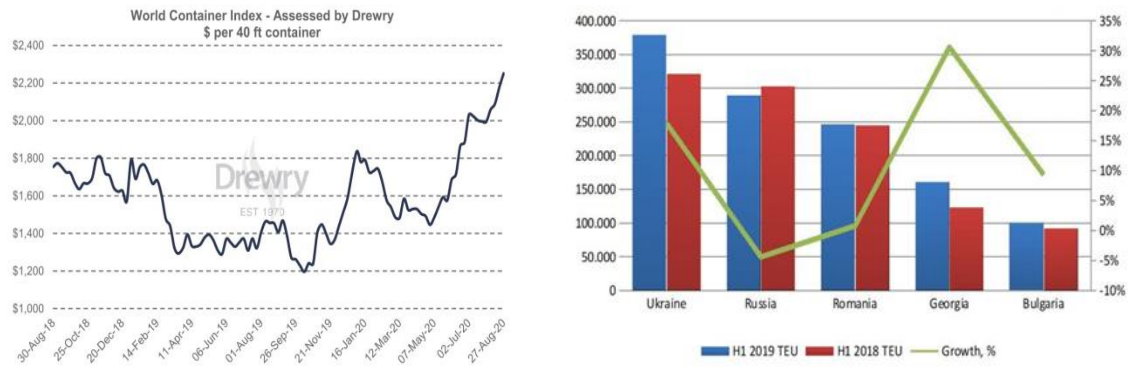


Fig. 2. WCI amendment for the last two years, https://www.drewry.co.uk/, (left) and container transport for the first half of 2019 in the Black Sea [8] (right)

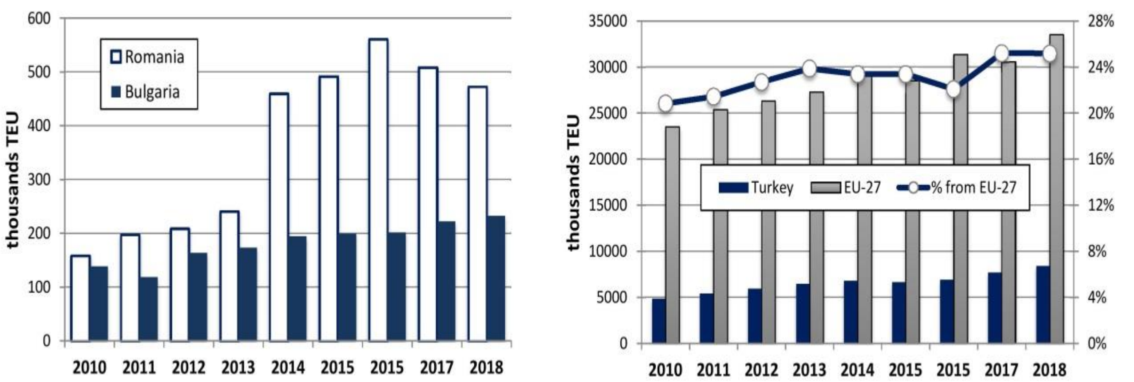


Fig. 3. Container transport for both EU countries in the Black Sea (left) and transported containers by Turkey and EU-27 (right) [9]

Thus, the percentage of containers with cargo handled by each country in the first half of 2019 is distributed as follows Ukraine - 32.21%, Russia (Black Sea) - 24.58%, Romania - 20.95 %, Georgia - 13.68% and Bulgaria - 8.58%. In terms of the leading carriers in the Black Sea, for the first time in recent years, ZIM entered the TOP-5 carriers, which are as follows: MAERSK, MSC, COSCO Shipping, ARKAS and ZIM. In total, these carriers controlled 71.40% of the market.

Eurostat statistics provide the development of container transport by country and for the E-27 as a whole. Fig. 3 presents a comparison between the volumes of container traffic for two EU member states in the Black Sea region. There has been continuous growth for Bulgaria since 2011, while Romania has declined volumes since 2015. Turkey is included in Eurostat's container transport statistics from 2010. Fig. 3 (right) compares the magnitudes of containers transported in Turkey and EU-27 countries. The percentage of Turkey container transport has been 20%-24% for the last eight years.

There are two container terminals in the ports of Poti and Batumi in Georgia. These ports serve 18 million people from the Caucasus region (Georgia, Azerbaijan, and Armenia) and another 145 million from landlocked countries in Central Asia (Kazakhstan, Uzbekistan, Turkmenistan, Kyrgyzstan, and Tajikistan). The growth of transported containers was 13% in the first quarter of 2018 compared to 2017 [10].

The Transport Corridor Europe-Caucasus-Asia (TRACECA)5 is an internationally recognised program to strengthen economic relations, trade and transport communication in the Black Sea region, the South Caucasus, and Central. The route includes the transport system of the 13 Member States: Azerbaijan, Armenia, Bulgaria, Georgia, Iran, Kazakhstan, Kyrgyzstan, Moldova, Romania, Tajikistan, Turkey, Ukraine, and Uzbekistan, including river transportation chains in the region [11, 12].

A better alternative to the TRACECA corridor is The Trans-Caspian International Transport Route (TITR), as shown in Fig. 4. Transportation of goods along this corridor began in 2013 by the port administrations of Azerbaijan, Kazakhstan, and Georgia. Proof of the vitality of this corridor is the announcement from "*Transport and Logstics.bg*" about train composition, which has travelled the distance from Khorgos, on the border between China and Kazakhstan to Izmit, Turkey, in 12 days.

The TITR organises the transport consisting of 43 FEUs carrying various goods. The block-train entered Kazakhstan via Altinkol railway station and travelled to the port of Aktau (Caspian Sea). From there, the containers were transported to the port of Baku in Azerbaijan by feeder ship. After crossing the Caspian Sea, the train got back on track, and through Akhalkalaki, Georgia reached the Turkish city of Izmit on the Baku-Tbilisi-Kars railway.

Fig. 4. Trans-Caspian International Transport Route (left) and the Caspian and Black Sea (right) (https://middlecorridor.com/en)

5 http://www.traceca-org.org/en/countries/).

Type	No TEU
Small feeder	Up to 1000
Feeder	1001 - 2000
Feeder max	2001-3000
Panamax	3001-5000
Post-Panamax	5001 – 8000
New Panamax	8001 – 1000
Ultra-large	above 10000

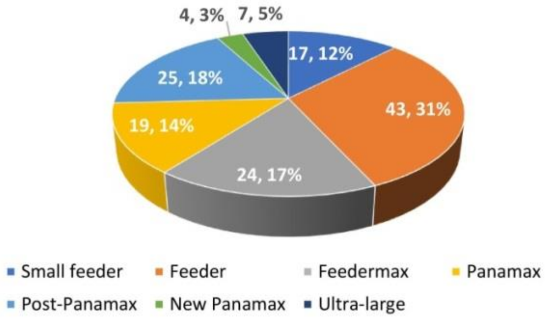


Fig. 5. Container ship types (left) and distribution of container ships by type visiting Black Seaports (right)

A recent study [13] provided statistical data for containerships visiting Black Sea ports. The ports of Varna, Burgas, Constanta, Odessa, Novorossiysk, Poti and Ambarli were visited by all possible container vessels (Fig. 5- left). Just over 50% of these ships are "Small feeder" and "Feeder"(Fig. 5 –right).

3. Ship design

A new design of multipurpose ships is performed to complete the fleet needed for the unsteady shipping through multimodal transport corridors across the Black Sea. A specialised container ship equipped with cell guides has the advantage of the container handling in the port, but the multipurpose vessel is universal. It can be used for different cargo flows within short sea shipping.

The ship design assesses the specific requirements, including aspects that relate to ship hull descriptors, capacity and visibility, ship operation, equilibrium, and initial stability, resistance and propulsion, motor match, lightweight, dead weight, cargo capacity, free-board, manoeuvrability, seakeeping, energy efficiency, ship strength, capital, operating and fuel and oil cost leading to required fright rate and cash flow analysis, due to the many variables involved in the design process.

The optimisation techniques can be categorised into three groups: mathematical programming techniques such as the genetic algorithm, stochastic process techniques such as the Markov process, and statistical methods such as the design of experiments [14]. The optimisation procedure generates a feasible region of possible design solutions. Still, not all design solutions are optimal for any given objective function, resulting in a trade-off between the objective functions [15]. To address the problem caused by the multiple objective functions, the Pareto (Frontier) optimality is employed [16], where a set of all Pareto optimal solutions represent the design space. The Pareto optimal solution is defined as the solution for which any improvement in one objective will worsen at least one other goal [17, 18].

The design includes several phases and processes to guarantee that the designed ship follows the customer's needs. The design is defined as a compromise multi-criteria decision support problem [19, 20] with multiple goal constraints. Given the owner's requirements about cargo capacity, speed, operational range, regulations and if existing data on similar ships to find the main ship dimensions and ship hull form descriptors [21] and satisfy system constraints related to ship cargo capacity and visibility, ship operation [22], equilibrium, and initial stability, resistance and propulsion, [23] ship-propeller-motor match [22, 24], cargo capacity, free-board, manoeuvrability [25], seakeeping [26], energy efficiency [27] and ship strength [28]. Safety bounds are imposed by ports and canals where necessary, and block coefficient lies between specific ranges [29, 30].

One of the most unstable governing parameters in the ship design is the voyage costs associated with the fuel costs, ports duties, tugs, pilotage, and canal charges. The vessel's operation at lower speeds results in fuel savings because of the reduced water resistance. The ship's revenue can be earned by transporting the cargo from one port to another port. However, the price to be charged to these services may vary where for the linear operator, it is tradition to include bunker and port handling costs in the freight rates. Defining the freight rate for cargo transportation on the assumed route requires numerous factors such as the real market demand of the region, more precise cost calculations, and others. However, for the present study, a fixed freight rate is assumed.

Two models in the ship design, related to the ship and voyage descriptions, are typically accounted for [31, 32]. The first includes the main ship dimensions, hull form generation, hydrostatics, free-board, resistance, propulsion, energy efficiency, lightship weight, cargo capacity, stability, and capital and decommissioning cost. The voyage model includes port sequence, voyage legs data, port/terminal data, cargo handled/port, round trip time/cost, annual cargo, and operational cost. The design solution has to satisfy the constraints related to entire ship systems.

The objective functions defined are to minimise the required fright rate, minimise fuel consumption, and determine the best ship-propeller-motor match. The design governing parameters are ship length, breadth, draft, depth, number of propeller blades, propeller speed, expanded area ratio, pitch ratio, and satisfy the energy efficiency design index, EEDI. The NSGA -II optimisation algorithm [33] satisfying a set of constraints is employed in the present study to ensure that the optimal solution can be obtained quickly with sufficient quantity and accuracy. Several studies related to ship design accounting for the limitations associated with the small and medium enterprises, SME end EEDI employing NSGA-II have been performed recently and can be seen in [34, 35].

The conceptual ship design performed here consists of a set of modules. It is considered a process of solving a system of equations that describes the ship performance using consistent approximations. The design solution is obtained by satisfying the constraints and requirements by modifying the controllable variables [32]. The concept design and optimisation methodology adopted here is shown in Fig. 6.

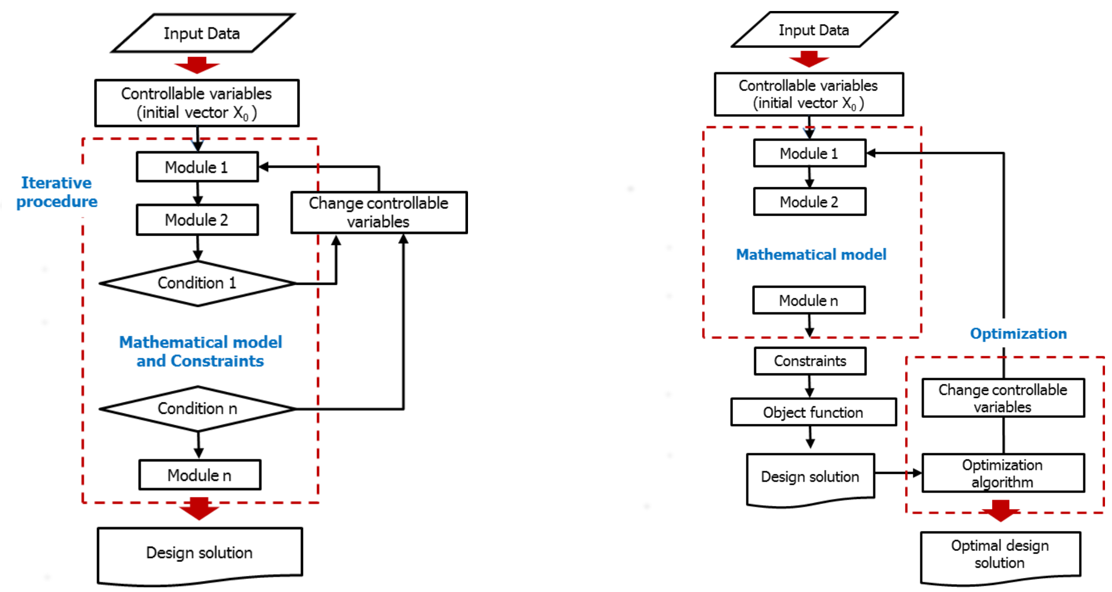


Fig. 6. Concept design and optimisation methodology [32].

The design process starts with defining the governing parameters in developing the ship model where several mathematical modules are implemented, and design variables, objective functions and constraints are determined. The initial hull offset is based on a sister ship. A Lackenby [39] transformation is used to adjust the original offset through the design parameters to calculate the hydrostatic and sectional area curve.

Several modules are used to generate the complete ship model, including operation, capacity, visibility, LW and DW, free-board, equilibrium and stability, seakeeping, bow design, resistance and propulsion, cavitation control, hull-propeller-motor design selection and match, strength assessment, control and manoeuvrability, cash- flow and required fright rate. The Energy Efficiency Design Index expresses the Greenhouse Gas emission footprint. The multi-objective optimisation is performed using the Genetic Algorithm NSGA-II [33].

The current study design a series of ships to be built in SME shipyards and operating in the Black Sea for transporting 20, 40 and 45-foot containers, identifying the main dimensions and ship form obtained from systematic form series input data transformation concerning L_{pp}, B, D, T and block coefficient, C_b [36], capacity using semi-empirical mathematical formulae from statistics, regression analyses of data of similar vessels [37-39] to estimate the structural weight regression equations based on a statistical analysis of existing ships can be used [40-42], visibility, free-board [43], initial stability [30], bow, and stern design [30, 44], resistance and propulsion [45], and propeller system engine match [22, 24], control and manoeuvrability [46-48], seakeeping [28], strength [49] energy efficiency index [27, 50], capital expenditure *CAPEX* and operational expenditures *OPEX* [40, 51] that leads to the required fright rate.

The operational and capital expenditure costs are related to changes that appear to be fixed costs, i.e., inflation, policy changes, and others. Still, the voyage costs are variable as a function of the activities occurring during the voyage service. The variable costs depend on every specific voyage, especially on the ports, distance, and cargo.

Parameter estimates of cost are based on design parameters such as ship size, weight, horsepower, etc., using a mathematical relationship between the input parameter and the cost historically determined through the regression analysis.

A cost breakdown divides costs into material, labour, overhead, and profit. The material involves all shipyard purchases: materials, equipment, subcontracted work, outside engineering services, etc. labour includes wages and benefits paid to shipyard employees whose work is directly connected with a ship. Overhead is the sum of all internal shipyard costs that cannot be directly attributed to any given contract [51, 52]

Estimating the cost of the overhead, O is generally approximated as a percentage of the labour cost. The profit, P_r is calculated as a percentage of the summation of all the material, labour, and overhead costs.

The *CAPEX* cost is estimated as:

$$CAPEX = [1 + Pr][1 + O][\sum(w_i C_i) + C_3 + \sum(MH_i C_{mi})] \tag{1}$$

where w_i and C_i are the weight and cost estimation of the hull structure (i=1) and equipment and fitting (i=2), C_3 is the cost of machinery and MH_i and C_{mi} are the man-hour estimation and the cost of man-hour of the hull structure (i=1), equipment and fitting (i=2) and propulsive machinery (i=3).

An essential step in the ship design is the trade route analysis, a restricted draft to define the cargo availability and the necessary fuel oil etc. and the total annual cost.

Many cargo ship operators figure on T_o=350 operating days per year, the remaining days devoted to shipyard repairs. Ships with faster port turnaround have less time for dockside repairs and may require an additional ten days' repair time per year.

The annual operating cost, OPEX, is given as:

$$OPEX = C_{port}n_V + A_{crew\ cost} + C_{crew\ ins} + C_{administrative} + C_{maintenace} + C_{cargo\ insurance} + C_{docking} + A_{fc} + A_{hc} \quad (2)$$

where C_{port} is the port duties, n_v is the voyages per year, $A_{crew\ cost}$ is the average annual crew cost, including benefits, $C_{crew\ ins}$is the annual cost of the crew member insurance, $C_{adminiatrative}$is the annual administrative cost, $C_{docking}$is the annual docking cost, A_{fc} is the annual fuel and oil cost, and A_{hc} is the annual handling cost.

The ship's revenue can be earned by transporting the container from one port to other ports, either door to door services or port to port. However, the price to be charged to these services may vary depending on several factors. For the liner operator, it is tradition to include bunker and port handling costs in the freight rates. However, for the case study purposes, a fixed freight rate is assumed.

To define the freight rate for the transportation of cargo on the assumed route requires to involve numerous factors such as the real market demand of the region, more precise cost calculations, and others. The decision making of investment is made through the standard discounted cash flow approach, which is based on the net present value, which is the sum of expected future cash flows minus the first investments. The required net profitability rate is assumed as $r = 2\%$, and the years of ship life operation are $o = 25$ years. The capital recovery factor, C_{rf}, is:

$$C_{rf} = \frac{r}{1-(1+r)^{o}} \quad (3)$$

The average annual inflation rate is assumed as $i_{nfl} = 3\%$, and the income tax rate is $t_x = 15\%$. The tax correction, C_{rft} is defined as:

$$C_{rft} = \frac{r+i_{nfl}+r\ i_{nfl}}{1-\left(r+i_{nfl}+r\ i_{nfl}\right)^{-o}(1-t_x)} \quad (4)$$

The discounted annual average cost of the investment, $C_{i,\psi}^{aaci}$, is:

$$C_{i,\psi}^{aaci} = CAPEX_i\ C_{rft} + OPEX_{i,\psi} + AFC_i \quad (5)$$

where AFC_i is the annual fuel cost.

The economic feasibility analysis covers the cash flow, which contains the costs of the ship from the construction to operating costs throughout the service life. On the other hand, with the cargo transported by the ship during the entire operation time, it is possible to calculate the total cost/cargo transported ratio, whose value equals the costs dispensed with the revenue obtained. This value is known as the required fright rate, $R_{i,\psi}^{fr}$, defined for the i^{th} ship in ψ^{th} route is defined as:

$$R_{i,\psi}^{fr} = \frac{C_{i,\psi}^{aaci}}{A_{i,\psi}^{cc}} \quad (6)$$

where $A_{i,\psi}^{cc}$ is the annual cargo capacity. The fleet design meets annual demand for cargo transportation, so the objective is to estimate the number of ships needed (dimensioning a fleet) and the dimensions of each of them and the number of trips made by each vessel over a year of operation.

For long journeys, the larger the ship (capacity to carry cargo), the better, because therefore, in one trip, more cargo is transported. With this, a smaller number of ships would be necessary for the composition of the fleet. Also, the ratio denominator that makes up the required freight rate decreases. On the other hand, when the size of the ship is increased excessively, the need arises to strengthen the ship structure (the larger the ship, the more flexible it becomes) with the use of more steel or high tensile steel (increasing the weight of steel and therefore the construction cost), also, the larger the ship, the higher the time spent in the ports and terminals for loading and unloading tends to increase the costs, that is, the numerator of the Required Freight Rate ratio. Thus, the solution is to find the set of main ship dimensions, which allows the vessel to transport the maximum load at a more competitive freight rate, lower total cost.

To minimise the required fright rate, $R_{i,\psi}^{fr}$ the governing parameters are the main dimensions of the ship, service speed, block coefficient, service life of the ship, price of steel used in the construction of the ship per tonne, distance navigated, unloading, and unloading times of ports and terminals where the ship is expected to operate, etc.

A systematic variation of the ship's main dimensions is employed to obtain the best freight rate. This is done as one of the dimensions was fixed, and the others were varied until all had been varied. From this set of main dimensions, the one that provided the lowest required shipping rate is adopted.

The depreciation is also analysed in the present study, which reflects the loss of performance due to age, higher maintenance expenses, a level of technical obsolescence, and expectations about the economic life of the vessel. It represents the amount the ship was paid in cash when the project started. It is just bookkeeping, so profit will be lower than cash flow by that amount. The interest, amortisation, cost of interest and depreciation and depth balance, calculated for a ship of L=150 m, B=28.3 m, D=13.04 m, T=7.86 m, is given in Fig. **7**.

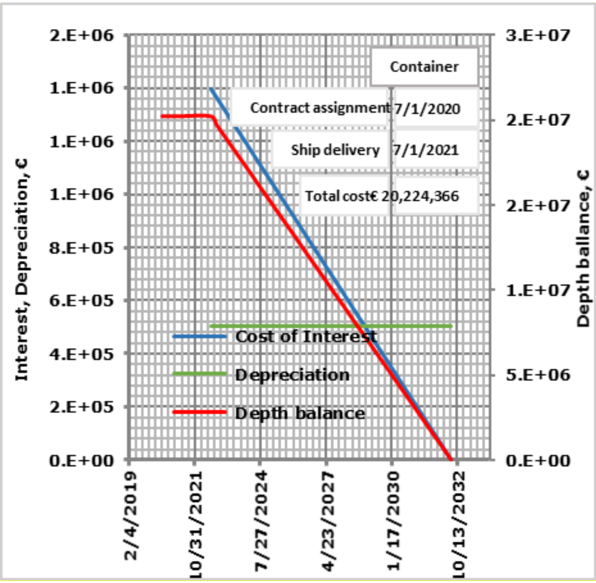


Fig. 7. Interest, amortisation, cost of interest and depreciation and depth balance

The parameters that are included in the economic analysis are the required net profitability rate, 2%, the number of years of ship operation 25, years, the average annual inflation rate, 3%, the residual value, 15%, the depreciation time, ten years, the contract assignment, 7/1/2020, the ship delivery, 7/1/2021, the time of construction, 12 months, and the days of operation per year, 350 days.

The Greenhouse gas emission footprint is expressed by the Energy Efficiency Design Index, *EEDI* and the optimisation procedure guarantees that the acceptable levels are satisfied. *EEDI* is defined in [53] and its required values in [54], adjusted by a reduction factor relative to *EEDI* baseline as a function of the primary and auxiliary engine power deadweight and service speed.

To avoid vessels becoming underpowered, *IMO* published a guideline related to the minimum propulsion power to maintain the manoeuvrability of ships in adverse conditions [25, 54]. Two *IMO* assessment levels have been developed: Level 1, which is a simple, generic method based on *DWT*, and ship type only input, leading to a crude, conservative approach, and Level 2 is based on individually estimated ship resistance component relating to the power prediction.

The simplified assessment procedure is based on the principle that if the ship has sufficient installed power to move with a particular advanced speed in head waves and wind, the ship will keep the course in waves and wind from any other direction. The minimum ship speed of advancement in head waves and wind is thus selected depending on ship design, in such a way that the fulfilment of the ship speed of advance requirements means fulfilment of course-keeping requirements. The energy efficiency design index, *EEDI*, calculated for the analysed multipurpose vessels is given in Fig. 8.

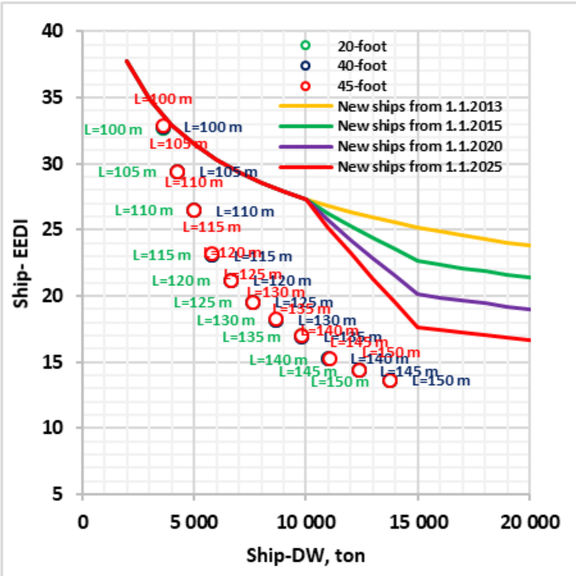


Fig. 8. Ship-*EEDI* as a function of *DW*

The recent development of short sea shipping in the Black Sea region has shown that intermodal transportation will play an important role. At the same time, the coaster fleet of the Black Sea region is of considerable age, and the increased freight rates enforce new orders of ships [55].

The designed ships in the present study are in the range of 4,000 to 14,000 DWT. The design governing parameters are the length between perpendiculars, moulded breadth, moulded depth, moulded draft, service speed, number of blades, propeller speed, expanded area ratio, pitch ratio and the constraints assumed for the present study are shown in Table 2, some of which have also been used in [35]. An additional constrain about the minimum engine power is included to guarantee the engine power is sufficient to perform satisfactory manoeuvring in severe weather conditions [56]. The Black Sea routes and assumed cargo demand used in the present study are given in Table 3.

The ship design and fleet sizing formulated here is for a given cargo to be transported at a constant speed between specified ports. Following the *IMO* regulations and data on similar ships to find the principal dimensions of ships and the size of the fleet. The objective functions defined are to minimise the required fright rate, minimise fuel consumption, and determine the best ship-propeller-motor match. The design governing parameters are ship length, breadth, draft, depth, number of propeller blades, propeller speed, expanded area ratio, pitch ratio, and satisfy the energy efficiency design index, *EEDI*. The NSGA -II optimisation algorithm [33] satisfying a set of constraints is employed in the present study to ensure that the optimal solution can be obtained quickly with sufficient quantity and accuracy.

Table 2. Constraints

Lower limitation	Description	Upper limitation
5.0	*L/B*	5.3
9.6	*L/D*	11.5
2.5	*B/T*	3.6
--	*Fn*	0.32
1.5	*B/D*	2.5
	Visibility	To be satisfied
	EEDI	To be satisfied
	Stability	To be satisfied
	Free-board	To be satisfied
	Seakeeping	To be satisfied
	Manoeuvrability	To be satisfied

Table 3. Analysed Black Sea routes

Indicator	Routes	Distance, nm	Cargo demand, tonne
$\psi = 1$	Varna-Poti	613	2,000,000
$\psi = 2$	Varna-Istanbul	149	1,000,000
$\psi = 3$	Varna-Novorossiysk	440	500,000
$\psi = 4$	Varna-Odessa	244	500,000

The principal objective is finding an optimal fleet ship size, considering the possible negative impact of a drop in the volume in the cargo flow. When the fleet size is defined, the cargo traffic flow is assumed at the beginning of the year. When the need for transporting cargo is greater than the ship cargo capacity, the excess cargo transportation will be subcontracted to an alternative transportation (charter) deliverer and returned by the end of the year. If the cargo demand requires fewer ships than the owned transportation cargo capacity, no chartering will occur.

In many cases, the cargo flow is unstable. It needs to be described in a probabilistic manner and to determine the optimal size of the ship fleet, the expected total cost per unit time needs to be minimised.

The present study compares the transportation of cargoes using different sizes of containers. The demand for transported cargo is given in tonne instead of the number of containers needed for this purpose. It is assumed that only 60% of the cargo capacity of containers is used for cargo transportation. This is explained by the fact that the total weight of the container should not exceed the maximum gross weight and depends on local road and rail transportations capacities. If the container is loaded to its maximum capacity, the weight needs to be evenly distributed over the floor area. If the cargo lays over about 50 % of the floor-length, its weight cannot exceed 66 % of the container max payload in the case of 66% of the length is 75% of the weight and for 75% is 80%.

In terms of cost, the price of containers depends on the size and the condition. The cost of the 20-foot is assumed to be approximately 75% of the 40-foot container. For new 20 - foot containers is in the range of $5,000 – $6,000 and for the 40-foot containers from $6,500 to $7,000, The price is different for used containers where for 20-foot containers is between $1,200 and $2,500, where for 40-foot containers is between $2,600 and $3,300 as can be seen in [57].

Each of these container sizes is designed to carry specific types of cargo, where 20-foot containers are related to more weight than bulk cargo, contrary to the 40-foot containers used to transport bulky loads. The 40-foot containers can't transport twice the 20-foot cargo weight, but at the same time, the 40-foot containers can transport more than twice the cargo volume of the 20-foot containers. However, cargo space is not always the most critical factor in choosing the size of containers for transporting specific cargoes.

The 40-foot containers provide more space for loading and storage, proportional to the length of the containers used. The 20-foot containers are best for transporting dense objects and heavy loads. For light cargoes, the 40-foot containers are preferable, and they can load more than twice the volume of the 20-foot containers.

There is a loading time issue with the 20-foot containers as they can take more time when being shipped by train or truck to reach the cargo ship since the 20-foot containers are transported on the rail in pairs. However, the shorter 20-foot containers are more adaptable to the limited cargo hull space, especially for small ships with a shorter cylindrical part of the ship hull.

The Intermodal Association of North America's ETSO database provides a monthly view of movements of 20-foot, 40-foot, and 45-foot containers in the Inland Point Intermodal market [58]. A long-term evolution has been shown in Fig. 9 wherein the year 2020, the 40-foot containers comprise over 51 per cent, 20-foot containers take 34 per cent, and 45-foot units are 15 per cent.

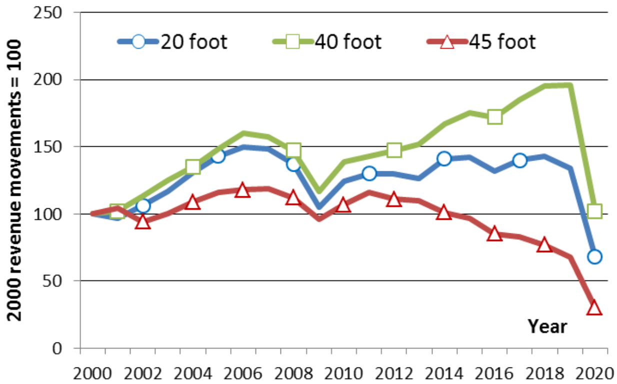


Fig. 9. Long-term evolution of 20, 40, and 45-foot containers use (adapted from [58].)

Table 4 shows the main characteristics of eleven designed ships, i=1, …, 11, of different sizes, that are part of a fleet for transporting cargo between Varna and Poti (ψ=1), including the ship units needed to cover the transportation demand and transported by 20, 40 and 45-foot containers for any ship. The ship's length is step-wise changed by five meters in the range between 100 and 150 m. The ratio of L_{pp}/B ranges from 5.1 to 5.3, L_{pp}/D ranges from 9.6 to 11.5, B/T ranges from 2.5 to 3.2, and B/D ranges from 1.6 to 2.5. The vessel speed V_s and C_b were constant at 14 knots and 0.63, respectively, varying the ship's breadth, depth, and draft.

Table 4 Designed ships, ψ =1

Ship	Lpp, m	B, m	D, m	T, m	20-foot		40-foot		45-foot	
					Ship Units	Cont. Units	Ship Units	Cont. Units	Ship Units	Cont. Units
i =1	100	18.87	8.70	5.24	7	323	10	189	9	165
i =2	105	19.81	9.13	5.50	7	358	9	206	9	180
i =3	110	20.75	9.57	5.77	6	436	7	258	7	210
i =4	115	21.70	10.00	6.03	5	512	6	294	6	245
i =5	120	22.64	10.43	6.29	5	558	6	316	6	265
i =6	125	23.58	10.87	6.55	4	661	5	382	5	322
i =7	130	24.53	11.30	6.81	4	715	5	408	5	362
i =8	135	25.47	11.74	7.08	4	806	4	485	4	387
i =9	140	26.42	12.17	7.34	3	869	4	515	4	460
i =10	145	27.36	12.61	7.60	3	989	4	598	4	489
i =11	150	28.30	13.04	7.86	3	1130	3	666	3	570

It can be noticed from Table 4 that for transporting similar cargo weight, the shorter ship, due to the shorter cylindrical part of the ship hull, are more efficient in transporting 20-foot containers compared to 40 and 45-foot containers. From a length of 150 of the ship, as an example here, a similar efficiency of transporting 20, 40 and 45-foot containers are observed.

4. Ship fleet sizing

The optimisation of fleet composition or completing the fleet is a complex problem that involves many variables and constraints. This task can be resolved in two stages [32]. In the first stage, after analysing the possible cargo flows, available financial resources, the number of the owned ships and other data determines the number of ships to be built. At the second stage, completing the fleet leads to defining the technical specification for the designed ship. This type of problem was solved in [59] in optimising the fleet composition.

The ship fleet sizing is based on the formal voyage description of the ship mission, for a round trip voyage of a set of ports and the inter-connecting routes, where for a given ship, the times and costs spent during the voyage to be defined and for a round trip detailed estimates of the OPEX are estimated, and a more elaborated technical-economical assessment of the ship as an investment is performed. The ship's optimal main dimensions and characteristics are defined by exploring ships' characteristics and running systematic variations of the main dimensions and an optimisation procedure by satisfying the imposed constraints [5, 60, 61].

The route established for the operation of the ships is $Port_i \rightarrow Port_{i+1} \rightarrow Port_i$ and using only one type of ship of different sizes, transporting the maximum cargo of $L_{\psi,\,max}$. The number of cranes in ports N_i^{crans} that any ship can use is defined as a function of the length of the ship as [62]:

$$N_i^{crans} = 0.0187 L_{oa,i} + 0.3572 \tag{7}$$

During a round trip, the ship is visiting N_i^{ports}, where the cargo $L_{i,\psi}$ is transported by the i^{th} ship in the ψ^{th} route, and any transported cargo is loaded and unloaded in the port. The cargo-handling time is defined as:

$$T_{i,\psi}^{handling} = \frac{2}{3}\frac{L_{i,\psi}N_i^{ports}}{C_{cran}N_i^{crans}} \tag{8}$$

where C_{cran} is the cargo-handling capacity of the cranes. The time of operation $T_{i,\psi}^{operation}$ is defined as a sum of the time of the handling operation $T_{i,\psi}^{handling}$, waiting time, $\mathrm{T}_{\mathrm{i,\psi}}^{\mathrm{waiting}}$, $T_{i,\psi}^{waiting}$ and voyage time, $T_{i,\psi}^{voayage}$.

The waiting time (days) in ports in a round trip is defined as:

$$T_{i,\psi}^{waiting} = \frac{3}{24}\left(2N_i^{ports} - 1\right) \tag{9}$$

The transportation efficiency, E_{tr} of any fleet configuration composed of n identical ships that operate in m ports is capable of transporting $L_{i,\psi}$ cargo per round trip and performing $N_{i,\psi}^{round\ trip}$ round trips in satisfying the cargo demand, D^{em} is defined as:

$$E_{tr} = \frac{D^{em}}{\sum_{\psi}^{m}\sum_{i=1}^{n} L_{i\psi}N_{i\psi}^{round\ trip}} \tag{10}$$

Fleet sizing aims to define the number of ships and sizes that need to be involved in cargo transportation producing a maximum benefit for the fleet. The fleet may consist of n different sizes of operating ships. There are several approaches to estimate the unit cost accounting for various factors. For example, the sum of operating, voyage, cargo handling, and capital costs per year is divided by the dead weight of the ship [63]. Estimating the freight rate for cargo transportation in the analysed route requires many factors, including the market demand, which is not the objective of the present study. The assumed freight rate reduces the shipping cost and makes a satisfactory level of earning in the present study. The freight rates for transporting cargo by the i^{th} ship in ψ^{th} route is estimated as $FR_{i\psi}$.

In addition to owned vessels, more vessels on a time-charter basis can be leased within a considered period, $T_{i,\psi}^{charter-IN}$ of the i^{th} ship in ψ^{th} route at the rate, $FR_{i,\psi}^{charter-IN}$. For each ship and route of transportation, the constant annual and variable costs $C_{i,\psi}^{var}$ are defined. The constant annual cost is associated with the capital expenditure and related required net profitability rate, a number of years of ship operation, average annual inflation rate, LIBOR (London Interbank Offered Rate), bank premium, capital recovery factor, tax correction, discounted average yearly cost of the investment, capital recovery period, depreciation time own investment, which lead to the constant depreciation payment. The variable cost is associated with any other operational cost, which in general varies with time.

The arrival rate of ships to ports may be assumed to follow the Poisson distribution with an arrival rate. The annual downtime cost for ships in the fleet, waiting in the port and handling cargo, $C_{fleet}^{down-TIME}$, is defined as:

$$C_{fleet}^{down-TIME} = \sum_{\psi=1}^{m}\left\{\sum_{i=1}^{n}\left[N_{i,\psi}^{voyage}\left(T_{i,\psi}^{handling} + T_{i,\psi}^{waiting}\right)\begin{pmatrix}C_{i,\psi}^{var}N_{i,\psi}^{own} + \\ T_{i,\psi}^{charter-IN}C_{i,\psi}^{charter-IN}N_{i,\psi}^{charter-IN}\end{pmatrix}\right]\right\} \tag{11}$$

where $N_{i,\psi}^{own}$ and $N_{i,\psi}^{charter-IN}$ are the number of the own and charter-IN ships of the i^{th} size and in ψ^{th} route, respectively. The control parameters used in defining the optimal fleet size are the number of vessels of different sizes in different routes, own, and chart-IN, within a considered service period. The revenue of the fleet is defined as:

$$R_{fleet} = \sum_{\psi=1}^{m}\left\{\sum_{i=1}^{n}\begin{bmatrix}FR_{i,\psi}L_{i,\psi}N_{i,\psi}^{own} + T_{i,\psi}^{charter-IN}C_{i,\psi}^{charter-IN}N_{i,\psi}^{charter-IN} + \\ T_{i,\psi}^{charter-OUT}C_{i,\psi}^{charter-OUT}N_{i,\psi}^{charter-OUT}\end{bmatrix}\right\} \quad (12)$$

The total costs, C_{fleet} includes the cost of operation, constant cost, leasing of ships on a time-charter basis. The cost of the ship-OFF, out of use, because of the lack of cargo leading to a reduction of the demand to be transported, $C_{i,\psi}^{OFF}$is assumed as 15 % of the operational cost.

A decrease in cargo transportation demand also reduces the fleet's revenue and operating costs. Each vessel of the fleet has to contribute to the revenue of the fleet during the service life. Otherwise, it is more efficient to be leased on a time-charter basis. The time-charted-OUT ships contribute to the revenue without considering the constant costs of the vessels.

The optimal fleet ship size is based on the maximum profit of the fleet cargo transportation, considering the possible negative impact of a drop in the volume in the cargo flow. When the fleet size is defined, the cargo traffic flow is assumed at the beginning of the year. When the need for transporting cargo is greater than the ship cargo capacity, the excess cargo transportation will be subcontracted to an alternative transportation (charter) deliverer and returned by the end of the year. If the cargo demand requires fewer ships than the existing transportation cargo capacity, no chartering will occur.

In many cases, the cargo flow is unstable, and to determine the optimal size of the ship fleet, the expected total cost per unit time needs to be minimised. The demand per unit time, as a simplification of the problem here, is assumed to be distributed by a uniform probability density function $f(L_\psi)$, where L_ψ is the volume of transported cargo, where $L_{\psi, min} \leq L_\psi \leq L_{\psi, max}$ and the cargo transported by the i^{th} ship in ψ^{th} route per unit time is $L_{i,\psi}$. The average cost of the i^{th} ship transporting a unit cargo in the ψ^{th} route is defined as the average cost of the i^{th} ship transporting a unit cargo by the charter-IN ships in the ψ^{th} route is $FR_{i,\psi}^{charer-IN}$. The constant cost per ship per unit time is $C_{i,\psi}^{ccnst}$ in the i^{th} ship size cargo capacity in the ψ^{th} route is defined as:

$$C_{i,\psi}^{ap-OWN} = L_{i,\psi}N_{i,\psi}^{OWN} \quad (13)$$

when $D_\psi^{em} > C_\psi^{ap-OWN}$, the cargo transported in the ψ^{th} route per unit time, $L_\psi^{OWN} = \sum_{i=1}^{n} C_{i,\psi}^{ap-OWN}$ will be equal to the capacity, $L_\psi^{OWN} = C_\psi^{ap-OWN}$and when $D_\psi^{em} \leq C_\psi^{ap-OWN}$, the cargo transported in the ψ^{th} route per unit time equals the demand, $L_\psi^{OWN} = D_\psi^{em}$.

Furthermore, the fleet cargo transportation cost per unit time of the OWN-ships is defined C_ψ^{ap-OWN}. When the demand is greater than the capacity$D_\psi^{em} > C_\psi^{ap-OWN}$, the charter-IN ships will be rented. The cargo transported by the charter-IN ship will be zero when $D_\psi^{em} \leq C_\psi^{ap-OWN}$if $D_\psi^{em} > C_\psi^{ap-OWN}$the difference between the demand and capacity will be transported by charter-IN ships. The mean value of the cargo transported by charter-IN ships is defined as $E\left(C_\psi^{ap-IN}\right)$. The fleet cost related to the charter-IN ships is estimated as $C_{fleet}^{var-charter-IN}$.

The variable fleet cost related to charter-OUT ships is considered zero since renting the ships is expected to be covered, and the total variable fleet cost is defined as:

$$C_{fleet}^{total,var} = C_{fleet}^{var-OWN} + C_{fleet}^{var-charter-IN} + C_{fleet}^{var-charter-OUT} + C_{fleet}^{down-TIME} \quad (14)$$

The cargo-handling capacity of the cranes is assumed as C_{cran} =360 Cont./day. The operation time of the ship is considered as 350 days per year. The port route distances and geographical locations have already been shown in Table 3. At defining the fleet size, a critical parameter is the cargo flow between analysed ports. For each cargo flow direction, the lower and upper levels of transported cargoes, used as an example here, are shown in Table 5.

Table 5 Lower and upper level of transported cargoes, tonne

	ψ=1	ψ=2	ψ=3	ψ=4
$L_{\psi,min}$	1,000,000	500,000	250,000	250,000
$L_{\psi,max}$	2,000,000	1,000,000	500,000	500,000

In addition to owned vessels, more vessels of a similar tonnage on a time-charter basis can be leased within a considered period $T_{i,\psi}^{charter-IN}$ of the i^{th} ship in ψ^{th} route at a rate, $FR_{i,\psi}^{charter-IN}$. The charter rate $FR_{i,\psi}^{charter-IN}$ is assumed as 1.5 times the annual variable cost of the i^{th} ship in the ψ^{th} route. For each ship and route of transportation, the constant yearly cost, C_i^{const} and variable cost, C_i^{var} are calculated based on the assumption that the required net profitability rate is 2%, for 25 years of ship operation, an average annual inflation rate of 3% and LIBOR (London Interbank Offered Rate) of 8% [18, 34].

The fleet number of ships transported a cargo of different designed ships as a part of the fleet composed of identical vessels as a function of ship length are shown in Fig. 10, and Fig. 11 shows the associated annual round voyages and fleet-annual average cost.

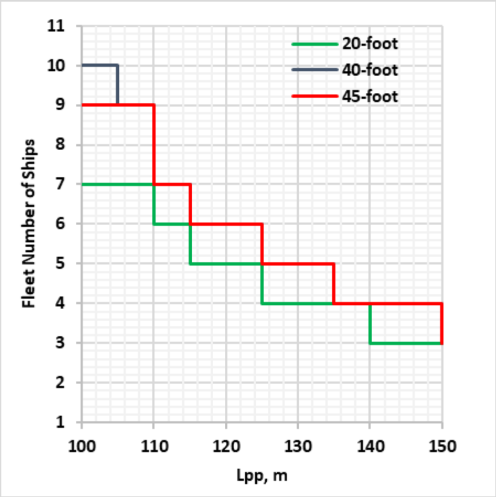
Using 20-foot containers to transport the same amount of cargo requires a smaller number of ships. The difference between the number of ships when 40 and 45-foot containers are used is only seen for a very short ship of L=100 m.

The using 40 and 45 containers transport more cargo for a ship with a length greater than 140m. The fleet annual cargo round voyages and the average cost for the ship using 20-foot containers are less than 40 and 45-foot containers (see Fig. 11).

The fleet-cargo transportation efficiency, calculated as the ratio between used and existing cargo space, is shown in Fig. 12, where the fleet is composed of n identical ships that operate in m ports capable of transporting $L_{i\psi}$, cargo per round trip and performing $N_{i,\psi}^{round\ trip}$ round trips in satisfying the cargo demand, D^{em} using different sizes of containers.

It has to be stressed that the number of containers that any ship may transport is not only based on the maximum container capacity of any particular ship, but it is also conditional to the static equilibrium and stability, which can be made much easier with a small container since they present more degree of freedom to be placed in different location of the dedicated cargo place and require less ballast.

In the case of unstable cargo flow, the expected total cost per unit time needs to be described in a probabilistic manner to determine the optimal size of the ship fleet. The defined ship fleet annual costs and ship fleet profit are shown in Fig. 13 to Fig. 14 for 20, 40 and 45-foot containers, indicating that the optimal solution is to have a design fleet size solution of case Nº 5 for 20-foot containers, shown in Fig. 13 and design fleet size solution of case Nº 6 for 40 and 45-foot containers in Fig. 14.



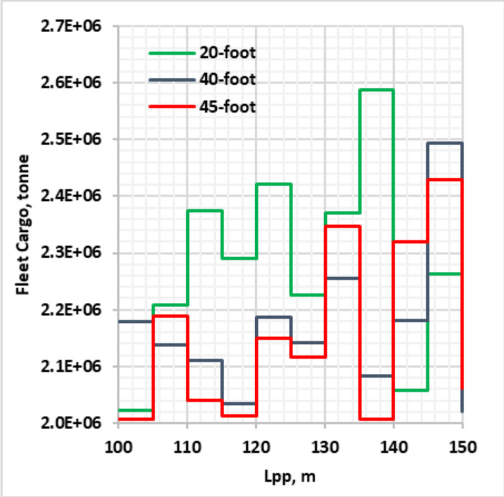
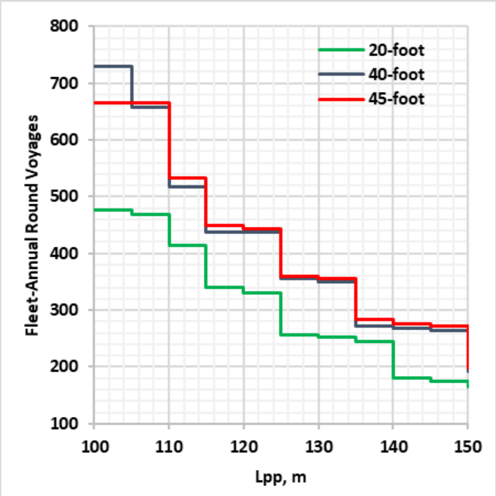


Fig. 10. Fleet ship units (left) and fleet cargo (right) as a function of ship length, ψ=1.



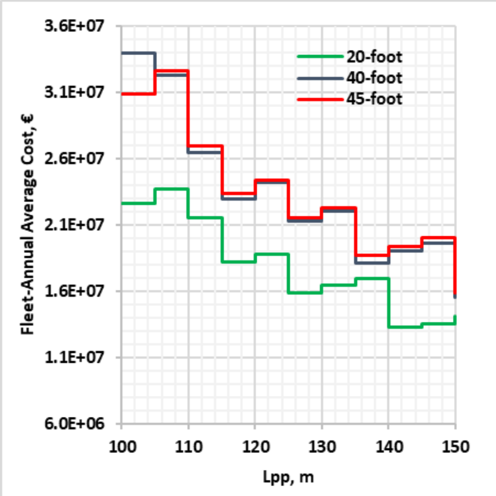


Fig. 11. Fleet-annual round voyages (left) and fleet-annual average cost (right) as a function of ship length, ψ =1

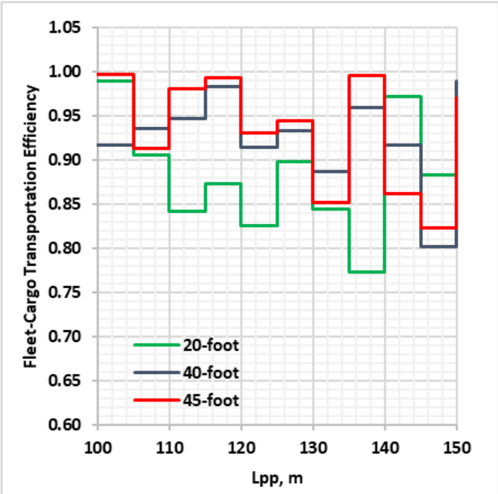


Fig. 12. Fleet-cargo transportation efficiency**,** ψ =1

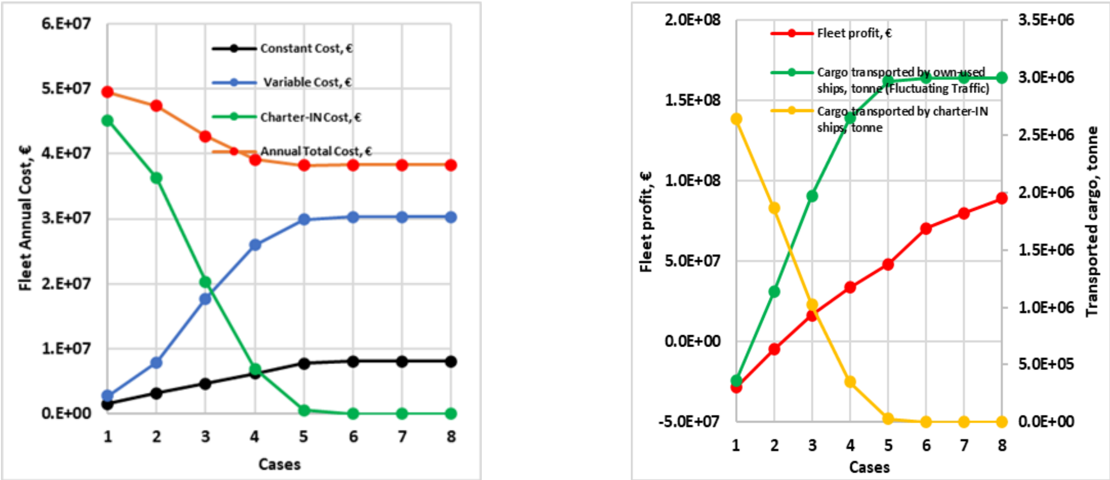


Fig. 13. Ship fleet annual costs, (left) and hip fleet profit (right), 20-foot containers.

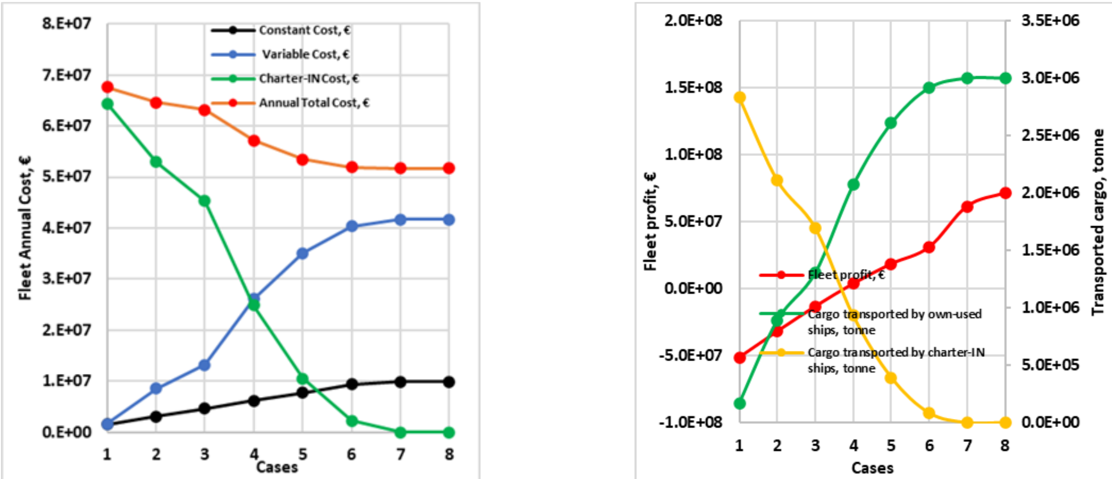


Fig. 14. Ship fleet annual costs, (left) and hip fleet profit (right), 40 and 45-foot containers.

The distribution of the unit of different ship sizes for transporting cargo in the ψ^{th} route, conditional on the own used ships and cargo transported only by 20-foot containers, is shown in Fig. 15 and for 40-and 45-foot containers in Fig. 16. The total distributed units of ships of different sizes should equal the own ships (Fig. 15, left and Fig. 16, left) and chartered-in (Fig. 15, right and Fig. 16, right). The x-axis in Fig. 15 and Fig. 16 shows the capacity of i^{th} ship-size used in all routes. The y-axis shows the transported cargo in any ψ^{th} route by all sizes of ships, and the z-axis shows the units of different ship sizes used in different routes. In some cases, one ship size serves in several routes. However, due to the lower utilisation, some ship sizes will not be utilised, and the cargo transported by the lower used ship size will be taken from the ship sizes that are more utilised. The diversity of ship sizes in the fleet will be reduced as a function of the number of owned ships.

However, it has to be pointed out that the theoretically estimated optimal fleet size solution and its usage in transporting the demand cargo contain partial ship units of different ship sizes, as can be seen in Fig. 15 and Fig. 16. The actual, real ship size units will be defined by rounding up the theoretically estimated ones, which will lead to diverse and most conservative ship size unit utilisation. The rounding up process should start from the most dominant used ship sizes down to the less prevalent used ship sizes keeping the fleet's total capacity equal or bigger to the cargo demand needed to be transported in different routes.

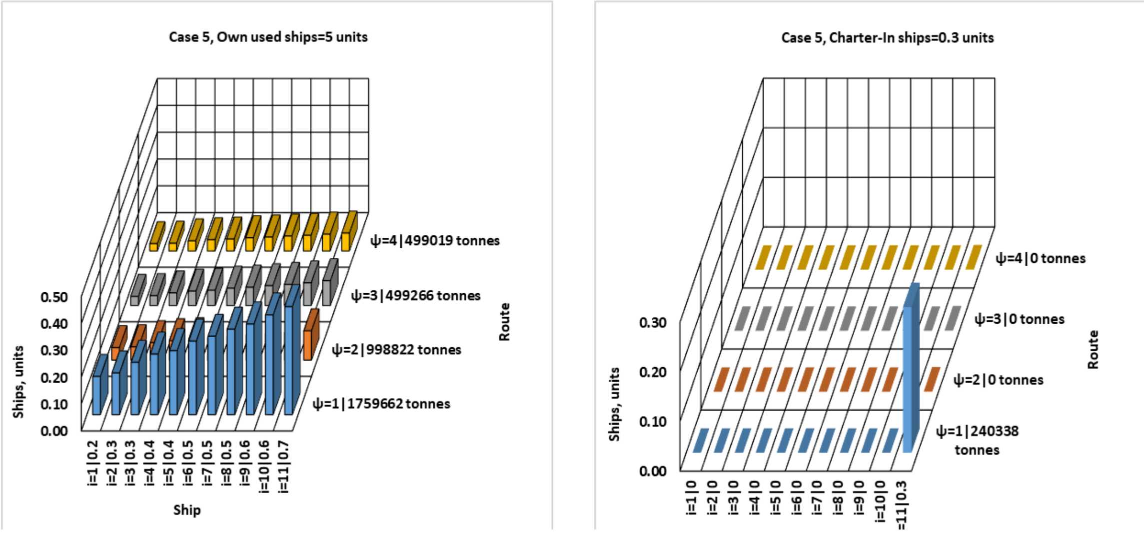


Fig. 15. Optimal fleet size solution, Nº 5 for 20-foot containers.

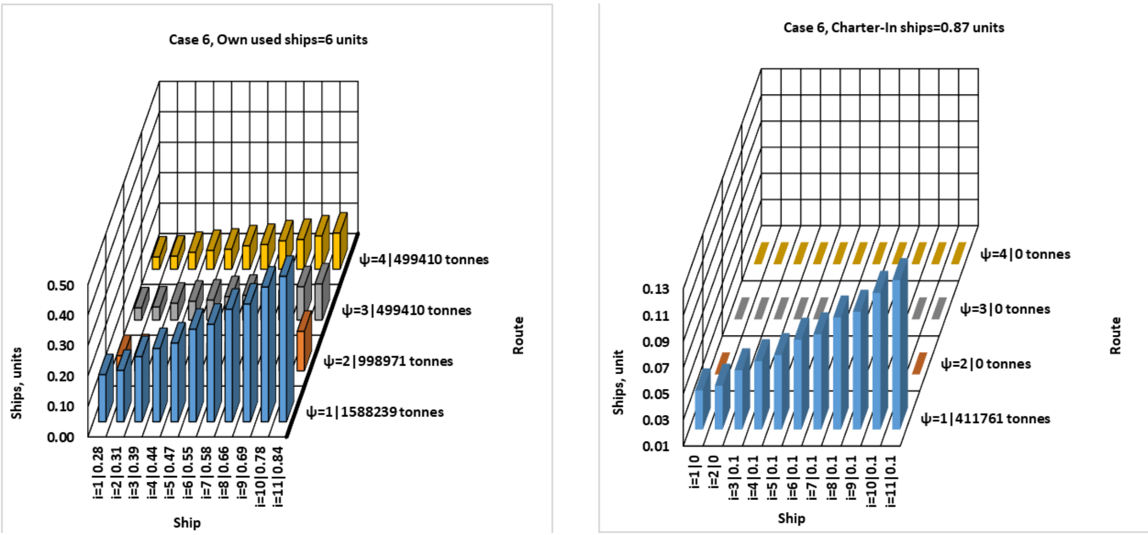


Fig. 16. Optimal fleet size solution, Nº 6 for 40 and 45-foot containers.

The cargo flow is assumed to be unstable, and to determine the optimal size of the ship fleet, the expected total cost per unit time needs were minimised. For each fleet, the average waiting and handling time and yearly voyage time was analysed. In Case 6, the optimal number of ships and size from the total cost viewpoint is six ship units. The fleet's average waiting and handling time is 44.5%; that is, the voyage time is 55.5 % of the service time. A high utilisation for the fleet is achieved only when it is being operated efficiently. For all analysed fleet ship configurations, the traffic intensity is less than one, which leads to no queue being built up because ships are arriving slower than processing time.

5. Conclusions

The study presented here performed multipurpose vessel fleet sizing for the Black Sea short shipping through multimodal transport corridors using the long-time experience and statistics in defining the optimal design solution obtained based on the energy efficiency design index, shipbuilding, operation, and resale costs at the end of the service life. Cargo transportation demand in the Black Sea as a part of a multimodal transportation frame was performed, estimating the potential need for ship fleet of multipurpose ships. A discussion about possible applications of a different fleet of ship sizes in improving the cargo transportation efficiency to maximise the economic impact conditional of the unsteady cargo flow and environmental impact. The study has shown that using 40-foot containers has some advantages compared to 20 and 45-foot containers. The encountered design solutions demonstrated a high utilisation for the fleet and operated efficiently without creating a queue since ships are arriving slower than processing time. A formulation for ship fleet sizing was used, simulating the transportation of only one size of containers at a time, but it can be easily extended for more realistic scenarios. Different assumptions were made related to the costs and cargo demand that are not essential for the formulation but needed for the example calculation.

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Petar Georgiev, petar.ge@tu-varna.bg
Technical University of Varna, Bulgaria
Yordan Garbatov, yordan.garbatov@tecnico.ulisboa.pt
Centre for Marine Technology and Ocean Engineering (CENTEC), Instituto Superior Técnico, Universidade de Lisboa, Lisbon, Portugal