

# Parametric method for evaluating optimal ship deadweight

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## ABSTRACT



*The paper presents a method of choosing the optimal value of the cargo ships deadweight. The method may be useful at the stage of establishing the main owners requirements concerning the ship design parameters as well as for choosing a proper ship for a given transportation task. The deadweight is determined on the basis of a selected economic measure of the transport effectiveness of ship – the Required Freight Rate (RFR). The mathematical model of the problem is of a deterministic character and the simplifying assumptions are justified for ships operating in the liner trade. The assumptions are so selected that solution of the problem is obtained in analytical closed form. The presented method can be useful for application in the pre-investment ships designing parameters simulation or transportation task studies.*

**Keywords:** ship design; owners requirements; optimal deadweight; required freight rate

## INTRODUCTION

Principles of engineering activity which are accepted in technique and technology should meet requirements of both technical safety and economic efficiency. Criterial measures used for evaluating qualities of engineering investment products have usually a combined financial and time-related nature. The navigating activity performed in the conditions of market competition requires thoroughness in selection of watercraft, for the transportation task to be performed optimally. Realisation of an investment project is connected with heavy capital involvement dedicated to cover the cost of ship building, purchase of a used ship, or ship charter - to bring certain investment gains. Economic and technical analyses discussing the issue of selecting optimal ship parameters to perform a given sea transportation task, [1, 2, 3 and 4] for instance, indicate that the problem analysis should take into account, among other factors, the following market conditions:

- investment goal;
- investment cost;
- cost of capital raising;
- balance of incomes and operating costs;
- risk of demand decrease, inflation phenomenon;
- risk of freight rate decrease, tax regulations;
- required profitability and activity of competitors.

Formulating and solving the above task requires a series of simplifying assumptions and approximate predictions to make the basis for conclusions on the optimal variant of

the investment decision. Despite its approximate nature, the procedure can bring better support for decision making than general feeling and intuition.

## STRUCTURE OF OPERATING COSTS

The operating costs of transport activity of the ship which depend on its deadweight can be divided into:

- direct costs, such as handling charges and movement cost;
- indirect costs connected with ship maintenance.

The direct costs include such items as:

- costs of (heavy and light) fuel, cost of oils and lubricants, harbour and canal dues, tug services, loading and unloading costs, commissions of agents, brokers and others.

The indirect costs concerning ship maintenance include such items as, for instance:

- salaries, social insurance, crew living cost, cost of ship repair and maintenance, non-life insurance costs, ship depreciation cost.

The handling and movement costs depend of sailing conditions, i.e.:

- number of loading and unloading harbours;
- length of the voyage route;
- weather conditions;
- efficiency of ship capacity utilisation (ballast voyages);
- cruising speed of the ship;

- main engine power output and the rate of fuel consumption;
- time of waiting on road;
- harbour dues, broker's commissions and other direct costs.

An important item in this list is the cost of fuel (bunker), oils, and lubricants, the proportion of which exceeds 50 % of variable costs. Their level depends on: the ship deadweight and power output, the main engine type (internal combustion engine, turbine, etc.), the type of fuel and its specific consumption, technical state of the propulsion system, and modernity of the marine power plant equipment.

The handling costs compose the next group of variable costs depending on ship deadweight – i.e. on the volume and type of the transported cargo, and on the handling rates charged by harbour authorities. The harbour and canal dues include wharfage, canal dues, and the costs of pilotage and tug services.

The tonnage maintenance cost includes crew wages and living costs, the costs of ship repair (repair fund allowance) and conservation, in particular the costs of general classification overhauls done every five years and intermediate routine repairs done every year. In a relatively long time period, the cost of ship repair stops is assessed approximately as equal to 10 % of the time of its operation.

The next cost is the costs of ship insurance (underwriting) of 'casco' type. Along with the capacity, the level of the insurance rate and the total insurance cost are affected by the evaluation of the failure frequency in the fleet operated by the ship owner and the prestige of the institution being the ship classifier. In case of great care taken of the ship and cargo, and failure-free ship operation the insurance rate can be reduced.

The crew wages compose less than twenty percent of the fixed costs – depending on the ship owner and ship flag (cheap flags). They include basic wages, payments for overtimes and doing special tasks, such as contracts for specific tasks for instance, social and health insurance costs, wages of crew being ship owner's reserve, representation costs and the captain fund. They also include the crew living cost, strongly affected by the number of crew members and law regulations referring to the ship of a given type and dimensions.

The activity of ship owner's land service forces in the area of operating costs consist in: (1) carrying out effective and flexible canvassing politics in order to increase the volume of the transported cargo and minimise ballast voyages; (2) reducing the level of expenses spent within the framework of transportation tasks, (3) attempting to shorten the time of ship lay time in the harbour and on road, (4) using bonus payments for failure-free operation, rational fuel consumption, damage-less loading, and proper ship maintenance.

## OPTIMISATION OF SHIP PARAMETERS

In technique and technology, optimisation consists in selecting a permissible solution which is the best in the sense of the assumed measure (criterion) of task evaluation. In shipbuilding and navigation the need for optimisation is observed in two activity areas:

- operating activity – where it consists in selecting ship parameters which are optimal in the sense of transportation task realisation evaluation;
- designing activity – where it consists in selecting parameters of the designed ship which are optimal in the sense of the adopted criterion of ship quality evaluation.

Before placing an shipbuilding order, the ship owner usually performs some analyses to assess optimal parameters of the ship to be built (formulation of design assumptions), see [4, 7 and 8] for instance. Selecting ship deadweight has both economic and technical aspects, as it remarkably affects the economic results of the entire investment project. When the selected deadweight is larger than that really needed, it results in excessive investment and operating costs, while when it is too small it leads to the loss of some profits due to not fulfilling part of transport demand.

In the below presented method, relevant selection of analytical relations and simplifying assumptions had made the basis for working out a mathematical model of the problem, in a closed analytical form, which can be used for evaluating optimal ship deadweight. The obtained analytical form of the solution makes it possible to evaluate a qualitative impact of model variables on the optimal ship deadweight, and test the effect of market conditions of the efficiency if ship owner's investment decisions.

## PROBLEM FORMULATION AND ASSUMPTIONS

A set of basic design assumptions for a ship with the given operating function usually includes such parameters as: deadweight  $P_n$ , net capacity  $P_l$ , number of passengers  $N$ , operating speed  $v$ , volume of holds  $V$ , radius of autonomous action  $R$ , and other quantities of lower importance. Analysed is the design task oriented on evaluating the ship deadweight  $P_n$ :

- at given speed  $v$ ;
- at given action radius  $R$ ;
- with cargo handling performed in  $s$  harbours;
- at investment profitability rate equal to  $r$ ;

to arrive at the lowest possible value of the required freight rate RFR in given technical and economic conditions, used as the measure of economic efficiency of the designed ship.

The real cargo supply in harbours has generally the stochastic nature, which in particular refers to tramping. The present method assumes a deterministic model of cargo supply, which takes into account the random nature of cargo supply by using the coefficient  $\varepsilon$  which expresses the average utilisation of ship net capacity in the voyage. In a relatively long time interval this coefficient estimates the averaged real cargo supply. The advantage of the proposed approach is easy calculation of this coefficient based on the records in logs of other ships operating on the analysed shipping lane.

The assumed criterial measure for general evaluation of the quality of the designed ship is the minimal value of the required freight rate RFR, which results from  $z$  reasons in [3, 5, 6], for instance. This coefficient determines the economic efficiency of the investment project and represents the lowest freight rate which the ship owner has to get to arrive at the assumed profitability rate  $r$  at given investment and operating costs, and at the assumption that the ship will be in service in  $Z$  days per year during  $m$  years.

Adopting the minimal RFR rate as the criterial measure in evaluating the ship deadweight is justified by the fact that for future real freight rates in force on a given shipping lane the highest profitability will be obtained by the ship having the lowest required freight rate. If the future real freight rates are higher than the minimal freight rate RFR, then the real profitability rate will be higher than the assumed  $r$ . In case the real freight rates turn out lower than the calculated RFR value, the investment project will not bring the assumed profitability  $r$ .



## MATHEMATICAL MODEL

In the presented method of evaluating optimal ship deadweight, the parameters of crucial importance for the mathematical model are: the operating speed of the ship, the capacity of cargo handling utilities, the number of cargo handling harbours, and the time of waiting for handling operations. The cost of building a ship planned to sail at a steady speed depends on its deadweight  $P_n$  and, according to [1, 2, 3], it increases more slowly than the linear function. Consequently, the predicted investment cost (the ship cost)  $J$  can be approximated by the relation:

$$J = K_j \cdot P_n^{2/3} \longrightarrow K_j = J_0 \cdot P_n^{-2/3} \quad (1)$$

where the proportionality coefficient  $K_j$  can be calculated based on prices  $J_0$  and deadweight values  $P_n$  of similar ships.

The annual operating cost AOC of the ship which depends on ship deadweight mainly refers to the cost of the consumed fuel and the cost of handling operations. The remaining components of the operating cost, such as crew wages, for instance, can be omitted assuming that their level does not depend, or only slightly depends, on ship deadweight.

The average annual costs of the lubricating oil and repair were taken into account in the coefficient  $\mu > 1$  which increases the cost of fuel. At these assumptions the annual operating cost AOC of the ship propulsion is:

$$AOC = \mu \cdot n \cdot T_M \cdot C_j \cdot G_j \cdot N_e \quad (2)$$

The power  $N_e$  can be expressed using the admiralty formula, then:

$$AOC = \mu \cdot n \cdot T_M \cdot C_j \cdot G_j \cdot \frac{D^{2/3} \cdot v^3}{Ca} = \mu \cdot n \cdot T_M \cdot C_j \cdot G_j \cdot \left[ \left( \frac{\varepsilon \cdot \lambda \cdot P_n}{\eta} \right)^{2/3} \cdot \frac{v^3}{Ca} \right] = K_c \cdot n \cdot P_n^{2/3} \quad (3)$$

where:

- $D$  – current ship displacement,
- $n$  – number of voyages per year,
- $T_M$  – time of one voyage,
- $C_j$  – unit fuel price, expressed in [\$/t], for instance,
- $G_j$  – specific fuel consumption, expressed for instance in [g/kWh],
- $\lambda$  – deadweight efficiency,
- $\varepsilon$  – net capacity efficiency,
- $\eta$  – deadweight-displacement coefficient,
- $Ca$  – admiralty constant.

The coefficients:

$$\lambda = \frac{P_n - Z}{P_n} \quad \eta = \frac{P_n}{D} \quad (4)$$

are assumed, or calculated based on data from similar ships. Here  $Z$  represents the mass of fuel reserve in one voyage. The factor  $K_c$  is equal to:

$$K_c = \mu \cdot \frac{R}{v} \cdot C_j \cdot G_j \cdot \left[ \left( \frac{\varepsilon \cdot \lambda}{\eta} \right)^{2/3} \cdot \frac{v^3}{Ca} \right] = \frac{\mu \cdot C_j \cdot G_j \cdot v^2 \cdot R}{Ca} \cdot \left( \frac{\varepsilon \cdot \lambda}{\eta} \right)^{2/3} \quad (5)$$

The level of the annual handling cost AHC depends on the mass of cargo, the number of voyages per year  $n$  and the unit handling rate  $W_j$  [\$/t]:

$$AHC = n \cdot (2 \cdot \varepsilon \cdot \lambda \cdot P_n) \cdot W_j = K_h \cdot n \cdot P_n \quad (6)$$

The parameter  $K_h$  represents:

$$K_h = 2 \cdot \varepsilon \cdot \lambda \cdot W_j \quad (7)$$

The time of voyage  $T$  is composed of the sailing time  $T_M$ , the time of waiting on road and in harbour  $T_O$ , and the time of cargo loading and unloading  $T_Q$  when the capacity of the handling facilities is  $Q$ :

$$T = T_M + T_O + T_Q = \frac{R}{v} + T_O + 2 \cdot \frac{Pl}{Q} = \frac{R}{v} + T_O + 2 \cdot \frac{\varepsilon \cdot \lambda \cdot P_n}{Q} \quad (8)$$

The number of ship voyages per year depends on the time of ship operation in the entire year  $Z_h$  and the time of one voyage  $T$ :

$$n = \frac{Z_h}{T} = \frac{Z_h}{\frac{R}{v} + T_O + 2 \cdot \frac{\varepsilon \cdot \lambda \cdot P_n}{Q}} = \frac{Z_h \cdot v \cdot Q}{R \cdot Q + T_O \cdot v \cdot Q + 2 \cdot \varepsilon \cdot \lambda \cdot v \cdot P_n} = \frac{K_q}{K_r + K_p \cdot P_n} \quad (9)$$

where:

$$\begin{aligned} K_q &= Z_h \cdot v \cdot Q \\ K_r &= R \cdot Q + T_O \cdot v \cdot Q \\ K_p &= 2 \cdot \varepsilon \cdot \lambda \cdot v \end{aligned} \quad (10)$$

The annual transportability of the ship is:

$$ACC = n \cdot \varepsilon \cdot \lambda \cdot P_n \quad (11)$$

The discounted financial balance of the investment project is:

$$\frac{AAC}{CRF(r, m)} = J + \frac{AOC + AHC}{CRF(r, m)} \quad (12)$$

where AAC represents the discounted annual average cost, while CRF stands for the capital recovery factor:

$$CRF(r, m) = \frac{r}{1 - (1 + r)^{-m}} \quad (13)$$

Taking into account the inflation rate  $i$  and the tax rate  $t$ , the discounted financial balance of the investment project is given by the relations:

$$\frac{AAC}{CRFT(r, m, i, t)} = J + \frac{AOC + AHC}{CRFT(r, m, i, t)} \quad (14)$$

$$CRFT(r, m, i, t) = \frac{(r + i + r \cdot i)}{1 - (1 + r + i + r \cdot i)^{-m} \cdot (1 - t)} \quad (15)$$

The discounted annual average cost AAC of the investment project is:

$$AAC(P_n) = J(P_n) \cdot CRFT(r, m, i, t) + AOC(P_n) + AHC(P_n) \quad (16)$$

Taking into account other costs is justified when they are affected by ship deadweight. In that case they should be summed up:

$$\begin{aligned} AAC(P_n) &= J(P_n) \cdot CRFT(r, m, i, t) + \\ &+ AHC(P_n) + \sum AOC_i(P_n) \end{aligned} \quad (17)$$

### DEADWEIGHT MINIMISING THE FREIGHT RATE RFR

If the cost AAC compensates the annual fixed freight incomes, then the rate at which this equality takes place will secure the investment efficiency rate  $r$  in the formulas for CRF and CRFT. The freight rate RFR is defined by the ratio of the annual freight incomes corresponding to AAC to the annual transportability ACC of the ship

$$\begin{aligned} RFR &= \frac{AAC}{ACC} = \frac{J \cdot CRFT + AOC + AHC}{ACC} = \\ &= \frac{K_j \cdot CRFT \cdot P_n^{2/3} + K_c \cdot n \cdot P_n^{2/3} + K_h \cdot n \cdot P_n}{n \cdot \varepsilon \cdot \lambda \cdot P_n} \end{aligned} \quad (18)$$

$$\begin{aligned} RFR &= \frac{\frac{K_j \cdot CRFT}{n} \cdot P_n^{-1/3} + K_c \cdot P_n^{-1/3} + K_h}{\varepsilon \cdot \lambda} = \\ &= \frac{P_n^{-1/3}}{\varepsilon \cdot \lambda} \cdot \left( \frac{K_j \cdot CRFT}{n} + K_c \right) + \frac{K_h}{\varepsilon \cdot \lambda} \end{aligned} \quad (19)$$

Transforming the above formula to the form explicitly dependent on deadweight we get:

$$\begin{aligned} RFR &= \frac{P_n^{-1/3}}{\varepsilon \cdot \lambda} \cdot \left( \frac{\frac{K_j \cdot CRFT}{K_q} + K_c}{\frac{K_r + K_p \cdot P_n}{K_q}} \right) + \frac{K_h}{\varepsilon \cdot \lambda} = \\ &= \frac{P_n^{-1/3}}{\varepsilon \cdot \lambda} \cdot \left( \frac{K_j \cdot CRFT \cdot (K_r + K_p \cdot P_n) + K_c}{K_q} \right) + \frac{K_h}{\varepsilon \cdot \lambda} \end{aligned} \quad (20)$$

The lowest freight rate RFR corresponds to the ship deadweight  $P_n$  which meets the necessary condition for the existence of the extremum of the function RFR:

$$\frac{\partial RFR}{\partial P_n} = 0 \quad (21)$$

This condition takes the form:

$$\begin{aligned} \frac{\partial RFR}{\partial P_n} &= \\ &= \frac{-1}{3} \frac{P_n^{-4/3}}{\varepsilon \cdot \lambda} \cdot \left( \frac{K_j \cdot CRFT \cdot (K_r + K_p \cdot P_n)}{K_q} + K_c \right) + \\ &+ \frac{P_n^{-1/3}}{\varepsilon \cdot \lambda} \frac{K_j \cdot CRFT \cdot K_p}{K_q} = 0 \end{aligned} \quad (22)$$

After multiplying both sides by the indicated parameter:

$$\begin{aligned} \frac{-1}{3} \frac{P_n^{-4/3}}{\varepsilon \cdot \lambda} \cdot \left( \frac{K_j \cdot CRFT \cdot (K_r + K_p \cdot P_n)}{K_q} + K_c \right) + \\ + \frac{P_n^{-1/3}}{\varepsilon \cdot \lambda} \frac{K_j \cdot CRFT \cdot K_p}{K_q} = 0 \cdot \left| \frac{-3 \cdot P_n^{4/3}}{(\varepsilon \cdot \lambda)^{-1}} \right. \end{aligned} \quad (23)$$

and ordering the terms, the equation takes the form:

$$\begin{aligned} \frac{K_j \cdot CRFT \cdot (K_r + K_p \cdot P_n)}{K_q} + \\ + K_c - 3 \cdot \frac{K_j \cdot CRFT \cdot K_p \cdot P_n}{K_q} = 0 \end{aligned} \quad (24)$$

And after multiplying again by the indicated parameter:

$$\begin{aligned} \frac{K_j \cdot K_r \cdot CRFT}{K_q} - 2 \cdot \frac{K_j \cdot K_p \cdot CRFT \cdot P_n}{K_q} + K_c = \\ = 0 \cdot \left| \frac{K_q}{2 \cdot K_j \cdot K_p \cdot CRFT} \right. \end{aligned} \quad (25)$$

we can determine the deadweight  $P_n$ , at which the required freight rate RFR is the lowest:

$$P_n = \frac{1}{2} \cdot (K_r \cdot K_p^{-1} + K_c \cdot K_q \cdot K_j^{-1} \cdot K_p^{-1} \cdot CRFT^{-1}) \quad (26)$$

Within the framework of the analysed model, the determined ship deadweight is the optimal deadweight represented by the ship with the minimal freight rate which can be expressed explicitly using the adopted variables of the mathematical model:

$$P_n = \frac{1}{2} \cdot \left( \frac{K_r}{K_p} + \frac{K_c \cdot K_q}{K_j \cdot K_p \cdot CRFT} \right) = \frac{Q}{4 \cdot \varepsilon \cdot \lambda \cdot v} \quad (27)$$

$$\left( R + T_0 \cdot v + \frac{\mu \cdot C_j \cdot G_j \cdot v^3 \cdot R \cdot (\varepsilon \cdot \lambda \cdot P_{n0})^{2/3} \cdot Z_h}{J_0 \cdot Ca \cdot \eta^{2/3} \cdot \frac{(r+i+r \cdot i)}{1 - (1+r+i+r \cdot i)^{-m} \cdot (1-t)}} \right)$$

The above relation can be applied in simulation analyses of the effect of individual model parameters on optimal ship deadweight.

### SAMPLE APPLICATION OF THE METHOD

The sample application of the method refers to the optimal deadweight calculations for a cargo ship sailing at a speed equal to 17,5 kn when the assumed action radius is equal to 8000 Mm. The calculations took into account technical and economic conditions of ship building and operation defined by the parameters given in Table 1 and the profitability rate  $r$  required by the ship owner.

The assumed criterion for deadweight evaluation was the minimal freight rate which secures the required profitability of the investment project. This optimal deadweight corresponds to the minimal RFR value. If the ship deadweight differs from the optimal value, the freight rate which secures profitability is higher.

Tab. 1. Sample evaluation of optimal ship deadweight

<b>CALCULATIONS OF OPTIMAL SHIP DEADWEIGHT BY MINIMISING FREIGHT RATE RFR</b>			
<b>Ship owner's assumptions</b>	<b>Symbol</b>	<b>Value</b>	<b>Unit</b>
Assumed ship speed	v	17.5	[kn]
Autonomous action radius	Ra	8000	[Mm]
Average annual inflation rate	i	0.03	[-]
Number of ship operation days per year	Zd	340	[days]
Time of ship operation in hours	Zh	8160	[h]
Required net profitability rate	r	0.09	[-]
Income tax rate	t	0.19	[-]
Number of years of ship operation	m	20	[-]
Unit handling cost	Wj	5	[\$/t]
Specific fuel consumption	Gj	160	[g/kWh]
Fuel price	Cj	600	[\$/t]
Handling capacity	Q	50	[t/h]
Time of waiting on road and in harbour	To	2	[days/voyage]
Time of waiting on road and in harbour	Toh	48	[h/voyage]
<b>Parameters of similar ship</b>			
Deadweight of similar ship	Pp	10532	[t]
Speed of similar ship	v	16.5	[kn]
Displacement of similar ship	D	14946	[t]
Engine power of similar ship	Ne	5741	[kW]
Admiralty coefficient	Ca	566	[-]
Price of similar ship	J	40 000 000	[\$]
Deadweight-displacement coefficient	Eta	0.705	[-]
<b>Assumed model parameters</b>			
Deadweight efficiency	lamb	0.9	[-]
Net capacity efficiency	eps	0.9	[-]
Service cost coefficient	mi	1.1	[-]
<b>Auxiliary model parameters</b>			
Building cost coefficient	Kj	83 250	[-]
Operating cost coefficient	Kc	501	[-]
Handling cost coefficient	Kh	8	
Cost coefficient	Kq	7 140 000	
Cost coefficient	Kp	28	
Cost coefficient	Kr	442 000	
Capital return factor	CRF	0.148	[-]
Tax correction CRF	CRFT	0.182	[-]
<b>Calculated technical ship parameters</b>			
<b>Optimal ship deadweight</b>	<b>Pnopt</b>	<b>11950</b>	<b>[t]</b>
Ship displacement	Displ	16959	[t]
Engine power	Power	5949	[kW]
Time of 1 voyage	Tr	892	[h]
Time of cruising	Tm	457	[h]
Time of handling	Tq	387	[h]
Number of voyages per year	LRR	9.1	[-]
Fuel consumption in 1 voyage	ZPR	435	[t]
<b>Calculated economic ship parameters</b>			
<b>Required Freight Rate</b>	<b>RFR</b>	<b>126.8</b>	<b>[\$/t]</b>
Capital Recovery Period	Time	6.8	[lat]
Invest Cost	Price	43 515 053	[\$]
Annual Cargo Capacity	ACC	88 517	[t]
Annual Cargo Freight	ACF	11 220 977	[\$]
Annual Fuel Cost	AFC	2 387 241	[\$]
Annual Cargo Handling Cost	AHC	885 173	[\$]
Annual Operating Cost	AOC	3 272 414	[\$]
Average Annual Cost	AAC	12 097 673	[\$]

## SUMMARY

The paper presents a method for selecting the optimal deadweight of a cargo ship. The method may be useful at the stage of establishing basic ship owner's requirements concerning ship design parameters, along with choosing a proper ship for a given transportation task. The deadweight is determined on the basis of a selected economic measure of ship's transport efficiency, which is the Required Freight Rate (RFR). The mathematical model of the problem is of deterministic nature. The adopted simplifying assumptions base on the data obtained for ships operating in the liner trade. The assumptions have been selected in such a way that the solution of the problem is obtained in a closed analytical form. The reported method can be used for calculating pre-investment ships design parameters, or in transportation task studies.

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