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A Merchant Ships Size Optimization Model

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ABSTRACT

This paper analyzes how a shipowner or charterer may determine the specification of optimal ship size for a given route with respect to certain market requirements.

The theory of optimal ship size, a methodology for estimating scale economics, and the various factors affecting ship size are examined using a typical conventional cargo ship and bulk cargo carriers based on shipowners' cost data.

I. Introduction

The selection of the vessel size as measured by cargo capacity is one of the most important decisions affecting the overall economics of a proposed ship in the preliminary designing stage.

What are the important factors underlying the increase in ship size in different types of ships? How does an owner use his own experience and cost data to determine the best ship size to maximize his profit? All these questions can be answered by the economic analysis based on his own cost data. The cost structures are different not only for the individual shipping agent, but also due to the type of shipping services and commodities.

The shipping services are categorized as liner, tramp, and industrial operation. Liner trades advertise scheduled service between the specified prots whereas the tramps do not. Industrial operations are captive services in which both ships and cargoes are controlled by a single entity. For shipping purposes, commodities can be divided into four groups: major bulk commodities which are shipped in large volume like oil, iron ore, coal, and grain; minor or semi-bulk commodities which are loaded in smaller volumes, such as phosphate rock, bauxite and alumina, sugar, and salt; unitized

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cargo for container, Ro-Ro, and LASH ships; and general cargoes which are relatively small shipment sizes.

Gilman (1977) 'Ref. 5' presented cost differences for various types of ships on a typical voyage. The range of the cost per day is from 7,628 dollars to 25,686 dollars. These substantial variances are found in the costs of operating ship of various types, depending on the character of the ship itself, the trade in which it is employed, the flag of registry and the operating policies of the owner. Since ocean shipping is a truly international business, ships are typically built wherever the most, favorable arrangements can be made.

Under these complexities problems in deciding the optimum ship size will arise.

II. General Description of the Problem

For the shipowner the purchase of a vessel is very risky, due to the high capital investment, high expenses of operation, and the rapid technical progress in shipbuilding, as well as the fluctuation in market demand for shipping services.

Economic analysis should be carried out at the earliest planning stage, the so-called preliminary design stage. During the preliminary design stage of vessels, many technical and economic problems are faced. Technical problems are resolved by computer modelling on the basis of the buider's own experience but mainly, by an appeal to world experiences and the publicly documented results of past research work conducted concerning ship production and operation 'Ref. 11'.

The economic problems has, however, another facet. The ship research institutions working in various countries must work out for themselves their own model of ship economics, particularly in that part which concerns production technology 'Refs. 4, 6, 8'.

When modelling a ship's economics, it is necessary to identify the economic dependencies appearing in the process of production and operation of ships within a determined economic system.

This economic problem deals with the examination of the trade in which the ship is proposed by an owner. This examination may only be an analysis of existing ships of the same group in the trade in order to determine where improvements could be made and establish the economic relationship between factors by using scale economies'Ref. 8'. On the other hand, it may be a complete investigation of ship operating economics.

As far as the shipowner's economic calculations are concerned, the determination of the components of the costs, such as capital costs, operating costs at sea and in port over the economic life of the ship, is an important element. The basis of the shipowner's economic calculations are the results of the following data :

1. full characteristics of the shipping routes, such as,
    a. set of ports including canal and access routes;
    b. duration of one round trip corresponding to the ship's operation on the liner or tramp; and

c. expected number of the voyages per year based on the expected volume of trade.

2. characteristics of the set of ports, such as,

a. average freight rate and value of the cargo carried;

b. canal charges en route before the port;

c. port charges and cargo handling rates in the port;

d. bunkering time in the port; and

e. unit cost of basic, light fuel, lubricant, and fresh water.

Using these previous sets of data, one determines costs for the required variants of ship operation.

The decisions about the type and size of the ship of interest to an owner need to be evaluated under a variety of market conditions since the uncertainty about future freight market conditions for the cargo liners will affect the decision policies. There is also the problem of the time-scale required as well as the financial risk involved.

In many shipping services, cargo availability is limited and ships in those trades are denied the economic benefits of larger ship sizes. This explains why general cargo liners seldom exceed 15,000 deadweight tons whereas tankers have grown to twenty times that capacity.

The economic modelling itself is of limited value without some method of selecting the best design-called the measure of effectiveness. The economic criteria, which provide the measure of effectiveness of a ship design, have been found by Benford (1968) 'ref. 1,' Goss (1968) 'Ref. 6,' and the auther (1983) 'Ref. 11'.

The cost model of this paper will not be used for the comparison of the several design alternatives, and will exclude physical constraints such as port depth and the market constraint which is randomly fluctuating over the planning horizon.

III. Formulation of the Problem

To create the maximim possibilities for making economic profits involved in the future production and operation of the ship, the optimal size of the ship can be determined by minimizing total lifetime costs per ton at sea and in port.

To minimize the total costs per ton in every aspect of shipping service, the objective function must be the total cost function which relates the size of the ship to specified route characteristics and market constraints. If the market condition can be assumed to be constant and enough cargo is available, then the problem is to find the economical ship size with minimum total transport cost per ton at sea and in port.

The two distinct measures of a ship's output are defined for this objective as :

The handling capacity (H_1) equals the amount of cargo that can be loaded into or discharged per unit of time. The unit of measure of H_1 is deadweight tons loaded or unloaded per hour. The hauling capacity (H_2) equals the size of the ship that is the holding capacity (H_0), multiplied by ship speed (V). The unit of H_2 is used as deadweight tonmiles per day. The hauling capacity can be defined as:

$$H_2 = H_0 . V \qquad (1)$$

Total costs per deadweight ton are composed of two separable parts, costs per ton at sea and costs per ton in port. For this a complete output of shipping service must include the loading of a cargo at a port i, the hauling from the port i to port j, and the unloading of the cargo at port j.

By this approach the total transport costs can be divided into two main categories: so-called ship's time(time-proportional) costs and cargo costs. The cargo costs are by and large proportional to the quantity of cargo 'Ref. 8'. A miles-proportional cost which relates to the voyage distance, such as the fuel cost at sea, can be regarded as the time-proportional cost at a given speed. The time costs incurred per day at sea and in port are not of the same nature. The cost of fuel is the most important cost only at sea and lay-time proportional port charges are only in port whereas some of the operating costs, such as the crew wages are related both at sea and in port.

For the national convenience the factor costs incurred only in port are ordered from 1 to k, those that are incurred both in port and at sea from k + 1 to n, and those incurred only at sea from n + 1 to u.

Therefore, Total time cost per day in port (TC_1) ;

$$TC_1 = \sum_{i=1}^{n} f_i(S) \qquad (2)$$

Total time cost per day at sea (TC_2) ;

$$TC_2 = \sum_{i=k+1}^{u} f_i(S) \qquad (3)$$

for i = k+1, ... , n, ... , u.

Total cargo cost per ton of cargo (TC_3) ;

$$TC_3 = \sum_{i=1}^{k} g_i(S) \qquad (4)$$

for i = 1, ... , k, where S is the ship size in deadweight tons, $f_i(S)$ is the function that relates time costs to ship size, and $g_i(S)$ is the i^{th} cargo cost per ton.

To transform daily port costs to costs per ton, divide TC_1 by the handling capacity in tons loaded/unloaded per hour H_1, and multiply by effective working hours per day P. The resultant cost should be multiplied by two, since each ton of cargo is handled twice in both ports to obtain the handling cost per ton.

Handling cost per ton in port (C_1);

$$C_1 = \frac{2 \cdot TC_1}{pH_1(S)} = \frac{2 \sum_{i=1}^{n} f_i(S)}{pH_1(S)} \qquad (5)$$

Similarly the daily sea costs can be transformed. Divide TC_2 by the hauling capacity in ton-miles per day H_2, and the cargo balance factor ℓ. This yields the costs per cargo ton-mile. Then this is multiplied by the round trip distance D miles to get the hauling cost per ton of cargo on the specified route.

$$C_2 = \frac{D \cdot TC_2}{\ell H_2(S)} = \frac{D \sum_{i=k+1}^{u} f_i(S)}{\ell H_2(S)} \qquad (6)$$

Where the cargo balance factor ($1 \leq \ell \leq 2$) is defined as

$$\ell = \frac{\text{total volume of cargo on both legs}}{\text{volume of cargo on the fat leg}}$$

Clearly, the cargo cost per ton increases linearly with the increasing of the size of the ship because the morecarried products need more spaces, so that the investment in the quay side and the interest cost for the cargo must be increased. Thus.

$$C_3 = \sum_{i=1}^{k} g_i(S) \qquad (7)$$

The total cost per ton of cargo becomes ;

$$TC(S) = C_1(S) + C_2(S) + C_2(S) + C_3(S) \qquad (8)$$

Shipbuilding and marine engineering cost studies 'Ref. 8' have shown that a geometric function is the most suitable form for expressing the relationship between handling and hauling capacities, and costs to the size of the ship. This model includes design parameters H_0, H_1 and V which are too ambitious in view of the limited knowledge of the relationship between ship design and shipping costs. However, a simplification is afforded by reducing the many design parameters to the most important one-the holding capacity which is the size. Then the two capacities can be written:

$$H_1 = h_1 S^{E_1} \qquad (9)$$

$$H_2 = h_2 S^{E_2} \qquad (10)$$

Where h_1 and h_2 are design parameters that vary among ship types. E_1 and E_2 are the output elasticities of two capacities with respect to ship size. The proportionality coefficient h_1 is different across ship types and varies by exogenous factors, such as cargo composition, port capital and labor productivity. Likewise, h_2 is design parameter which relates to a stowage factor that varies by ship types.

The i^{th} factor cost per day, $f_i(S)$, which relates the ship's time costs can be defined :

$$f_i(S) = P_i q_i S^{e_i} \tag{11}$$

for i = 1, . . . , k, . . . , n, . . . , u, where P_i is the i^{th} factor price and $q_i S^{e_i}$ represents the i^{th} factor requirement per day.

Substituting the Equations (9) through (11) into Equations (5) and (6), the total transport costs per ton for D nautical miles of a roundtrade route are :

$$TC(S) = \frac{2 \sum_{i=1}^{n} p_i q_i S^{e_i - E_1}}{p h_1} + \frac{D \sum_{i=k+1}^{u} p_i q_i s^{e_i - E_2}}{\ell h_2} + \sum_{i=1}^{k} p_i q_i S^{e_i} \tag{12}$$

for i = 1, ... , k, . . . , n, ... , u factors.

The optimum ship size can be found by minimizing the total costs per ton in port and at sea, TC(S) under the given assumptions.

IV. Estimates of the Size Elasticities

The hyposeses on elasticities are based on marine engineering principles. These estimates have been computed by Thorburn (1060), Heaver (1968), Goss and Jones (1971), Janssön and Shneerson (1982), and the Auther (1983) 'Refs. 6, 8, 11' by using technical principles. More details of these technical principles to estimate the size elasticities of the outputs, which are the hauling and handling capacities, and the costs, which consist of the capital costs, the operating costs, the fuel costs and the port costs as cargo costs.

The size elasticities of the output capacities (E_1, E_2) and the costs (e_1, e_2, e_3, e_4) of this model can be summarized as follows in Table 1.

The reader should be aware that the results in Table 1 come from a variety of different models and some of the empirical results did not have an exceptionally high multiple correlation coefficient, so that the analysis of a shipowner should use his own results based on his experience. Therefore this summary is not conclusive, but can be a guide for deriving his own results.

If the estimates of e_i, i = 1, ... , 4 and E_i, i = 1, 2 are inserted explicitly into the total cost

Table 1. **Summary of the Size Elasticities of the Output and Cost.**

Ship Type	Out Outputs		Range of Elasticiites
	Handling	Hauling	
	E_1	E_2	
Dry bulk cargo carrier	0.1	1.0	$0.1 \leq E_1 \leq 0.33$
General cargo ship	0.15	1.1	$1.0 \leq E_2 \leq 1.2$
Container ship	0.25	1.2	

Ship Type.	Costs				Range of Elasticities
	Capital	Operating	Fuel	Cargo (Port)	
	e_1	e_2	e_3	e_4	
Dry bulk cargo carrier	0.7	0.4	0.7	1.0	$0.6 \leq e_1 \leq 0.85$
General cargo ship	0.7	0.4	0.7	1.0	$0.3 \leq e_2 \leq 0.6$ $0.6 \leq e_3 \leq 1.0$
Container ship	0.85	0.4	0.7	1.0	$e_4 = 1.0$

function, Equation (12), the final formula for this model will be :

$$TC(S) = \frac{2}{ph_1} (p_1 q_1 S^{e_1 - E_1} + p_2 q_2 S^{e_2 - E_1} + p_4 q_4 S^{e_4 - E_1}) + \frac{D}{\ell h_2} (p_1 q_1 S^{e_1 - E_2} + p_2 q_2 S^{e_2 - E_2} + p_3 q_3 S^{e_3 - E_2}) \qquad (13)$$

Since the model assumes the zero cargo cost, the last term drops out from Equation (12). From Equation (13) the handling cost per ton increases with the ship size because the differences $e_i - E_1$, i = 1, 2, 4 are all positive values, and the hauling cost per ton decreases with the ship size because the differences e_i-E_2, i = 1, 2, 3 are all negative. Therefore the optimum ship size for a given route is obtained by trading off economies of size in hauling operations and diseconomies of size in handling operations.

V. Conclusions

This thesis has demonstrated how a shipowner or charterer might determine the economical size of the ship in a given dense cargo route to minimize his total transport cost per ton of a particular ship. Although the value of the estimates may vary among the type of vessels, type of shipping service as well as different shipping operators, the principle of the model can be applied by any type of ship. Furthermore, the model can be extended to use the comparison of alternatives for ship designs based on the minimum required freight rate which can be defined as the minimum total transport cost per ton.

The model may be justified in the thin trade route with multiports. If the demand imposes a constraint on the maximum feasible ship size, the optimum ship size should be determined simultaneously with the optimal frequency of shipping service. And the model can be improved by using multivariables, such as shaft horsepower, handling rate, speed and size of the ship as independent variables.

Furthermore the discussed marine engineering principles and similar time costs may be applied for the analysis of the naval vessels.

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