COSTS OF SHIP DESIGN PARAMETERS

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FOR PRESENTATION TO

THE ROYAL INSTITUTION OF NAVAL ARCHITECTS(AUST.)

IN CANBERRA ON

12TH JULY 1972

CONTRIBUTIONS TO THE DISCUSSION OF THIS PAPER ARE INVITED; THEY SHOULD BE TYPEWRITTEN AND SHOULD REACH THE HON. SECRETARY, THE ROYAL INSTITUTION OF NAVAL ARCHITECTS (AUSTRALIA), BOX 4762 G.P.O., SYDNEY, N.S.W. AUSTRALIA NOT LATER THAN 7th JULY 1972.

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April 1972

Techniques are presented which enable a ship designer to evaluate the relative costs of each of the vessel's design parameters. Demonstration of the lowering of the applicable cost criterion for bulk carriers and tankers is then given. It is shown that a true minimum cost criterion is achieved when the incremental costs associated with changes in each of the ship design parameters are uniform. Techniques are also presented to calculate the break-even costs of up-grading shore-side and on-board cargo handling facilities.

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1. Introduction

Optimisation techniques in preliminary ship design, such as those shown for tankers by Nowacki [1970] and for bulk carriers by Fisher [1971a] are valid and useful when costs (capital and operational) are known as general functions of the primary design parameters of the vessel. Most often, however, the absolute levels are not known accurately. That is especially true when the designs called for are of a unique nature, due to greater size than previous vessels, or due to unusual configurations resulting from "boundary conditions" pertinent to the design, construction or operation of the vessel.

In ascertaining the absolute levels of costs, which is vitally necessary in optimisation studies (the play-off of capital against operational costs), the time and place of construction and operation have much significance in establishing the validity of the estimates. This tends to render any previously developed, non-local cost functions invalid. Equally, when the configuration of the vessel is unique, weight estimates based on previous designs are also inadequate. This will be an important consideration when the recent IMCO* agreements limiting individual tank sizes becomes effective.

There exists then a barrier to the use of general optimisation techniques when general weight and cost functions fail to give reasonably accurate forecasts of the absolute levels of the various weights and costs. Fisher [1971b] suggests that, to circumvent that barrier, a different design process be used.

Specifically, it is suggested that the full details of a 'good' design be obtained through the purchase of that information from designer

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* Intergovernmental Maritime Consultative Organisation

and shipyard, even though that design may not be the one finally selected. Then, further refinements can be based on those figures, introducing errors of much smaller magnitude than would be encountered if invalid cost and weight functions were used in an optimisation procedure. This paper aims at providing the tools for making those refinements for bulk carriers and tankers, and should be of assistance to both owners and shipyards. The techniques can be applied to other vessel types as well.

If capital costs are the criteria by which the design is to be judged, the same techniques presented here can be used if only the relative proportions of the construction costs of previous designs are known. That would partially obviate the need for a design that would be used only for evaluation, and most likely not for construction.

One of the noteworthy aspects of the developed partial derivative expressions is that the influence of parametric variations can be seen directly, rather than remaining hidden within the subtleties of computer programming techniques.

2. Analysis versus Empiricism

A considerable number of published papers are devoted to the application of analytical concepts to the design of certain aspects of ship construction and operation. These range from grillage analysis for deck structures to queuing theory for fleet operations. In some instances the "purity" of the analytical foundations for the work is reduced by the necessary introduction of empirical information, such as classification society rules. (See, for example, the work by Buxton [1966].)

The necessity of the empirical dilution of the analyses arises from either non-availability of the applicable analytical mechanisms, or from "economic/political" considerations. The latter situation occurs because we seek to operate in a general society which is governed and run according to certain regulations and concepts. That is unavoidable. The former situation, however, obtains through choice exercised by the technological community at large. That choice is, presumably, a carefully considered one, in which the expected benefits are weighed against the costs of developing the appropriate analytical techniques.

There is no fundamental law which guarantees that a solution obtained by pure analysis is "better" than one derived with the aid of empirically-based information. The only guarantee that can be made is that there exists a correlation between analysis and appreciation of relationships. Dr. R.C. Parker [1971] emphasizes that point from a different approach:

> Technology cannot claim the authority of science and frequently makes use of empirical observations without an understanding of their meaning.

It is for that reason that elementary analytical techniques applied to the whole of preliminary ship design are introduced here.

An intermediate stage, that is, a mixture of empiricism and analysis, can be quite misleading, and should be used only to aid in the decision-making process leading to the choice mentioned above. An example of the effects of incorrectly applying analytical techniques to empirically-derived information is discussed in Appendix III-B. Both Sato [1967] and Conn [1970] differentiate empirical formulae for hull steel weights. Referring to them, Professor Conn cautions:

> The formulae...which are obtained by differentiation should be regarded as first approximations only, as the differentiation of an empirical expression is not a practice to be recommended.

This paper, while utilising several empirical relationships, uses elementary calculus techniques to reveal relationships which would otherwise remain unknown or be of suspect validity. If the results are arguable because of the inclusion of the empirical formulae, additional information is nevertheless obtained on which to base the choice: should further work be done toward increasing the purity of the analysis, or should it be abandoned at this point? Do the probable benefits of that work outweight the costs, or has no new light been shed on the subject of ship design? The answers to those questions are a matter of subjective judgement. A general answer is given in Dr. Parker's [1971] paper:

> The small scientific effort was launched because it was judged that, though the probability of success was low, the potential gain from even a partial breakthrough would be enormous...This decision has proved to be correct and in recent years more and more empirical relationships have been put on a sound scientific basis so that we can build on solid rock, and not on shifting sand.

The author's opinion is that although the specific conclusions of this study may be arguable, the apparent benefits resulting from further analyses will far outweight the costs. Nevertheless, it is with Professor Conn's caution in mind that this paper has been written.

3. Application

Suppose "F" is one of the cost, weight or other design items or groups pertinent to a vessel's construction or operation. Also, suppose "P" is a primary or secondary design parameter. Once the weights and costs associated with a given "good" design are known, and "F" is evaluated, then the F-space can be examined by such expressions as:

$$F_2 \approx F_1 + (P_2 - P_1) \cdot \frac{\partial(F)}{\partial(P)} .$$

When presented in the matter shown above (by the use of partial derivatives) the results for different P's can be linearly superimposed for small changes of those parameters. For example, with W'_L being the total lightship weight of the 'good' design, the new W_L for a 3% increase of beam and a 5% reduction of block coefficient would be estimated by:

$$W_L \approx W'_L + 0.03\ B' \cdot \frac{\partial(W_L)}{\partial(B)} - 0.05\ C'_B \cdot \frac{\partial(W_L)}{\partial(C_B)}\ .$$

In this paper, the primary design parameters used are length, beam, depth, block coefficient and service speed. The secondary design parameter, whose influence is examined by identical techniques, is the cargo handling rate. For illustrative purposes, two fictitious vessel designs are used: a bulk/ore carrier (constructed in a high-cost country) and a tanker (low cost). The details of those designs appear in Table I.

The figures presented in subsequent sections indicate the incremental changes in "F" for 1% changes in each of the primary design parameters. It is assumed for presentation purposes that each of the P's are increasing, but the results are equally valid, with opposite signs (+ or -) for decreases in the parameters.

4. Weight Derivatives

The general relationships are:

$$\Delta = W_L + W_D = L \cdot B \cdot T \cdot C_B.$$

$$W_D = W_C + W_F + W_W + W_{FR}.$$

$$W_L = (W_S + W_M + W_O) \cdot (1 + m).$$

With the depth/draught ratio constant (see Appendix II-D), for the primary design parameters L, B, D and C_B, the displacement derivatives are given by:

$$\frac{\partial(\Delta)}{\partial(-)} \approx \frac{\Delta'}{(-)'}\ ,$$

TABLE I

DESIGN AND OPERATIONAL DETAILS OF 148 kDWT ORE CARRIER (DIESEL) AND 253 kDWT TANKER (STEAM)

Category	Item	Symbol	Ore	Tanker
Particulars (meters)	Length B.P.	L	299.6	320.0
	Beam	B	39.5	54.5
	Depth	D	24.2	28.0
	Draught	T	17.1	21.0
	Block Coeff.	C_B	0.865	0.800
	Prism. Coeff.		0.871	0.806
Weights (1000's tons)	Displacement	Δ	176.1	295.6
	Lightship	W_L	28.3	42.2
	Steel	W_S	23.5	36.8
	Mach'y	W_M	1.9	2.1
	Outfit	W_O	2.2	2.3
	Margin	m	0.0254[1]	0.0243[1]
	Deadweight	W_D	147.8	253.4
	Cargo	W_C	145.8	242.9
	Fuel	W_F	1.5	8.7
	Water Misc.	W_W	0.3	0.5
	Fuel Reserve	W_{FR}	0.2	1.3
Powering	Service H.P.	S_N	23,800	36,000
	Installed H.P.		28,600	40,000
	Service Speed	V	14.4	16.0
	Ballast Speed		16.5	19.2
	Type		Diesel	Steam
			10 @ 90cm.	1 boiler

Notes:

1 - Lightship Margin, m, is defined by:

$$W_L = (1+m)\cdot(W_S + W_M + W_O).$$

2 - Overhead Cost Fraction, q_o, is defined by:

$$Q_T = (1 + q_o)\cdot(Q_S + Q_M + Q_O).$$

TABLE I

(continued)

Category	Item	Symbol	Ore	Tanker
Operations (Days)	Annual Service	T_0	360	360
	Sea Time	$T_S \cdot N_V$	245	313
	Manoeuvering	$T_F \cdot N_V$	46	23
	Cargo Hndlng	$T_C \cdot N_V$	69	24
	Annual Voyages	N_V	14	7.5
	Voyage Dist.		3220	8700
	Cargo E-W		Ballast	Crude Oil
	Cargo W-E		Ore	Ballast
	No. of Crew		32	29
Capital Costs ($1000's)	Total	Q_T	20,020	18,620
	Steel	Q_S	5,591	7,650
	Machinery	Q_M	5,230	4,042
	Outfit	Q_O	6,036	3,825
	Overhead	q_o	0.188[2]	0.200[2]
Voyage Costs 1st Year ($1000's)	Total	Q_{AD}	1068	1673
	Fuel	Q_F	422	1500
	Port	Q_P	138	79
	Cargo Hndlng	Q_H	508	94
Annual Costs ($1000's)	Total	Q_{AI}	1352	1563
	P & I Insur.	Q_{PI}	39	80
	H & M Insur.	Q_{HI}	683	930
	Hull Maint.	Q_{HM}	155	185
	Mach'y Maint.	Q_{MM}	111	48
	Crew	Q_C	340	300
	Stores	Q_{SS}	24	20
Cargo Rates (tons/hr)	Loading		7000	8000
	Discharging	R_D	1500	6000

while the speed derivative is identically zero. (Primed values are those applicable to an established design, with weights and costs evaluated.)

Derivatives of steel, machinery and outfitting weights are obtained from Appendices I, II and III respectively, leading to the following light ship weight derivatives:

$$\frac{\partial(W_L)}{\partial(-)} = \left[\frac{W_S'}{(-)'} \cdot a_s + \frac{W_M'}{(-)'} \cdot a_m + \frac{W_O'}{(-)'} \cdot a_o \right] \cdot (1 + m),$$

in which a_s, a_m and a_o are given in Table II. Other values of coefficients may be utilised, in accordance with the derivations of those shown values. Close study should be given to the appendices prior to usage.

An example of the use of Table II, for the example bulk carrier with diesel machinery, is:

$$\frac{\partial(W_L)}{\partial(B)} = \left[0.90 \, \frac{W_S'}{B'} + 0.65 \, \frac{W_M'}{B'} + 0.75 \, \frac{W_O'}{B'} \right] \cdot (1 + m).$$

The deadweight (W_D) of the vessel is considered variable, leading to:

$$\frac{\partial(W_D)}{\partial(-)} = \frac{\partial(\Delta)}{\partial(-)} - \frac{\partial(W_L)}{\partial(-)},$$

in which expressions for the two terms on the right side of that equation are given previously.

The fuel weight derivatives are prescribed by the required changes of powering. They are derived in Appendix IV-A, and are in the form of:

$$\frac{\partial(W_F)}{\partial(-)} = a_p \cdot \frac{W_F'}{(-)'},$$

in which values of a_p are given in Table II.

Small changes in the primary design parameters will lead to insubstantial changes in the fresh water and miscellaneous weights (W_W) included in the deadweight. The same is true for the fuel reserve (W_{FR}).

TABLE II

Coefficients for weight and Cost Derivatives

Parameter	L	B	D	C_B	V
a_s (bulk)*	1.42*	0.90*	0.72*	0.34*	0.0
a_s (tanker)*	1.65*	0.87*	0.78*	0.35*	0.0
a_m (steam)	0.35	0.26	0.0	0.09	1.23
a_m (diesel)	0.87	0.65	0.0	0.22	3.04
a_o (bulk)	0.75	0.75	0.0	0.0	0.0
a_o (tanker)	0.25	0.17	0.08	0.03	0.0
a_p	1.00	0.75	0.0	0.25	3.50
b_m (steam)	0.55	0.41	0.0	0.14	1.92
b_m (diesel)	0.93	0.70	0.0	0.23	3.25

* The values of 'a_s' shown here apply to the two example vessels only. For generally applicable values, see Appendix I. Note that the total steel weight scale factor is 3.04 for that bulk/ore carrier, and 3.30 for the example tanker.

Thus all derivatives of W_W and W_{FR} are taken to be zero.

The cargo capacity (W_C), then, has derivatives given by:

$$\frac{\partial(W_C)}{\partial(-)} = \frac{\partial(\Delta)}{\partial(-)} - \frac{\partial(W_L)}{\partial(-)} - \frac{\partial(W_F)}{\partial(-)} .$$

For the example tanker with steam machinery:

$$\frac{\partial(W_C)}{\partial(L\ )} = \frac{\Delta'}{L'} - \left[1.65\ \frac{W'_S}{L'} + 0.35\ \frac{W'_M}{L'} + 0.25\ \frac{W'_O}{L'}\right]\cdot\ (1+m)$$

$$- 1.00\ \frac{W'_F}{L'}$$

For the two example vessels (Table I), the change of lightship and fuel weights for 1% increases in the primary design parameters are shown in Figure 1. The left-hand portion of the figure ('Total Weights") indicates the proportional contributions in the original design. The vertical scale of the heavy bars is used for a reference 1%. It is observed that for both vessels, a 1% increase of length leads to a substantially greater increase in steel weight alone. The tanker's steel weight increases by 1.22% of the total lightship plus fuel weight; or by 1.22/0.74 = 1.65% of the original steel weight, with that last value corresponding to "a_s" in Table II.

In Figure 1, the difference between diesel and steam machinery is also seen, along with the different fuel requirements for an intermediate voyage (6440 miles total) and a long voyage (17,400 miles). For the machinery weights having a 1.5/1 ratio in proportional contributions in the original designs (.06/.04), the ratio of the increment for a 1% increase in speed becomes 0.19/0.05 = 3.8/1. The ratio 3.8/1.5 = 2.5 corresponds to the ratio of values of "a_m", being 3.04 and 1.23, respectively, for diesel and

FIGURE 1

Incremental changes of LIGHTSHIP AND FUEL WEIGHTS due to 1% increase of design parameters, as a percentage of original weights.

	TOTAL WEIGHTS		LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
STEEL	.81	.74	1.15	1.22	.73	.64	.58	.58	.27	.26	-	-
OUTFIT	.08	.05	.06	.01	.06	.01	-	-	-	-	-	-
MACH'Y	.06	.04	.06	.02	.04	.01	-	-	.01	-	.19	.05
FUEL	.05	.17	.05	.17	.04	.13	-	-	.01	.04	.18	.60
TOTAL	1.00	1.00	1.32	1.42	.87	.79	.58	.58	.29	.30	.38	.65

FIGURE 2

Incremental changes of CAPITAL COSTS due to 1% increase of design parameters, as a percentage of original costs.

	CONSTRUCTION COSTS		LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
STEEL	.28	.41	.47	.81	.30	.43	.24	.38	.11	.17	-	-
OUTFIT	.26	.22	.27	.06	.27	.04	-	.02	-	.01	-	-
MACH'Y	.30	.20	.29	.14	.21	.11	-	-	.07	.04	1.01	.50
MISC & OVERHEAD	.16	.17	-	-	-	-	-	-	-	-	-	-
TOTAL	1.00	1.00	1.03	1.01	.78	.58	.24	.40	.18	.22	1.01	.50

steam (Table II).

For the tanker, the depth and block coefficient do affect the outfitting weights, but the effect is too small to appear in the figure.

5. Capital Cost Derivatives.

For tankers and bulk carriers, the total capital cost is given by:

$$Q_T = (Q_S + Q_M + Q_O) \cdot (1 + q_o),$$

in which the overhead cost fraction (q_o) is considered constant for small changes of the primary design parameters. The steel, machinery and outfitting derivatives are established in Appendices I, II and II. The general form of the total cost derivatives is:

$$\frac{\partial(Q_T)}{\partial(-)} = \left[a_s \cdot \frac{Q'_S}{(-)'} + b_m \cdot \frac{Q'_M}{(-)'} + a_o \cdot \frac{Q'_O}{(-)'} \right] \cdot (1 + q_o)$$

Values of b_m and a_o appear in Table II, and a_s may be derived from Appendix I.

It may be noted that the steel and outfitting cost derivative coefficients are the same as those for the corresponding weight coefficients. Explanations for that are given in Appendices I-C and III-A. For the example bulk/ore carrier with a diesel plant:

$$\frac{\partial(Q_T)}{\partial(C_B)} = \left(0.34 \frac{Q'_S}{C'_B} + 0.23 \frac{Q'_M}{C'_B} \right) \cdot (1 + q_o).$$

(note that $a_o = 0.0$ for C_B).

For a tanker with a steam plant:

$$\frac{\partial(Q_T)}{\partial(V)} = \left(1.92 \frac{Q'_M}{V'} \right) \cdot (1 + q_o).$$

In Figure 2 the changes of capital costs due to 1% increases of the design parameters for the example vessels are shown. Again, the left-hand portion indicates the initial distribution of the cost components, with the height of the bars being a reference 1%. Note that the initial distribution includes miscellaneous and owner's overhead expenses, whereas the other five pairs of columns do not.

The disparity in proportional contributions between weight changes (Fig. 1) and cost changes (Fig. 2) may be noted, arising from the fact that outfitting and machinery are much more costly per unit weight than is steel.

6. Annual Cargo Capacity.

If the vessels are operating on a single route, completing N_V round trip voyages per year, then a change in one of the primary design parameters will affect the annual cargo capacity (W_A) in two ways. Firstly, for constant loading and discharge rates, the cargo-handling time per voyage will increase as the cargo capacity of the vessel (W_C) increases. That will in turn tend to lessen the number of completed voyages, and so decrease the annual cargo capacity.

Secondly, with the capacity per voyage increased (despite a smaller N_V), the total W_A will also be increased. These two aspects arise from the two terms on the right-hand side of the relationship:

$$\frac{\partial(W_A)}{\partial(\,-)} = \frac{\partial(W_C \cdot N_V)}{\partial(\;-\;)} = W_C \cdot \frac{\partial(N_V)}{\partial(-)} + N_V \cdot \frac{\partial(W_C)}{\partial(-)} \;.$$

Derivatives of N_V are obtained in Appendix IV-B, and are based on the basic relationship:

$$T_O = N_V \cdot (T_S + T_C + T_F),$$

in which the three terms in parentheses represent, respectively, the sea time, cargo-handling time and fixed time losses per voyage; and in which T_O is the total operating days per year. Figure 3 indicates the changes of W_A applicable to the two example vessels.

In that figure, the reversal of contributions for a 1% increase in speed may be noted. This arises from the fact that requirements for a speed increase tend to decrease the cargo capacity per voyage (W_C), whereas changes in the other four primary design parameters have the opposite effect.

The equations above and the presented examples assume that the vessel operates in ballast in one direction, and fully laden in the other. If that is not the case, then a factor 'n', being the number of revenue earning legs of each voyage, must be introduced into the equation:

$$W_A = n \cdot W_C \cdot N_V.$$

For a triangular route having one ballast-carrying leg, n=2, which is the same value for a single route with profitable trade in both directions.

Comparing Figures 2 and 3, it is noted that for the example tanker a 1% increase in length adds 1.01% to the construction cost, but adds only 0.86% to the annual cargo capacity; whereas a 1% increase in depth adds 0.40% to the cost and 1.03% to the annual capacity. Other similar comparisons are evident.

7. Voyage Costs.

Voyage costs are considered to be those operating expenses that are dependent on the number of voyages completed annually. In this study they constitute the fuel, port and direct cargo-handling expenses:

$$Q_{AD} = Q_F + Q_P + Q_H.$$

The fuel costs follow directly from the fuel weights, discussed in

FIGURE 3

Incremental changes of ANNUAL CARGO CAPACITY due to 1% increase of design parameters, as a percentage of the original capacity.

	LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
PART DUE TO CHANGE OF CARGO CAPACITY PER VOYAGE	+.95	+.92	+1.04	+1.05	+1.10	+1.10	+1.15	+1.15	-.08	-.14
PART DUE TO CHANGE IN ANNUAL NUMBER OF VOYAGES	-.19	-.06	-.21	-.07	-.22	-.07	-.23	-.07	+.72	+.88
TOTAL	+.76	+.86	+.83	+.98	+.88	+1.03	+.92	+1.08	+.64	+.74

FIGURE 4

Incremental changes of ANNUAL FUEL COSTS due to 1% increase of design parameters, as a percentage of the original fuel costs.

	LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
DUE TO CHANGE OF POWER REQUIREMENTS	1.00	1.00	0.75	0.75	-	-	0.25	0.25	3.50	3.50
DUE TO INCREASE OF PORT TIME RESULTING FROM CHANGE OF CARGO CAPACITY	-.19	-.06	-.21	-.07	-.22	-.07	-.23	-.07	+.02	+.01
DUE TO INCREASE IN ANNUAL NUMBER OF VOYAGES RESULTING FROM HIGHER SPEED	-	-	-	-	-	-	-	-	+.70	+.87
TOTAL	0.81	0.94	0.55	0.68	-.22	-.07	+.02	.18	4.22	4.38

Section 4. For incremental changes in the primary design parameters, the fuel increment will have two or three components, depending on the parameter. It is governed by the relationship:

$$\frac{\partial(Q_F)}{\partial(-)} = \frac{\partial(\gamma \cdot W_F \cdot N_V)}{\partial(-)} = \gamma \cdot W_F \cdot \frac{\partial(N_V)}{\partial(-)} + \gamma \cdot N_V \cdot \frac{\partial(W_F)}{\partial(-)} .$$

When the parameter is design speed, $\partial(N_V)/\partial(V)$ has two terms. That equation may be viewed in another manner.

Firstly, for all five parameters, a change of hull configuration or speed resulting in new powering requirements will contribute to the incremental change of annual fuel costs. Secondly, the change in the annual number of voyages completed due to altered cargo capacity and subsequent cargo-handling time* will also have an effect. And thirdly, when the parameter is the design speed, the annual fuel costs will change due to the directly affected number of voyages completed. The expressions for the derivatives are established in Appendix IV.

Figure 4 illustrates the different contributions to incremental annual fuel costs for the example bulk/ore carrier. In that figure it may be noted that the first component's contribution to the change in annual fuel cost corresponds to "a_p" in Table II. The second and third components are the same as the second contribution to the change of annual cargo capacity (Fig. 3).

Insufficient information is available at present to ascertain the "equivalent" of port costs for vessels using off-shore loading and discharge terminals, including slurried ore facilities such as that recently

*That assumes adequate cargo availability to utilise, if necessary, the greater cargo capacity.

established in New Zealand ("Ocean Industry", Aug. 1971). Derivatives of port costs for normal port usage are obtained in Appendix V-A.

Direct cargo handling costs are assumed to be proportional to the annual cargo movement. It is realised that a more exact relationship can be devised, but the correction to that assumption would be an order of magnitude smaller than the incremental cost arising from a small change in one of the design parameters. The correction is, therefore, ignored, considering the approximations already contained in the derivatives. That concept - disregarding small corrections to larger approximations - is observed throughout this paper.

The magnitude of direct cargo handling expenses is very difficult to establish. Sometimes it is absorbed into port costs, maintenance and repair costs, or not even considered pertinent to the operation of the ship sub-system. For this study they are assumed to be \$0.25 per ton of cargo handled for the bulk/ore carrier, and \$0.05 per ton for the tanker. Those values have not been adequately confirmed by industrial sources.

The incremental changes of voyage costs for 1% increases in the design parameters for the example vessels are shown in Figure 5. Inasmuch as fuel constitutes 39% of the original voyage costs for the bulk/ore carrier (left column, Fig. 5), the 4.22% change of fuel costs (right side Fig. 4) corresponds to the 1.67% indicated in Fig. 5 (1.67/4.22 = 0.39). Other relationships between Figures 4 and 5 are similar.

FIGURE 5

Incremental changes of VOYAGE COSTS due to 1% increase of design parameters, as a percentage of the original voyage costs.

	VOYAGE COSTS		LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
FUEL	.39	.89	.32	.84	.22	.61	-.09	-.06	+.01	.16	1.67	3.92
PORT	.13	.05	.13	.04	.13	.04	.12	.04	.08	.02	.09	.04
CARGO HANDLING	.48	.06	.36	.05	.39	.06	.42	.06	.44	.06	.30	.04
TOTAL	1.00	1.00	.81	.93	.74	.71	.45	.04	.53	.24	2.06	4.00

FIGURE 6

Incremental changes of FIXED ANNUAL COSTS due to 1% increase of design parameters, as percentage of original costs, *excluding crew and stores.

	FIXED COSTS*		LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
HULL & MACH'Y INSUR.	.69	.75	.71	.75	.54	.43	.18	.30	.13	.16	.70	.37
P & I INSUR.	.04	.06	.04	.06	.04	.07	.04	.07	.04	.07	-	-
HULL MAINT	.16	.15	.11	.10	.11	.10	.11	.10	-	-	-	-
MACH'Y MAINT	.11	.04	.11	.03	.08	.02	-	-	.03	.01	.39	.09
TOTAL	1.00	1.00	.97	.94	.77	.62	.33	.47	.20	.24	1.09	.46

8. Fixed Annual Costs

The fixed annual costs (Q_{AI}) independent of the number of voyages completed, consist of those attributable to insurance, maintenance and repair, crew, stores and supplies. The insurance costs (Q_I) are subdivided into hull and machinery insurance (Q_{HI}), and protection and indemnity (Q_{PI}). The maintenance and repair costs are also subdivided into the categories hull M&R (Q_{HM}), and machinery M&R(Q_{MM}).

Those costs are not truly fixed, which may be realised if the extreme situation $N_V \to 0$ is considered, arising from lack of adequate charter markets, industrial disputes, etc. But for this study, in which small changes of design parameters are considered, the costs mentioned above will, for all intents and purposes, be constant.

The derivatives of the various components of Q_{AI} are formulated in Appendix VI. The last part of that appendix establishes that the derivatives of the crew, stores and supplies costs are identically zero. The incremental changes of the four non-zero components for the two example vessels appear in Figure 6. Attention should be given to the fact that, as formulated, derivatives of Q_{HM} w.r.t. C_B and V are zero.

9. Cargo Handling Rates.

Cargo handling rates are the major secondary parameters in ship design. They may be thought of as boundary conditions on the ship's operations in the same manner that a draught limitation is a boundary condition on the design. The purpose of this section is to demonstrate the significance of that boundary condition, and the "apparent" funds available for the improvement of the shore-side cargo handling rates. The following section considers on-board facilities.

The costs associated with improvement of cargo loading and discharge rates are the additional capital and operational costs for effecting those improvements, plus the vessel's added voyage costs. The design of the vessel is unaffected by improvements in shore-side cargo handling rates, but the annual cargo capacity will change as a result of faster turn-around times; thus increasing N_V.

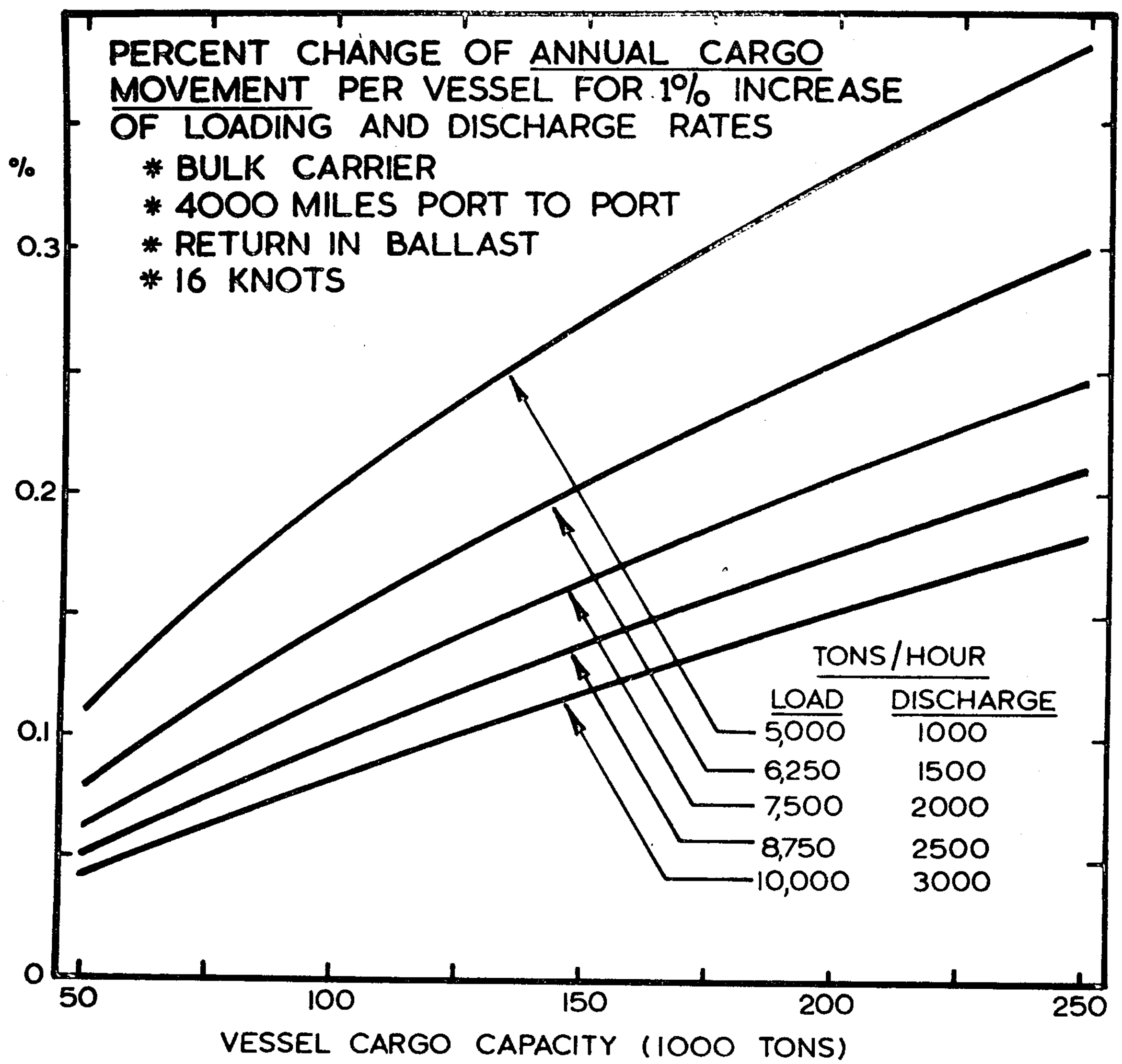
In this section it is assumed that any improvements in cargo loading rates are matched by similar (percentage) improvements in discharge rates. Modifications to the developed relationships, required if that is not the case to be examined, are straight forward, and are utilised in section 10. Derivatives of the annual cargo capacity (W_A) and the voyage costs (Q_{AD}) w.r.t. the cargo handling rate (R_D) are formulated in Appendix VII.

The generalised application of those relationships is seen in Figure 7, for a 16 knot bulk carrier operating on a 4000 mile route each way, assuming T_F = 1.0 day per voyage, and T_O = 360 days. The top curve in the figure illustrates that a vessel having W_C = 200 ktons will realise a 3.3% increase of W_A for a 15% increase in both the loading and discharge rates. From the form of the derivatives of both Q_{AD} and W_A w.r.t. R_D, it is observed that the percentage increase in voyage costs will be the same as that for the annual cargo capacity. The "apparent" savings come from the realisation that the other costs contributing to the minimum required freight rate, namely fixed annual costs and capital recovery, remain unchanged.

If the freight rate (FR) is established, then the gross "apparent" annual savings per vessel resulting from improvements in the cargo handling rates are given by:

$$FR \cdot \delta(W_A) - \delta(Q_{AD}),$$

FIGURE 7


PERCENT CHANGE OF ANNUAL CARGO MOVEMENT PER VESSEL FOR 1% INCREASE OF LOADING AND DISCHARGE RATES
* BULK CARRIER
* 4000 MILES PORT TO PORT
* RETURN IN BALLAST
* 16 KNOTS
%
0.3
0.2
0.1
0
50
100
150
200
250
VESSEL CARGO CAPACITY (1000 TONS)
TONS/HOUR
LOAD DISCHARGE
5,000 1000
6,250 1500
7,500 2000
8,750 2500
10,000 3000

in which $\delta(W_A)$ and $\delta(Q_{AD})$ represent the incremental changes of the annual cargo capacity and the annual voyage costs, respectively. If less than that equivalent annual sum is spent to achieve the increased handling rates, then the return on the increased investment will be greater than that expected for the capital recovery of the vessel itself.

For this study, an equivalent before-tax capital recovery factor (CR) of 0.2 is used, yielding minimum required freight rates for the example bulk/ore carrier of \$3.82/ton. An improvement of cargo handling rates by 10% leads to increases of Q_{AD} and W_A of 0.62% for the bulk/ore carrier.

The break-even point for expenditure to achieve that increased cargo movement is an equivalent annual cost of \$32,500. If, say, 6 comparable vessels use the same ore loading and discharge facilities, than nearly \$200,000 per annum is available to increase the cargo handling rates by 10%.

If the avoidance of industrial disputes could increase the annual average effective loading and discharge rates, calculations similar to those above can be used to determine the equivalent finance benefits available to achieve that higher average cargo handling rate.

10. On-Board Discharge Facilities.

All conventional tankers and a number of bulk/ore carriers carry the means to discharge their own cargoes. For tankers the additional capital and weight penalties are not nearly as significant as is the situation for bulk/ore ships, when contrasted with shore-side facilities. In this section, demonstration of the calculation of the break-even cost for the addition or up-grading of the on-board cargo discharge facilities is given.

When the discharge rate is considered variable, but the cargo loading rate is constant, the derivatives of Q_{AD} and W_A w.r.t. R_D are the same as those appearing in Appendix VII, with the factor $(1+\varepsilon)/\varepsilon$ omitted. A further difference when considering an on-board cargo discharge system is the addition to the derivative of W_A w.r.t. R_D of a term accounting for the increased lightship weight. It arises from the relationship:

$$\frac{\partial(W_A)}{\partial(R_D)} = \frac{\partial(W_C \cdot N_V)}{\partial(R_D)} = W_C \cdot \frac{\partial(N_V)}{\partial(R_D)} + N_V \cdot \frac{\partial(W_C)}{\partial(R_D)} \cdot$$

For shore-side facilities, the last term is identically zero; whereas for on-board cargo discharge facilities it is:

$$-N_V \cdot \delta(W_O)/(R_D'' - R_D'),$$

in which $\delta(W_O)$ is the additional outfitting weight due to the proposed self-unloader, R_D'' is the discharge rate for the new self-unloader, and R_D' is that applicable to the existing design.

Thus, the equivalent annual break-even cost of adding or up-grading on-board cargo discharge facilities is given by:

$$FR \cdot \delta(W_A) - \delta(Q_{AD}) - \delta(Q_{AI}),$$

in which the first two terms are defined in section 9, but calculated according to section 10; and where $\delta(Q_{AI})$ represents the additional fixed annual costs arising from slightly modified insurance, maintenance and repair costs attributable to the self-unloader.

Using the example bulk/ore carrier, the addition of a 15,000 ton/hr self-unloader is considered, adding 800 tons to the lightship weight (this is an unconfirmed estimate).

The increment of fixed annual costs is estimated to be 7% of the total insurance plus M&R costs, which becomes 5.2% of Q_{AI}. This 10 fold improvement in the discharge rate (with loading rate constant) results in a 13.7% increase in W_A and a 14.2% increase in Q_{AD}. The consequent break-even point is an equivalent annual cost of \$840,000 for the installation of the .

self unloader. Using an overall CR of 0.20, that means a break-even capital cost of $4.2 million.

11. Incremental Freight Rates.

Using an overall capital recovery factor (CR), the capital costs may be given as equivalent annual costs, and when added to the voyage and fixed annual costs, may be used to obtain a minimum acceptable freight rate.

When considering small changes in the design parameters, the increment of all equivalent annual costs may be divided by the consequent change in annual cargo capacity, yielding an incremental freight rate, δ(FR). Non-dimensionalisation of δ(FR) w.r.t. the original FR indicates the relative worth of the change of the design parameter. The summary of those calculations for 1% increases in the design parameters for the two example vessels is shown in Figure 8.

The left-hand columns of that figure indicate the proportional contributions to the original FR', using an overall before-tax CR of 0.2. All numbers shown within the columns are non-dimensionalised w.r.t. FR'. Note that, unlike Figure 6, the costs attributable to crew, stores and supplies are included here.

It is purely coincidence that the non-dimensional incremental freight rates for speed are so evenly matched for the two extremely different example vessels. For the design speed increment, capital recovery is the dominant fraction of δ(FR) in the bulk/ore carrier, whereas voyage costs dominate in the tanker example. The coincidence of the total δ(FR) is, therefore, quite surprising.

FIGURE 8

Relative incremental FREIGHT RATES due to 1% increase of design parameters, as a percentage of the original required freight rates, for two example vessels, using CR = 0.20.

	ORIGINAL DESIGN		LENGTH		BEAM		DEPTH		BLOCK		SPEED	
	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr	ore	tnkr
CAPITAL RECOVERY	.62	.54	.84	.63	.59	.32	.17	.21	.12	.11	.98	.36
FIXED* ANNUAL COSTS	.21	.22	.20	.20	.14	.11	.06	.08	.03	.04	.26	.11
VOYAGE COSTS	.17	.24	.18	.26	.15	.17	.09	.01	.10	.05	.54	1.30
TOTAL	1.00	1.00	1.22	1.09	.88	0.60	.32	.30	.25	.20	1.78	1.77

(*INCLUDING CREW, STORES AND SUPPLIES)

It may be desired to consider the requisite change in design parameter to effect a 1% change in the annual cargo capacity (W_A). That change would be reciprocal of the total value shown in Figure 3. For the tanker, the change of speed necessary would be 1/0.74 = 1.35%. Figure 8, as shown, is for only a 1% change of parameter. But due to the non-dimensionality of it, that Figure is also valid for a 1% change of W_A, which is desired to indicate the relative merits of design changes that could improve the economic efficiency of the vessel.

Note that Figure 8 represents:

$$\frac{(\text{change in cost})/(\text{change in } W_A)}{(FR)'}.$$

Thus if the speed of the tanker, for example, is changed by 1.35%, and not 1%, both the change in cost and the change in W_A will be identically affected.

12. Design changes.

Using the values presented in Figures 3 (Annual Cargo Capacity) and 8 (Incremental Freight Rates), it is possible to suggest a design alteration for both example vessels that would result in considerable savings for the same annual movement of cargo. If overall freight rate is not the applicable criterion, then Figure 2, 5 or 6 should be used in place of Figure 8.

For the bulk/ore carrier, it is assumed that a draught limitation exists, with the present value (17.1m) being the maximum. The very high block coefficient (0.865) is most likely at its feasible upper limit. It is noted that the design has a high L/B ratio (7.58). If the beam is increased by 10%, as seen in Table III-a, an additional 168 ktons could be carried annually at a net equivalent annual cost of $470,000.

TABLE III

Calculation of Annual Savings

Resulting from Design changes

P	$\delta(W_A)$ for 1% $\delta(P)$	$\delta(P)$	$\delta(W_A)$ 1000's tons	$\delta(FR)$ \$/ton	$\delta(Q)$ \$1000's annually

(a) Bulk/Ore Carrier (W_A' = 2030) (FR' = 3.164)

B	0.83%	+10.0%	+168	2.784	+470
V	0.64%	-12.9%	-168	5.632	-950
	Total changes		-0-		-480

(b) Tanker (W_A' = 1822) (FR' = 3.820)

C_B	1.08%	+6.2%	+123	0.764	+95
V	0.74%	-9.1%	-123	6.761	-830
	Total changes		-0-		-735

(c) Tanker (W_A' = 1822) (FR' = 3.820)

L	0.86%	+7.8%	+123	4.164	+510
V	0.74%	-9.1%	-123	6.761	-830
	Total changes		-0-		-320

If the design speed is reduced, independently, from 14.4 to 12.5 knots, approximately 168 ktons less would be moved annually, for a savings of \$950,000. By superimposing those two design alterations, the minimum acceptable freight rate can be reduced from \$3.16 per ton to \$2.93 per ton.

For the example tanker, the draught limitation is again assumed applicable. The extreme beam (54.5m) is most likely at the upper limit for the construction facilities. Therefore the block coefficient can be raised from 0.80 to 0.85, accompanied by a decrease in design speed from 16 to 14.5 knots for an equivalent annual (before-tax) savings of over \$700,000 (Table III-b). That would reduce FR from \$3.82 per ton to \$3.43/ton.

Although the non-dimensional incremental freight rate for length is greater than unity (see Figure 8), a successful trade-off between length and speed can be effected. For the example tanker, if the block coefficient is to be maintained at 0.80, the length can be increased by 7.8% to compensate for the 9.1% speed decrease. Table III-C indicates an annual equivalent cost reduction of \$320,000, or an \$0.17 per ton decrease in the freight rate.

It is not necessary to limit the proposed changes to several percent. The reason for doing so here is that the accuracy of the derivatives is most likely acceptable only for variations in the design parameters of less than about 10%. Beyond that, trends are indicated, but absolute values arising from the design changes become questionable. It would be suggested, for example tanker, that L and C_B be increased by the amounts greater than those shown in Tables III-B and III-C, with speed decreased from 16.0 to12.0 knots, for a total savings of over \$1 million annually. But the 25% reduction in speed strains the credibility of the figures presented.

From another point of view, the beam limitation on the example tanker can be overcome by the construction of two longitudinal sections, welded together while afloat. The break-even point for the added capital cost for the operation can be calculated in the same manner as given in the previous paragraphs.

In the situation where capital cost is the criterion, rather than overall freight rate, the play-off of one design parameter against another may require a conditon other than fixed total annual cargo movement, inasmuch as the route may be unspecified. That condition could be the minimisation of the capital cost per DWT.

It may be observed, however, that if all the non-dimensional costs or freight rates were equal, it would not be possible to alter any of the design parameters to lessen that cost or freight rate. The only exception to that arises when one or more of the parameters is subject to an external boundary condition.

13. Conclusions

From the previously presented Figures, the relative merits of each design parameter can be assessed, in association with all possible criteria. For the example vessels, they are summarised in Table IV. In some instances the order of merit would be altered for only small changes in some empirical estimates. Added significance is given to the order of merit listings, however, when it is realised that the two example vessels have significantly different overall dimension ratios.

The criterion which is applicable depends on the expected use of the vessel, as well as the role of the viewer.

TABLE IV

Order of Merit Listings for

Incremental Increases in Design Parameters

	148 kDWT Bulk/Ore Carrier					253 kDWT Tanker				
	L	B	D	C_B	V	L	B	D	C_B	V
Lightship Weights	5	4	3	1	2	5	4	2	1	3
Annual Cargo Capacity	4	3	2	1	5	4	3	2	1	5
Capital Costs	5	3	2	1	4	5	4	2	1	3
Voyage Costs	4	3	1	2	5	4	3	1	2	5
Fixed Annual Costs	4	3	2	1	5	5	4	3	1	2
Incremental Freight Rate*	4	3	2	1	5	4	3	2	1	5

* using a capital recovery factor of 0.20.

If the vessel is to be built and operated under long-term charter, the owner's criterion may be distinctly different from the charterer's. Vessels designed for the tramp trade, or short-term charter, would have a different criterion applied than would one that was going to be operated by the owner on a regular route for its useful life. The possibility of construction or operational subsidies will also greatly affect the choice of criterion.

But Table IV illustrates that, for the two example vessels, there is little difference in the orders of merit for the different criteria. Note also that there is much consistency between the two different vessels.

If the overall freight rate increment (Figure 8) is the applicable criterion, then it is clear that the block coefficient is the first design variable that should be increased. The boundary condition applicable to the block coefficient is not, however, as clearly defined as is the one for draught (and consequently, depth). Rather than being a precisely measurable one, it is highly dependent on the state-of-the-art of propulsion techniques. The evidence presented here clearly indicates that block coefficient is, by a significant margin, a less costly design parameter than any but depth, over which it has a small advantage.

It may be that a_p (Table II or Appendix II-E) for the block coefficient should be greater than the present value of 0.25. Even if it were 0.50, the relative $\delta(FR)$'s in Figure 8 would rise from 0.25 and 0.20, to 0.34 and 0.27, for the bulk/ore carrier and tanker, respectively. In both cases those values are still significantly less than those for the beam increase (0.83 and 0.54), although essentially the same as those for depth.

From the opposite point of view, for the two example vessels, the speed is the first design variable that should be reduced. Figure 3 indicates that such reduction will have the least effect on annual cargo capacity.

It remains unpracticable to draw general conclusions from the results derived from the two example vessels. But conclusions may be safely proposed regarding the applicability of the techniques employed.

In a general form, there is no doubt that the design of vessels suitable for the carriage of homogeneous cargoes can be defined to give a true minimum cost of transport, the achievement of which will be recognised by the equality of the incremental overall costs associated with changes in the unconstrained design parameters.

The calculation of those incremental costs requires further refinement. It may be that the steel and outfitting costs should be function of the dimensions as well as of the weights.

Similar derivatives can be established for non-bulk vessels, such as container ships. In that situation, the incremental costs would be based on changes of dimensions suitable for the carriage of one more row, column or level of containers.

The techniques demonstrated here also allow evaluation of the break-even costs to alter boundary conditions applicable to the design and operation of the vessel. In some instances it may require technological advances, but for others it may necessitate breaking psychological barriers on the part of the owners, operators and builders.

It appears clear that the application of the techniques presented can benefit the industry, but precise use of them await the abundant supply of data from builders, owners and operators. Their frequent reluctancy to make it public is sometimes understandable, but is not always justifiable. In attempting to determine the proportions of the capital cost of steel, machinery, outfitting and other components, a major owner/operator of a fleet of very large crude oil carriers (VLCC's) has stated in private correspondence,

> You may be surprised to know how far away we ourselves are from knowing precisely what the major cost elements involved in the building of a VLCC represent so far as the shipbuilder is concerned.

Perhaps this paper contains a partial incentive to determine that type of information and to make it public.

Nomenclature

Symbol	Definition (units)
a_m	machinery weight derivative coefficient.
a_o	outfitting weight and cost derivative coefficient.
a_p	powering derivative coefficient.
a_r	repair and maintenance coefficient for machinery.
a_s	steel weight and cost derivative coefficient.
B	beam (meters or feet).
b_i	coefficients in derivatives of W_S.
b_m	machinery cost derivative coefficient.
b_q	cost per horsepower derivative coefficient.
b_t	beam/draught ratio.
b_w	weight per horsepower derivative coefficient.
C_B	block coefficient.
C_F	frictional resistance coefficient.
CR	capital recovery factor (year $^{-1}$).
C_R	residual resistance coefficient.
C_T	total resistance coefficient.
D	depth (meters or feet).
F	general cost, weight or other design item.
FR	freight rate (\$/ton).
kDWT	1000's of deadweight tons
L, LBP	length between perpendiculars (meters or feet).
l_b	length/beam ratio.
l_d	length/depth ratio.
m	lightship weight margin fraction.

M&R	abbreviation: maintenance and repair.
n	number of revenue-earning legs per voyage.
N_V	number of voyages per year (voy./yr.).
P	general primary or secondary design parameter.
P&I	abbreviation: protection and indemnity.
Q_A	total annual costs ($/yr.).
Q_{AD}	sub-total annual costs dependent on N_V ($/yr.).
Q_{AI}	sub-total annual costs independent of N_V ($/yr.).
Q_C	annual crew costs ($/yr.).
Q_F	annual fuel costs ($/yr.).
Q_H	annual direct cargo handling costs ($/yr.).
Q_{HI}	annual hull and machinery insurance costs ($/yr.).
Q_{HM}	annual hull maintenance costs ($/yr.).
Q_I	annual total insurance costs ($/yr.).
Q_M	capital cost for machinery ($).
Q_{MM}	annual machinery maintenance costs ($/yr.).
Q_O	capital cost for outfitting ($).
q_o	overhead fraction for capital costs.
Q_P	annual port costs ($/yr.).
Q_{PI}	annual P&I insurance costs ($/yr.).
Q_S	capital cost for steel ($).
Q_{SS}	annual stores and supplies costs ($/yr.).
Q_T	total capital cost for vessel ($).
R_D	rate of cargo discharge (tons/day).
R_F	frictional resistance (tons).
R_R	residual resistance (tons).
R_T	total resistance (tons).
S_N	normal (service) shaft horsepower (h.p.)

T	draught (meters or feet).
T_C	cargo handling time per voyage (days/voy.).
T_F	fixed time losses per voyage (days/voy.).
T_O	days in service per year (days/yr.).
T_S	sea time per voyage (days/voy.).
V	normal (service) ship speed (knots).
W_A	annual cargo movement (tons/yr.).
W_C	cargo carried per voyage (tons/voy.).
W_D	deadweight (tons).
W_F	fuel weight consumed per voyage (tons/voy.).
W_{FR}	fuel reserve carried (tons/voy.).
W_L	lightship weight (tons).
W_M	machinery weight (tons).
W_O	outfitting weight (tons).
W_S	steel (hull) weight (tons).
W_W	water and misc. weights (tons/voy.).
w.r.t.	abbreviation: with respect to.
x,y,z	general coefficients or exponents.
Z	midship section modulus.
β	exponent of "B" for steel weight.
γ	fuel cost per ton (\$/ton).
Δ	displacement (tons).
δ	exponent of "D" for steel weight.
ε	ratio of cargo loading to discharge rates.
η	exponent of "C_B" for steel weight.
λ	exponent of "L" for steel weight.
σ	steel weight scale factor.
ω	general coefficient or exponent.

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(NECIES: North-East Coast Institution of Engineers and Shipbuilders)
(RINA: Royal Institution of Naval Architects)
(SNAME: Society of Naval Architects and Marine Engineers)

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Appendix I - Derivatives of Hull Steel Costs

A. Introduction

Historically there has been significant variation in the assigned magnitudes of dependence that each major parameter has on the hull steel weight. Appendix VIII discusses that variation, which shows, for example, that in the relationship

$$W_s \propto L^{\lambda} \; B^{\beta} \; D^{\delta} \; C_B^{\eta},$$

the value of "δ" has been taken as a constant (with T/D constant) ranging from -0.27 to +0.35 for tankers, and from -0.13 to +0.43 for bulk carriers.

This appendix presents numerical approximations for those exponents, which are derived from two large sets of tables of mean statistical steel weights for systematic variations of the major dimensions of tankers and bulk carriers. Those tables are published by det Norske Veritas [1970], and are restricted to T/D being constant at 0.78. The validity of the presented expressions for λ, β, δ and η is assured only within the following limits:

L/B	:	5.0 to 7.0
L/D	:	10.0 to 14.0
C_B	:	0.78 to 0.87
Length	:	220 to 360 meters (bulk carriers)
		250 to 420 meters (tankers)

B. Expressions for Exponents/Derivatives

It will be noticed, for reasons beyond the scope of discussion in this paper, that the expressions pertinent to bulk carriers are generally far simpler than the corresponding ones for tankers. The accuracy of the expressions far exceeds the accuracy required by the other parts of this paper, but is maintained throughout this appendix to avoid the necessity of publishing more accurate expressions at a later date.

The partial derivative of the steel weight w.r.t. the length, for example, is given by:

$$\frac{\partial (W_s)}{\partial (L)} = \lambda \cdot \frac{(W_s)'}{(L)'}$$

In general the partial derivative of steel weight is given by:

$$\frac{\partial (W_s)}{\partial (-)} = a_s \cdot \frac{(W_s)'}{(-)'}$$

in which a_s is given by the general expressions:

$$\begin{aligned} a_s = & \left(\frac{L}{100}\right)^2 \cdot \left[b_1 \cdot \frac{L}{B} + b_2 \cdot \frac{L}{D} + b_3\right] \\ & + \left(\frac{L}{100}\right) \cdot \left[b_4 \cdot \frac{L}{B} + b_5 \cdot \frac{L}{D} + b_6\right] \\ & + \left[b_7 \cdot \frac{L}{B} + b_8 \cdot \frac{L}{D} + b_9\right] \end{aligned}$$

with "L" in meters. Values of the b_i's are given in Table A1 for bulk carriers and tankers, assuming that the draught/depth ratio is constant (see Appendix II-D).

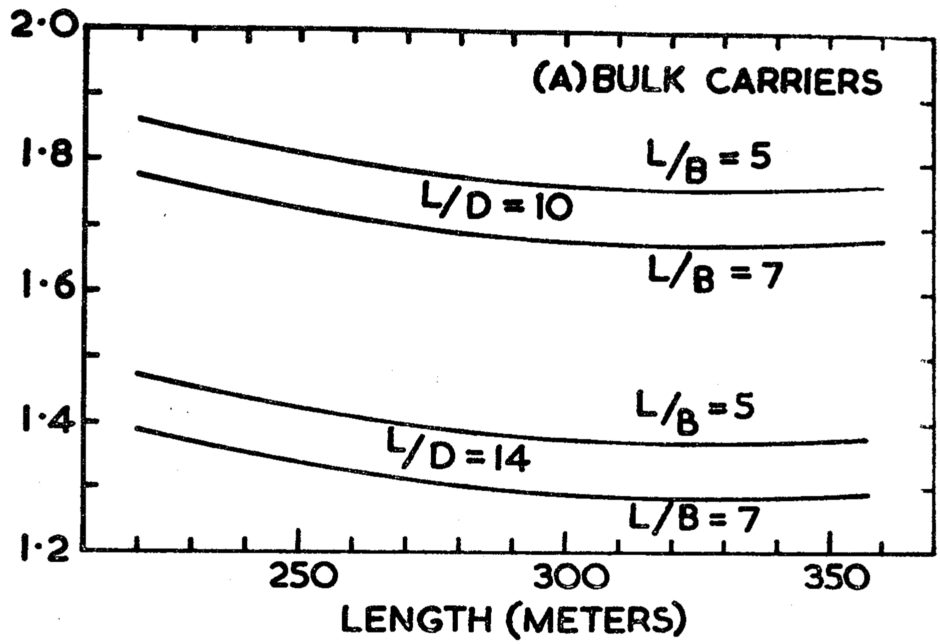
Graphical representations of the values of the derivative coefficient "a_s" are given in Figures A1, A2, A3 and A4.

It may be noted that, if the steel weight of an existing design is known, then the steel weight for a lengthened design can be approximated by:

$$W_S = (L - L') \cdot \frac{\partial (W_S)}{\partial (L)} = (L - L') \cdot \lambda \cdot \frac{(W_S')}{(L')}$$

FIGURE A1

LENGTH DERIVATIVES FOR STEEL WEIGHTS



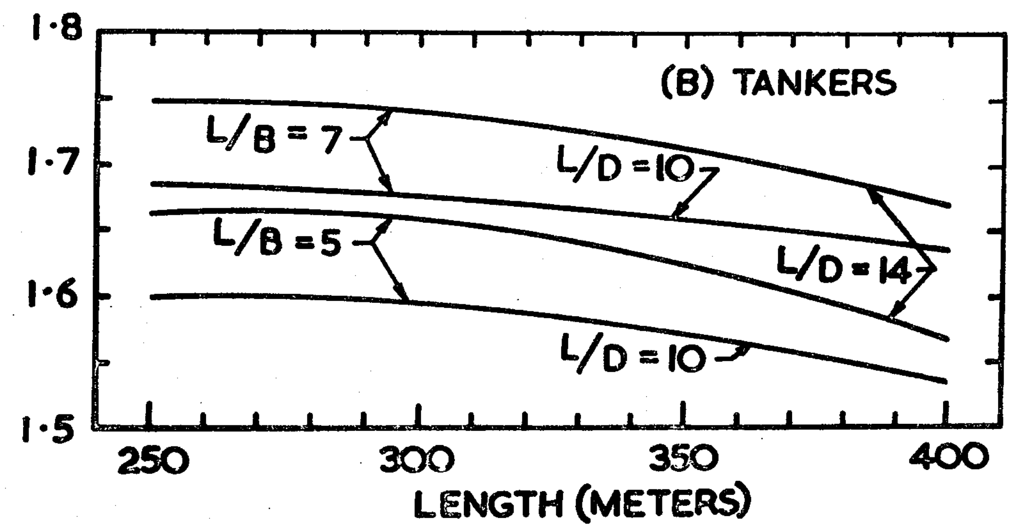


FIGURE A2

BEAM DERIVATIVES FOR STEEL WEIGHTS

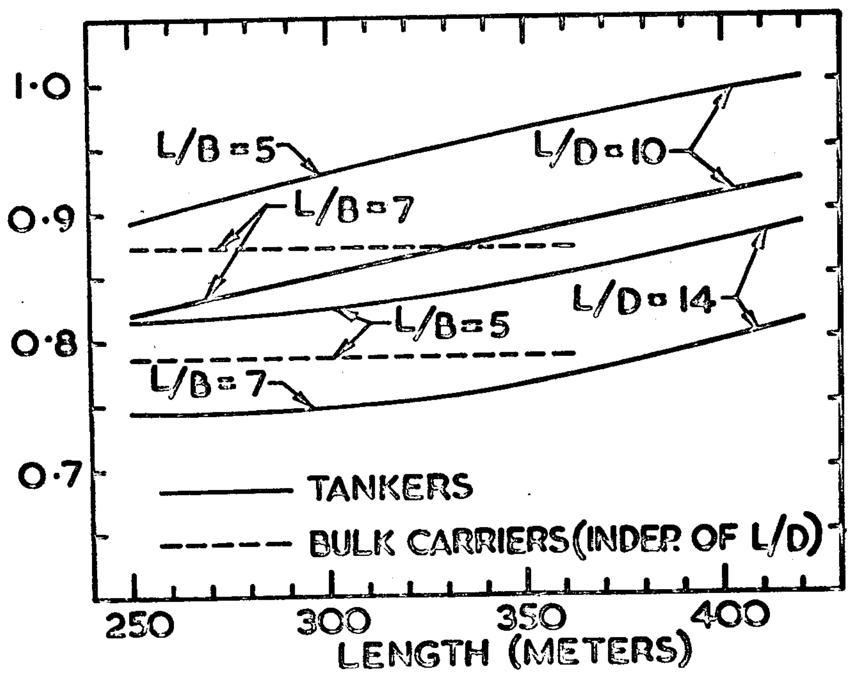


FIGURE A3

DEPTH DERIVATIVES FOR STEEL WEIGHTS (T/D) = 0·78

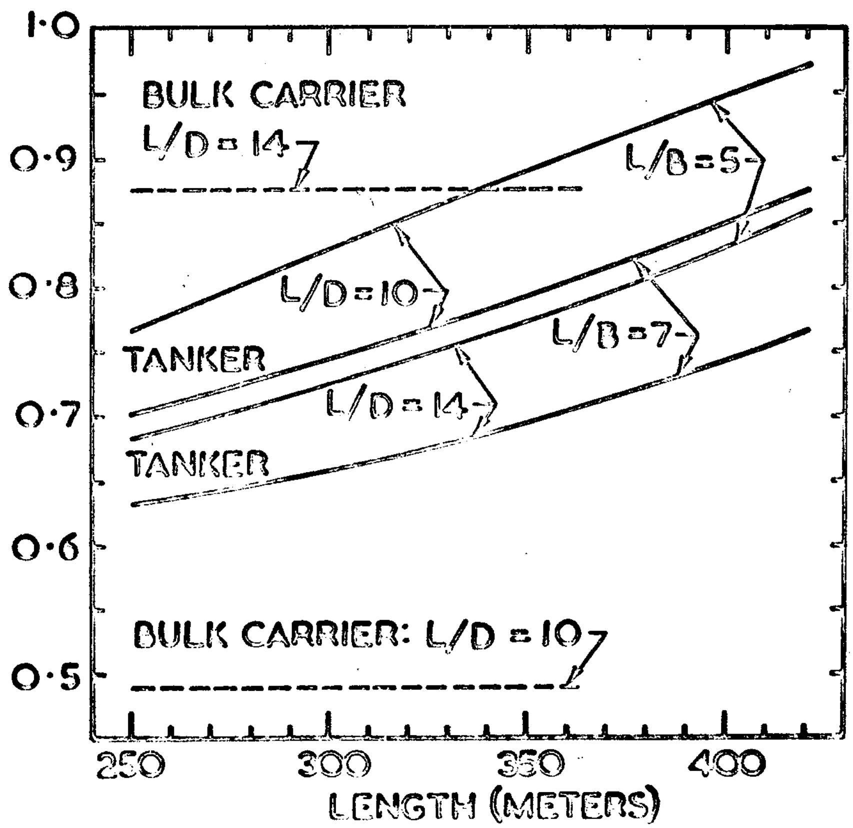
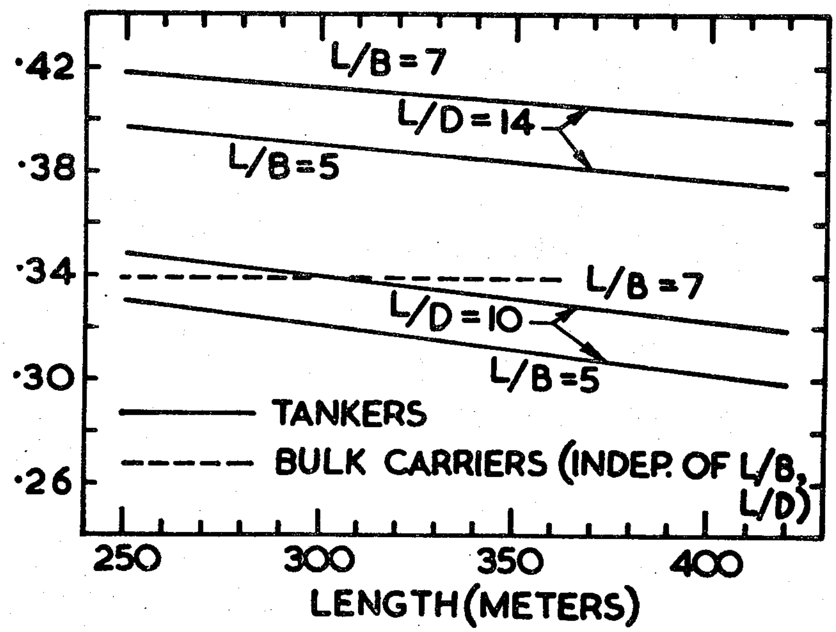


FIGURE A4

BLOCK COEFFICIENT DERIVATIVES
FOR STEEL WEIGHTS



$^L/_B = 5$ and $^L/_D = 10$, "σ" has the value of 3.26 at L = 250m, and 3.48 at L = 420m. The other extemes in this study correspond to $^L/_B = 7$ and $^L/_D = 14$, for which "σ" has the values of 3.13 at L = 250m, and 3.23 at L = 420m.

TABLE A-I

COEFFICIENTS FOR STEEL WEIGHT DERIVATIVE EXPRESSIONS

$$a_s = \left(\frac{L}{100}\right)^2 \cdot \left[b_1 \cdot \frac{L}{B} + b_2 \cdot \frac{L}{D} + b_3\right]$$

$$+\left(\frac{L}{100}\right) \cdot \left[b_4 \cdot \frac{L}{B} + b_5 \cdot \frac{L}{D} + b_6\right] + \left[b_7 \cdot \frac{L}{B} + b_8 \cdot \frac{L}{D} + b_9\right]$$

TANKERS b	LENGTH	BEAM	DEPTH	BLOCK
1	+0.00923	+0.00521	+0.00555	-
2	-0.00508	+0.00693	+0.00429	-
3	-0.02720	-0.1056	-0.07284	-
4	-0.05528	-0.03625	-0.04670	+0.00095
5	+0.02856	-0.05141	-0.03333	+0.00139
6	+0.1543	+0.8281	+0.7012	-0.03738
7	+0.1239	+0.02205	+0.05174	+0.00763
8	-0.02408	+0.06648	+0.03762	+0.01358
9	+1.0114	-0.1501	-0.1920	+0.2027
BULK CARRIERS				
1	-	-	-	-
2	-	-	-	-
3	+0.09583	-	-	-
4	-	-	-	-
5	-	-	-	-
6	-0.6242	-	-	-
7	-0.0425	+0.0425	-	-
8	-0.0970	-	+0.0970	-
9	+3.957	+0.575	-0.480	+0.338

Note: "L" is in meters

Appendix II - Derivatives for Machinery Installations

The division for machinery costs lies, not with the ship type, but with the basic propulsion plant. In this study, the two categories considered are low-speed direct-connected diesel, and oil-fired geared steam turbine. The only cause for machinery costs to change when the five principal design parameters change is the required change in powering. Thus the derivatives are of the form:

$$\frac{\partial(Q_M)}{\partial(-)} = \frac{\partial(Q_M)}{\partial(S_N)} \cdot \frac{\partial(S_N)}{\partial(-)} .$$

A. Cost-Power Relationships

For steam machinery (single screw), Benford [1967] gives: $Q_M = \omega_3 \cdot (S_N)^{0.6}$. Three years later Miller [1970], quoting Benford [1967], gives the same expression, but with the exponent 0.5. According to those, the derivative of cost w.r.t. power is either $0.6 \cdot (Q_M'/S_N')$ or $0.5 \cdot (Q_M'/S_N')$. However, Dart [1970] gives: $Q_M = \omega_4 + \omega_5 \cdot S_N$, in which $\omega_4 = \$2.352 \times 10^6$ and $\omega_5 = \$0.112 \times 10^3/\text{h.p.}$, valid in the range 13,000 to 26,000 s.h.p. At the centre of that range, 20,000 s.h.p., $Q_M = \$4.592 \times 10^6$, and $\partial(Q_M)/\partial(S_N) = \$0.112 \times 10^3/\text{h.p.}$. That is, $\partial(Q_M)/\partial(S_N) = 0.49 \cdot (Q_M'/S_N')$. Correspondence with Professor Benford [Nov. 1971] indicates that the apparent fluctuation is due to variations in the data used to up-date existing information. He is now of the opinion that a coefficient of 0.6 is appropriate. It is not clearly understood why the exponent must be either 0.5 or 0.6. Considering the variability of it, but not wishing to assign to it undue accuracy, a value is chosen giving:

$$\frac{\partial(Q_M)}{\partial(S_N)} = 0.55 \cdot \frac{(Q_M')}{(S_N')}$$

for single-screw, oil-fired, geared steam turbine units.

Fisher [1971] presents data for a series of low-speed direct-connected diesels, from which the relationship for single screw vessels,

$$\partial(Q_M)/\partial(S_N) \;=\; 0.93 \cdot Q_M'/S_N'$$

can be established. The coefficient varies from 0.87 to 0.97, but without definite trends at low or high power.

B. Power-Length Relationship

The derivative of required power w.r.t. length is considered in two parts: the frictional contribution to the total resistance; and the "residual" resistance. For a constant frictional resistance coefficient, C_F, (which is acceptable for small changes of Reynolds number), the frictional resistance, R_F, is proportional to the wetted surface, which is itself proportional to the length. For small longitudinal changes of displacement (Δ), the residual resistance, R_R, per unit of displacement is safely assumed constant. Thus, the residual resistance is proportional to the displacement, which is proportional to the length (considering changes of ship length to be changes of parallel midbody length). With both parts of the total resistance (R_T) proportional to length, at constant speed, the horsepower is then directly proportional to length. Thus,

$$\partial(S_N)/\partial(L) \;=\; 1.0 \cdot S_N'/L'.$$

C. Power-Beam Relationship

Again, the derivative is considered in the two parts of the frictional and residual resistance calculations. With C_F constant, as in the previous section, R_F is proportional to the wetted surface, which Saunders [1957] demonstrates to be proportional to the square root of the beam.

From tabulated values of C_R presented by Fisher [1971], it can be observed that C_R is proportional to $(B/T)^x$, in which x varies from 0.7 to 1.2. With the wetted surface proportional to $(B)^{0.5}$, as above, then $R_R \propto \omega_6 \cdot (B)^y$, where y is in the range 1.2 to 1.7. Thus the total power can be written in the form: $S_N \propto (\omega_7 \cdot B^y + \omega_8 \cdot B^{0.5})$, in which the first term is residual and the second is frictional horsepower. From that,

$$\partial(S_N)/\partial(B) \propto (y\omega_7 \cdot B^{y-1} + 0.5 \cdot \omega_8 \cdot B^{-0.5}),$$

which can be written as

$$\frac{\partial(S_N)}{\partial(B)} = \left[\frac{y + R_F/(2 \cdot R_R)}{1 + R_F/R_R}\right] \cdot \frac{S'_N}{B'} .$$

The value of the coefficient is given in the following table:

y \ R_F/R_R	2	3	4
1.2	0.73	0.68	0.64
1.7	0.90	0.80	0.74

For large, slow-speed vessels, a considered judgment leads to:

$$\partial(S_N)/\partial(B) = \frac{3}{4} \cdot \frac{S'_N}{B'} .$$

D. Power-Depth Relationship

For constant cargo density, a change in internal volume indicates a change in payload. The requisite change in displacement is achieved by maintenance of the same depth/draught ratio.

$$\frac{\partial(S_N)}{\partial(D)} = \frac{\partial(S_N)}{\partial(T)} \cdot \frac{\partial(T)}{\partial(D)} = \frac{\partial(S_N)}{\partial(T)} \cdot \frac{T'}{D'} .$$

Regarding frictional resistance, a change of draught has the same effect as a change of beam; thus $R_F \propto T^{\frac{1}{2}}$.

From part C, above, $R_R \propto (1/T)^y$, with y in the range 1.2 to 1.7. Similarly, $S_N \propto (\omega_7 \cdot T^{-y} + \omega_8\, T^{0.5})$; from which

$$\frac{\partial(S_N)}{\partial(T)} = \left[\frac{-y + R_F/(2 \cdot R_R)}{1 + R_F/R_R}\right] \cdot \frac{S_N'}{T'} .$$

The value of the coefficient is given in the following table:

y \ R_F/R_R	2	3	4
1.2	-.07	+.08	+.16
1.7	-.23	0.05	+.06

The considered value of the coefficient is taken to be zero; i.e., for small changes of draught, there is no change of powering required. Hence,

$$\partial(S_N)/\partial(D) \approx 0.$$

E. Power-Block Coefficient Relationship

For small changes of C_B, frictional resistance will be unaffected. As in part B, above, the residual resistance will change in proportion to the displacement, i.e., $R_R \propto C_B$, for all other dimensions constant. Thus

$$\frac{\partial(S_N)}{\partial(C_B)} = \frac{R_R'}{R_T'} \cdot \frac{S_N'}{C_B'} \approx \frac{1}{4}\,\frac{S_N'}{C_B'} ,$$

in which the value $\frac{1}{4}$ is chosen as representative for large slow-speed vessels.

F. Power-Speed Relationship

$\partial(S_N)/\partial(V)$ represents the change in required powering per unit change of speed. As a first approximation, C_F is assumed constant and C_R is taken to be proportional to the square of the speed, for small perturbations. Thus,

$$S_N = \omega_9 \cdot \left[C_F' \cdot V^3 + C_R' \cdot V^5/(V')^2 \right],$$

from which:

$$\frac{\partial(S_N)}{\partial(V)} = \frac{S_N'}{V'} \cdot \left[\frac{3C_F/C_R + 5}{C_F/C_R + 1} \right].$$

The value of the coefficient for various ratios is given in this table:

C_F/C_R	2	3	4
coeff.	3.67	3.50	3.40

Again, for this study centering on large, low-speed vessels, the choice is taken to be $^7/_2$. Thus,

$$\partial(S_N)/\partial(V) = (^7/_2) \cdot (S_N'/V').$$

G. Machinery Weights

For the direct-connected diesel, the information presented by Fisher [1971] indicates that

$$\frac{\partial(W_M)}{\partial(S_N)} \simeq 0.87 \cdot \frac{W_M'}{S_N'},$$

with the coefficient varying from approximately 0.84 at 15,000 installed BHP to 0.91 at 40,000 installed BHP (single screw).

For single-screw steam installations, the coefficient for the weight/power derivative is 0.5 from Benford [1971], 0.495 from Mandel [1966] and varies from 0.3 to 0.4 according to Sato [1967]. Sato presents data to which a curve has been fitted. The validity of his curve at higher powers (> 35,000 SHP) appears questionable. A constant value of 0.35 is believed most appropriate, and is used in this study.

The derivatives of machinery weight w.r.t. primary design parameters are given by:

$$\frac{\partial (W_M)}{\partial (-)} = \frac{\partial (W_M)}{\partial (S_N)} \cdot \frac{\partial (S_N)}{\partial (-)} .$$

H. Summary of Appendix II

The derivatives of machinery cost are given by:

$$\frac{\partial (Q_M)}{\partial (-)} = \frac{Q'_M}{(-)'} \cdot b_q \cdot a_p ,$$

and the machinery weight derivatives are given by:

$$\frac{\partial (W_M)}{\partial (-)} = \frac{W'_M}{(-)'} \cdot b_w \cdot a_p .$$

For steam installations, $b_q = 0.55$ and $b_w = 0.35$. For diesel power plants, $b_q = 0.93$ and $b_w = 0.87$. Values of a_p are given in the following table.

Parameter	L	B	D	C_B	V
a_p.	1.00	0.75	-	0.25	3.50

Appendix III - Derivatives of Outfitting Costs

A. Bulk Carriers

Fisher [1971] states that the outfitting cost per ton is constant for bulk carriers. For similar vessels, that paper also gives:

$$W_O = W'_O \cdot \left(\frac{1}{4} + \frac{3}{4} \cdot \frac{L \cdot B}{L' \cdot B'}\right).$$

However, the paper by Gilfillan [1969] gives:

$$W_O = W'_O \cdot \left(\frac{1}{2} + \frac{1}{2} \cdot \frac{L \cdot B}{L' \cdot B'}\right).$$

The difference between the two is that the latter places greater emphasis on the aspects of outfitting which occur regardless of vessel size. For the significantly larger bulk carriers being constructed today, contrasted with those studied by Gilfillan [1969], that "constant" aspect will be diminished. Thus, for bulk carriers:

$$\frac{\partial(Q_O)}{\partial(-)} = a_o \cdot \frac{Q'_O}{(-)'} ,$$

in which $a_o = 0.75$ for derivatives w.r.t. L and B, and is zero for the other three parameters.

B. Tankers

Nowacki [1970] uses an approximation for outfitting weight as

$$W_O = (4.7 - 0.0034 \cdot L) \cdot L \cdot B/100,$$

in which units are in feet and long tons. It is incorrectly ascribed to Gilfillan [1967], originating rather with Parker [1967], who also suggests

$$W_O = W'_O \left(\frac{2}{3} + \frac{1}{3} \cdot \frac{L \cdot B}{L' \cdot B'}\right).$$

The derivative of W_O w.r.t. length, from the first expression, is negative for values of $L > 692$ ft. From the second expression, it is always positive, being

$$\partial(W_O)/\partial(L) = \frac{1}{3}\frac{W'_O}{L'} .$$

That ramification of the first expression (i.e., negative derivative w.r.t. length) was most likely not considered at the time of its development. Moreover, positive coefficients for that derivative would be obtained for general cargo ships [Benford, 1967], for container ships [Miller, 1970], in addition to those for bulk carriers given in the previous section of this appendix.

Sato [1967] deals with the outfitting in significant detail, and indicates that the portion of the outfitting cost that is a function of the dimensions of the vessel will be proportional to $[L \cdot (B + D)]\ C_B$. Thus the previous expression may be considered modified to:

$$W_O = W'_O \left(\frac{2}{3} + \frac{1}{3} \cdot \left[\frac{L \cdot (B + D)}{L' \cdot (B' + D')}\right]^{0.75} \cdot \left[\frac{C_B}{C'_B}\right]^{0.1} \right).$$

Using this last expression, for $B/D \approx 1.9$, coefficients are derived for tankers, giving

$$\frac{\partial(Q_O)}{\partial(-)} = a_o \cdot \frac{Q'_O}{(-)} ,$$

with values for a_o appearing in Table II.

Appendix IV - Derivatives of Fuel Costs

A. Cost-Weight Relationship

Regardless of the type of machinery, fuel is purchased on a cost-per-unit-weight basis. The cost of fuel per voyage is given by $\gamma \cdot W_F$, in which γ is the cost per unit weight, and W_F is the fuel weight consumed per voyage. Thus the annual fuel cost, Q_F, is given by $N_V \cdot \gamma \cdot W_F$, where N_V is the number of voyages per year. With γ constant under all conditions,

$$\frac{\partial(Q_F)}{\partial(-)} = \gamma \cdot N_V \cdot \frac{\partial(W_F)}{\partial(-)} + \gamma \cdot W_F \cdot \frac{\partial(N_V)}{\partial(-)},$$

in which $$\frac{\partial(W_F)}{\partial(-)} = \frac{\partial(W_F)}{\partial(S_N)} \cdot \frac{\partial(S_N)}{\partial(-)}.$$

The first term on the right side of the first equation accounts for the fact that a different amount of fuel may be consumed per voyage due to a change in a design parameter. The second term reflects the change in the number of voyages per year, if any, resulting from a parameter variation.

The last factor in the second equation may be written as:

$$\frac{\partial(S_N)}{\partial(-)} = a_p \cdot \frac{S'_N}{(-)'},$$

in which values of a_p are given in Appendix II-H. For small changes of powering requirements, the fuel consumption rate per horsepower-hour is constant. Thus $\partial(W_F)/\partial(S_N) \simeq W'_F/S'_N$.

B. Derivatives of N_V

In general, with T_O being the total time in service per year,

$$T_O = N_V \cdot (T_S + T_C + T_F),$$

in which T_S is the time spent at sea per voyage, T_C denotes time spent on cargo handling (loading and discharging), and T_F indicates fixed time losses per voyage (weather delays, manoeuvering, docking, etc.). Assuming that the ratio of ballast speed to service speed is constant, then $T_S = T'_S \cdot (V'/V)$; i.e. time at sea is inversely proportional to service speed.

A first approximation to T_C is a linear relationship between T_C and the cargo capacity, W_C: $T_C = T'_C \cdot (W_C/W'_C)$. Thus, from the equation for T_O,

$$\frac{\partial(N_V)}{\partial(-)} = \frac{-T'_O}{(T'_S + T'_C + T'_F)^2} \cdot \left[\frac{\partial(T_S)}{\partial(-)} + \frac{\partial(T_C)}{\partial(-)}\right].$$

The only primary design parameter for which $\partial(T_S)/\partial(-)$ is non-zero is "V", in which case the derivative is $(-T'_S/V')$. The last term in the previous equation can be written:

$$\frac{\partial(T_C)}{\partial(-)} = \frac{\partial(T_C)}{\partial(W_C)} \cdot \frac{\partial(W_C)}{\partial(-)} = \frac{T'_C}{W'_C} \cdot \frac{\partial(W_C)}{\partial(-)}.$$

Expressions for $\partial(W_C)/\partial(-)$ appear in Section 4.

Thus, for the design parameters L, B, D and C_B,

$$\frac{\partial(N_V)}{\partial(-)} = \frac{-N'_V \cdot N'_V}{T'_O} \cdot \frac{T'_C}{W'_C} \cdot \frac{\partial(W_C)}{\partial(-)},$$

and for the design parameter V,

$$\frac{\partial(N_V)}{\partial(V)} = \frac{+N'_V \cdot N'_V}{T'_O} \cdot \left[\frac{T'_S}{V'} - \frac{T'_C}{W'_C} \cdot \frac{\partial(W_C)}{\partial(V)}\right].$$

C. Summary of Appendix IV

Using the relationship $Q_F = \gamma \cdot W_F \cdot N_V$, the following is obtained:

$$\frac{\partial(Q_F)}{\partial(-)} = Q'_F \cdot \left[\frac{a_p}{(-)'} - \frac{N'_V \cdot T'_C}{W'_C \cdot T'_O} \cdot \frac{\partial(W_C)}{\partial(-)}\right],$$

and when the derivative is w.r.t. design speed, V, add the term:

$$\frac{Q'_F \cdot N'_V \cdot T'_S}{V' \cdot T'_O}$$

Note that the units associated with T_O are days/year, and for T_C and T_S

they are days/voyage. Expressions for $\partial(W_C)/\partial(-)$ are in Section 4. and values of a_p are in Table II.

The last term on the right hand side of the equation above represents the change of fuel usage due to differing lengths of time in port, arising from variations in cargo capacity. The first term in the fuel cost derivatives results directly from differing power requirements due to altered vessel configuration or speed. The extra term for the derivative w.r.t. speed reflects the change in fuel usage from a differing number of annual voyages.

Appendix V - Additional Voyage Cost Derivatives

In this appendix, the derivatives of the remaining voyage costs are obtained, the fuel cost derivative appearing in Appendix IV.

A. Port Costs

From information given by Fisher [1971], about 20% of port costs, excluding cargo handling, will be a function of the number of voyages (or port entries and exits), and 80% will result from gross tonnage considerations. For tankers not entering ports, those proportions will be different. That situation is not considered here. With gross tonnage proportional to the product L • B • D [Fisher, 1971a], and modifying it for C_B considerations,

$$Q_p = Q'_P \cdot \frac{N_V}{N'_V}\left[\frac{2}{10} + \frac{8}{10}\,\frac{L \cdot B \cdot D \cdot (C_B + 0.8)}{L' \cdot B' \cdot D' \cdot (C'_B + 0.8)}\right],$$

thus leading to, for design parameters L, B and D,

$$\frac{\partial(Q_P)}{\partial(-)} = -\,Q'_P \cdot \frac{N'_V}{W'_C} \cdot \frac{T'_C}{T'_O} \cdot \frac{\partial(W_C)}{\partial(-)} + \frac{8}{10} \cdot \frac{Q'_P}{(-)'}.$$

For the other two primary design parameters:

$$\frac{\partial(Q_P)}{\partial(C_B)} = -\,Q'_P \cdot \frac{N'_V}{W'_C} \cdot \frac{T'_C}{T'_O} \cdot \frac{\partial(W_C)}{\partial(C_B)} + \frac{8}{10}\,\frac{Q'_P}{(C'_B + 0.8)}$$

$$\frac{\partial(Q_P)}{\partial(V)} = Q'_P \cdot \frac{N'_V}{T'_O} \cdot \left[\frac{T'_S}{V'} - \frac{T'_C}{W'_C} \cdot \frac{\partial(W_C)}{\partial(V)}\right].$$

Those three expressions incorporate the last two equations in Appendix IV-B. Expressions for $\partial(W_C)/\partial(-)$ may be found in section 4. The C_B correction to gross tonnage recognises the lack of direct correlation between under water volume and total enclosed volume.

Notice that the term containing the factor $\partial(W_C)/\partial(-)$ has the same sign for all derivatives, but has the opposite effect when it is w.r.t. V, inasmuch as $\partial(W_C)/\partial(V)$ is negative. The reason is that as L, B, D or C_B increase, the cargo capacity increases, requiring greater port time for cargo loading and discharge, thus reducing N_V. If, however, V increases, greater space is devoted to machinery, having the opposite effect on available cargo capacity.

B. Cargo Handling

A first approximation to cargo handling costs is a linear relationship between those costs, Q_H, and the vessel cargo capacity, W_C:

$$Q_H = Q_H' \cdot \frac{N_V}{N_V'} \cdot \frac{W_C}{W_C'} .$$

Therefore

$$\frac{\partial(Q_H)}{\partial(-)} = \frac{Q_H'}{N_V'} \cdot \frac{\partial(N_V)}{\partial(-)} + \frac{Q_H'}{W_C'} \cdot \frac{\partial(W_C)}{\partial(-)} .$$

Using Appendix IV-B, for design parameters L, B, D and C_B:

$$\frac{\partial(Q_H)}{\partial(-)} = \frac{Q_H'}{W_C'} \cdot \left[1 - \frac{N_V' \cdot T_C'}{T_O'}\right] \cdot \frac{\partial(W_C)}{\partial(-)} .$$

For the velocity:

$$\frac{\partial(Q_H)}{\partial(V)} = \frac{Q_H'}{W_C'} \cdot \left[1 - \frac{N_V' \cdot T_C'}{T_O'}\right] \cdot \frac{\partial(W_C)}{\partial(V)} + \frac{Q_H'N_V'}{V'} \cdot \frac{T_S'}{T_O'} ,$$

in which $\partial(W_C)/\partial(-)$ appears in section 4.

Of the two terms on the right hand side of the next to last equation, the first represents the change of cargo handling costs due to altered vessel capacity; and the second represents the effect of the changed number of annual voyages resulting from different loading and discharge times due to the altered capacity. In the last equation the third term arises from the change in the annual number of voyages due to a change in speed.

Appendix VI - Derivatives of Fixed Annual Costs

A. Insurance

For both tankers and bulk carriers, the protection and indemnity insurance premium, Q_{PI}, may be approximated by a linear function of deadweight [Fisher, 1971]. Benford [1967] points out that rates are quoted on a gross tonnage basis, that tonnage being almost linear w.r.t. deadweight tonnage, for small variations of dimensions.

The hull and machinery insurance premium, Q_{HI}, is expressed as a percent of the total construction cost of the vessel, Q_T, that percentage varying slightly with the size of the vessel. For small changes of deadweight, assuming it to be a constant percentage appears reasonable in all respects [Fisher, 1971]. Thus with the total annual premium designated Q_I,

$$\frac{\partial(Q_I)}{\partial(-)} = \frac{\partial(Q_{PI})}{\partial(-)} + \frac{\partial(Q_{HI})}{\partial(-)} = \frac{\partial(Q_{PI})}{\partial(W_D)} \cdot \frac{\partial(W_D)}{\partial(-)} + \frac{\partial(Q_{HI})}{\partial(Q_T)} \cdot \frac{\partial(Q_T)}{\partial(-)} .$$

in which $\partial(Q_{PI})/\partial(W_D) = Q'_{PI}/W'_D$, and $\partial(Q_{HI})/\partial(Q_T) = Q'_{HI}/Q'_T$. Expressions for $\partial(W_D)/\partial(-)$ are in section 4, and those for $\partial(Q_T)/\partial(-)$ are in section 5.

B. Maintenance and Repair

The annual cost for diesel machinery maintenance is directly proportional to S_N, according to Fisher [1971], whereas it is proportional to $S_N^{2/3}$ for steam machinery [Benford, 1967].

Hull maintenance and repair encompasses the hull structure (including deck house) and outfitting. Modern bulk carriers have a minimum amount of hull machinery aboard, thus Q_{HM}, the annual hull maintenance and repair (M & R) costs, will be proportional to an equivalent surface area: $Q_{HM} \propto (L \cdot B \cdot D)^{2/3}$.

For tankers the same will be true, except for the component due to cargo pumps - a potentially major item on modern tankers. However, confidential information received from a major Australian operator of tankers indicates that less than 1% of the annual M & R costs are attributable to the cargo pumps. It is, therefore, negligible.

The machinery M & R costs are given by

$$\frac{\partial(Q_{MM})}{\partial(\;-\;)} = \frac{\partial(Q_{MM})}{\partial(\;S_N\;)} \cdot \frac{\partial(S_N)}{\partial(\;-\;)} = a_f \cdot a_r \cdot \frac{Q'_{MM}}{(-)'} \;.$$

For steam installations, $a_r = 0.67$, while for diesel installations, $a_r = 1.00$, as given above. Values of a_p come from Appendix II-H, and are listed in Table II.

For hull M & R cost derivatives w.r.t. L, B and D, from above,

$$\frac{\partial(Q_{HM})}{\partial(\;-\;)} = 0.67 \cdot \frac{Q'_{HM}}{(-)'}$$

The derivatives of Q_{HM} w.r.t. C_B and V are zero.

C. Crew, Stores and Supplies

For small variations in the primary design parameters, the crew number may be considered constant. Therefore all derivatives w.r.t. crew number are identically zero; which also renders the derivatives of stores and supplies costs, Q_{SS}, zero [Fisher, 1971].

Appendix VII - Cargo Handling Rates

The primary appearance of the cargo handling time (T_C) is in the determination of the annual number of voyages (N_V). From Appendix IV-B,

$$N_V = T_O / (T_S + T_C + T_F),$$

from which

$$\frac{\partial(N_V)}{\partial(T_C)} = -\frac{N_V^2}{T_O}$$

The only costs affected by a change in T_C are the annual costs dependent on N_V, namely $Q_{AD} = Q_F + Q_P + Q_H$ (section 7). Using the relationship:

$$\frac{\partial(Q_{AD})}{\partial(T_C)} = \frac{\partial(Q_{AD})}{\partial(N_V)} \cdot \frac{\partial(N_V)}{\partial(T_C)},$$

the following is obtained:

$$\frac{\partial(Q_{AD})}{\partial(T_C)} = -\frac{N_V'}{T_O'} \cdot Q_{AD}'.$$

The total annual cargo transported is also dependent on T_C, by way of N_V:

$$\frac{\partial(W_A)}{\partial(T_C)} = -\frac{N_V'}{T_O'} \cdot W_A'.$$

Implicit in the above derivations is the fact that the cost of loading or discharging each ton of cargo is the same, independent of the rate of cargo handling. It is assumed that changes in the rate of cargo handling are achieved by capital and operational costs discussed elsewhere in the paper.

If R_D is the cargo discharge rate (tons/day), and if the cargo loading rate is εR_D, then the following relationships are valid:

$$T_C = \frac{W_C}{R_D} + \frac{W_C}{\varepsilon R_D} = \left(\frac{1 + \varepsilon}{\varepsilon}\right) \cdot \frac{W_C}{R_D}.$$

$$\frac{\partial(Q_{AD})}{\partial(R_D)} = \left(\frac{1 + \varepsilon}{\varepsilon}\right) \cdot \frac{W'_A \cdot Q'_{AD}}{T'_O (R'_D)^2}$$

$$\frac{\partial(W_A)}{\partial(R_D)} = \left(\frac{1 + \varepsilon}{\varepsilon}\right) \cdot \frac{(W'_A)^2}{T_O (R'_D)^2}.$$

Those are derived using the relationship: $W_A = N_V \cdot W_C$.

Appendix VIII - Historical Examination of Derivatives of Hull Steel Costs

A. Introduction

The purpose of including this appendix is to give the reader an appreciation of the diversity of concepts regarding approximations of steel weights for large vessels. It may be advisable to accept the information in Appendix I with a grain of salt - that salt being the apparent discrepancies or inconsistencies noted in this Appendix.

Consistent with Murphy's Law, the information pertinent to this, the major cost component, has seen greater variation than that of any other component. For bulk carriers, steel weight derivatives are available from three primary and two secondary sources; and for tankers, from four primary sources. Because of the significant variations, all previously available information is summarised in this appendix.

Occasionally it is necessary to assume length/beam or length/depth ratios. Statistics from the 'Motor Ship' survey of 'Ships on Order [June 1971]' indicate that for 70 different designs of bulk carriers over 40 kDWT, the average values of L/B, L/D and B/T were 6.6, 11.8 and 2.5 respectively. For 60 different designs of tankers over 100 kDWT, the values of those ratios are 6.2, 11.8 and 2.5. (That is, tankers are beamier than bulk carriers, but have comparable sections and profiles.) Those values can be used with the knowledge that 10% variations in them consistently result in less than a 3% variation in the obtained derivative coefficient, of which an example is given later. For this study, a constant depth/draught ratio is assumed (Appendix II-D).

B. Bulk Carriers

Aldwinckle's [1970] study involves considerable structural detailing for bulk carriers. His work, however, is limited to the longitudinal material only, for which a general expression gives:

$$W_S \propto L^{1.878} \cdot B^{0.963} \cdot D^{-0.189} \cdot T^{0.158} \cdot C_B^{0.197}.$$

For D/T being constant, the third and fourth factors combine to give $D^{-0.031}$. From that expression:

$$\frac{\partial(W_S)}{\partial(L)} = 1.88 \frac{W_S'}{L'}$$

The other derivative coefficients are easily observed.

Murray [1965] suggests, for all material, including ends:

$$W_S \propto L^{1.65} \cdot (B + D + {}^{T}/_{2}) \cdot (C_B + 0.8).$$

Using the principle dimension ratios for bulk carriers given in section A, the derivative coefficients for L, B and D are 1.65, 0.57 and 0.43, respectively. (If ${}^{L}/_{B} = 6.0$, instead of 6.6, the last two coefficients would be 0.585 and 0.415.) For $C_B \simeq 0.8$, the corresponding derivative coefficient is 0.50; and for $C_B \simeq 0.9$, it is 0.53.

Hagen [1967] derives an expression for all steel weights (including ends) as

$$W_S \propto Z^{0.69} \cdot L \cdot (1.104 - 0.016 \frac{L}{B}) \cdot (0.53 + 0.04 \frac{L}{D}) \cdot$$
$$(1.98 - 0.04 \frac{L}{D}) \cdot (1.146 - 0.0163 \frac{L}{D}),$$

in which Z is the midship section modulus. Using Aldwinckle's [1970] value, namely

$$Z \propto L^{2.267} \cdot B \cdot (C_B + 0.7),$$

the derivative coefficients can be obtained.

Those are three previous primary sources of bulk carrier steel weights. The two secondary ones are modifications to Murray's [1965] expression. Buxton [1965] suggests

$$W_S \propto L^{1.8} \cdot B^{0.6} \cdot D^{0.4} \cdot (C_B + 0.8),$$

and Telfer [1965] suggests

$$W_S \propto L^{5/3} \cdot (3B + D + T).$$

The coefficients obtained from each of these five sources are shown in Table A2. In that table, the column designated σ is the weight scale factor, i.e., the weight scales as the σ power of the linear dimensions.

The consequence of that table is disquieting. The variations in coefficients, especially the beam and depth ones, are too large to make an average value acceptable. Some of the differences between those coefficients from Aldwinckle [1970] and the others are attributable to the fact that his includes only longitudinal material. But it has not been established that such consideration resolves all differences.

C. Tankers

Sato [1967] uses a steel weight given by:

$$W_S \propto (C_B)^{1/3} \cdot \left[\omega_1 \cdot \frac{L^{3.3} \cdot B}{D} + \omega_2 \cdot L^2 \cdot (B + D)^2 \right],$$

in which ω_1 and ω_2 are constants being 5.11×10^{-5} and 2.56×10^{-5}, respectively, for lengths in meters and weights in metric tons. Using the average values of the principal dimension ratios (section A), it is noted that the first term in Sato's equation contributes 56.8%, 52.2% and 48.6% of the total for lengths of 250*, 325 and 400 meters, respectively. The first term has a total steel weight scale factor of 3.3, and for the second term it is 4.0. The values of the derivative coefficients that result from either term acting independently are given in Table A3. Using the relative weightings for each term, final values of the derivative coefficients can be obtained.

Buxton [1966] presents a series of formulations applicable to transverse as well as longitudinal material, but only for the cargo tank sections of the vessel. He summarises his results with

$$W_S \propto L^{2.2} \cdot B^{0.8} \cdot D^{0.2}.$$

He suggests that once end weights are taken into consideration, the relative magnitude of the exponent for depth will rise slightly.

Another study on steel weights for tankers is that by Moe [1968], in which detailed weight calculations are made for all components of the midship structural configuration. In Figures 21, 25 and 27 of that paper, steel weights are plotted as functions of $^B/_D$ with L constant, $^L/_D$ with $^L/_B$ constant, and $^L/_B$ with $^L/_D$ constant, respectively. If it is assumed that:

$$W_S \propto L^x B^y D^z,$$

the relative slopes of the curves in those three figures leads to $x/y \approx 3.0$, $y/z \approx 3.7$. If, further, the sum $(x + y + z)$ is taken to be 3.2, the same as that corresponding to Buxton's [1966] summary, then

$$W_S \propto L^{2.25} \cdot B^{0.75} \cdot D^{0.20},$$

---

* L = 250 m. corresponds to approx. 120 kDWT; L = 325 m. to 270 kDWT; and L = 400 m. to 500 kDWT.

giving reasonable confirmation of Buxton's [1966] results.

As with bulk carriers, Hagen [1967] gives a general expression for the steel weight (including ends) for tankers:

$$W_S \propto Z^{0.65} \cdot L \cdot \left[1.104 - 0.016\frac{L}{B}\right] \cdot \left[\frac{22.8}{35.8 - L/D}\right] \cdot \left[\frac{35.9}{14.0 + L/D}\right] \cdot \left[1.120 - 0.0163\frac{L}{D}\right].$$

Using Buxton's [1966] expression for section modulus, given by

$$Z \propto L^{2.3} \cdot B \cdot (C_B + 0.7),$$

values of the derivative coefficients are obtained.

Of these four sources of information on tanker steel weights, Sato's [1967] is the only one having a negative depth derivative coefficient. All of the obtained coefficients are shown in Table A4.

For tankers, unlike the situation for bulk carriers, it appears that there is consistency between the three of the four primary sources. However, the differences in beam and depth derivative coefficients between Sato's [1967] equation and the others is too large to dismiss.

Table A-II

Historic Steel Weight Derivative Coefficients for Bulk Carriers

Source	L	B	D	C_B	σ
Aldwinckle [1970][a]	1.88	0.96	-0.03	0.20	2.81
Hagen [1967]	1.61	0.78	-0.13	0.37[b]	2.26
Murray [1965]	1.65	0.57	0.43	0.50[c]	2.65
Buxton [1965]	1.80	0.60	0.40	0.50[c]	2.80
Telfer [1965]	1.67	0.76	0.24	-	2.67

a - longitudinal material only.

b - reduced from $0.69/(C_B + 0.7)$ at $C_B \approx 0.8$.

c - reduced from $1.00/(C_B + 0.8)$ at $C_B \approx 0.8$.

Table A-III

Independent Derivative Coefficients

from Sato's [1967] Equation

	L	B	D
First Term	3.30	1.00	-1.00
Second Term	2.00	1.30	0.70

Table A-IV

Historic Steel Weight Derivative

Coefficients for Tankers (a_s)

Source	L	B	D	C_B	σ
Moe [1968][d]	2.25	0.75	+0.20	-[d]	3.20
Hagen [1967]	2.06	0.73	+0.35	0.36[e]	3.14
Buxton [1966][d]	2.2	0.8	+0.2	-[d]	3.20
Sato [1967] L = 250 m.	2.74	1.13	-0.27	0.33	3.60
" " L = 325 m.	2.68	1.14	-0.19	0.33	3.63
" " L = 400 m.	2.61	1.15	-0.13	0.33	3.63

d - long'l and transverse material in cargo tank sections only.

e - reduced from $0.65/(C_B + 0.7)$ at $C_B \approx 0.85$.

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THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

WRITTEN DISCUSSION

AND AUTHOR'S REPLY

COSTS OF SHIP DESIGN PARAMETERS

BY

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12TH JULY 1972

WRITTEN DISCUSSION

PROF. J.F.C. CONN (F.R.I.N.A.) This is an original, interesting and informative paper which breaks new ground in the philosophy of ship design. The advent of advanced facilities for calculation has opened new possibilities in design, notably in the assessment of economic return. Hence there is the welcome prospect of participation in discussion and decision by owners and port authorities as well as by naval architects.

The author develops what may be termed differential methods to considerable advantage. Despite my own warnings on the subject, which he quotes, such methods, notably in hull steel weight estimates, can hardly be avoided by the practical designer. One difficulty in their use centres on the reliability and trustworthiness of the basic data employed for the production of the necessary derivatives. An examination of the figures in Table A-I discloses a certain lack of consistency, to give an obvious example.

One is rather suprised by the simplicity of the power/length, the power/beam and the power/depth relationships.

Only experience with the author's methods can disclose whether his assumed relationships are adequate or not, but he has made a bold attempt to codify and solve and otherwise intractable problem. The time at my disposal does not permit of serious checking and examination of the methods but the author merits the thanks of all naval architects for a stimulating and useful paper.

MR. S. SATO I thank the author for referring to the contents of my 1967 S.N.A.M.E. paper. I do have some comments regarding my formulae, etc. referred to in this paper.

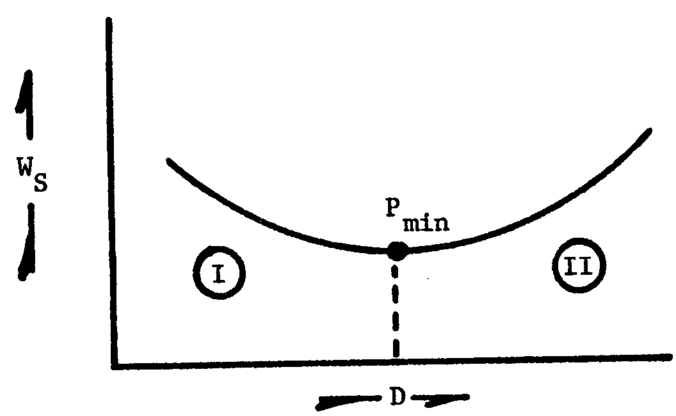
I. Hull Steel Weight Formula.

My formula has been derived from computed weights according to changes of principal dimensions on the basis of draught/depth being constant and displacement constant, with other parameters not always independent of each other because length and/or breadth are decreased in the case of increasing depth.

Accordingly, my formula may not be suitable for getting derivatives for the parameters although it has been tried in my paper to give a rough estimation of effects of principal dimensions on hull steel weight.

Choosing length (L), breadth (B), depth (D), draught (T) and block coefficient (C_B) as parameters to express a formula for hull steel weight, all parameters except 'D' show that hull steel weight increases by increasing these parameters, but 'D' doesn't always show such an inclination.

Hull steel weight has the inclination of the figure below according to changes of 'D' if all parameters except 'D' are constant. There is a minimum weight point (P_{min}) at an intermediate value of 'D'.



W_S : Hull steel weight

P_{min}: Minimum point

L, B, T, C_B : Constant

The figure shows that the hull steel weight derivative with respect to 'D' is negative in region 'I', zero at point 'P_{min}', and positive in region 'II'. Therefore it is impossible to express a relation between hull steel weight and 'D' for both regions at the same time by a product formula.

I estimate that, generally speaking, point 'P_{min}' is around L/D = 13 for VLCC's having conventional proportions of principal dimensions. I suggest therefore that the hull steel weight derivative with respect to depth that is used be a different value according to the ratio L/D for the "good design."

I well know that almost all of the present VLCC's have L/D < 13; but the draughts of VLCC's already reach the critical margins. Thus VLCC's having L/D ≥ 13 will be designed and constructed in the near future.

II. Machinery Weight.

In the present paper it is stated that the coefficient for the machinery weight derivative due to power varies from 0.3 to 0.4 according to the curve in my 1967 paper.

But according to that curve, the result of the derivative calculation varies from 0.4 to 0.45 in the range of 20,000 to 40,000 S.H.P.

III. Outfitting Weight.

Judging from data of our recent VLCC's, I find that the formula in my 1967 paper gives a better approximation than the estimation from the modified formula in the present paper; but I would like to say additionally that each shipyard has its individual definition for machinery and outfitting weights.

Regarding hull steel weight, we now have another formula for the tank part of the steel weight for recent VLCC's. It is:

$$W_S \propto \frac{L^{3.3}B}{D} + (4.18 \times 10^3 D + 3.8 \times 10^1 B^2 + 1.07 \times 10^2 D^2) L \sqrt{D}$$

If the hull steel weight derivatives due to L, B, and D are obtained in the same manner as they are in Appendix VIII of the present paper, they are the values given in the following table.

SHIP	L	B	D	σ
L = 250 m.	1.95	0.77	0.45	3.17
L = 325 m.	1.98	0.83	0.40	3.21
L = 400 m.	1.96	0.86	0.38	3.20

Five years have passed since I presented my paper to S.N.A.M.E. and I now firmly believe that our tanker design method has progressed considerably in the area of weight estimation, power estimation, etc., though little change has been made in the design philosophy of my paper.

I anticipate a future publication concerning my organisation's* tanker design method.

I appreciate the reference to my paper and having the opportunity to give my opinion on certain aspects of this paper.

DR. I.L. BUXTON (M.R.I.N.A) The author has presented a worthwhile and stimulating paper which is a valuable contribution to the increasing number of papers which treat the ship design process in a much more rigorous manner than hitherto.

The approach of using derivatives is a good one, as it is often the rate at which a parameter is changing that is more important than its absolute value. When the ship designer is comparing alternatives, it is essential to be able to obtain the correct relative values. The designer who has access to a good stock of consistent data is at an advantage over those who do not. This applies particularly in such fields as powering, weight and cost estimating. Other authors, including Mr. Fisher, have deplored the lack of data,

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* - Hitachi Shipbuilding and Engineering Company.

because it is easy to draw incorrect conclusions from the inevitably inadequate data available near the boundaries of existing knowledge. The present paper and the Nowacki and Fisher references all point to much larger block coefficients for bulk vessels, using the powering algorithms available, although pointing out that more accurate methods are needed.

One of the best and most consistent methodical series is that carried out by the British Ship Research Association. The earlier results have already been published (R.I.N.A. 1961 and 1966), but since then, improved forms and extended parameters have been tested. The series has very good resistance characteristics especially at high block coefficients. Although not yet published, it has been widely used by B.S.R.A. and its Member Firms. One important conclusion which can be drawn is that powering penalties for increasing block coefficient above about 0.85 are extremely severe. For example, the derivative of resistance coefficient is about 0.5 at 0.84, but has jumped to about 3 at 0.86, at speed-length ratios representative of actual ships. Thereafter the resistance rises even faster; up to about the eighth power of block coefficient at around $C_B = 0.87$. These figures can be compared with the author's 0.25.

On the question of the derivatives of power with respect to breadth and draft, Moor and Small's [1960] revised Mumford indices suggest that the author is being too optimistic, assuming values of 0.75 and 0 respectively. Moor's figures for EHP point to indices in the region of 0.9 and 0.55 respectively for the ships considered. It seems doubtful whether the corresponding figures for DHP would be much lower. In summary therefore, it is necessary to treat with great reserve the author's detailed conclusions where the improvements claimed have been achieved as a result of changes in the powering and its associated effects - machinery and fuel costs.

Power is of course strongly related to speed as well as dimensions. Can the author say how much influence exclusion of cargo value has on optimal speed, through its effect on inventory costs? Commercial considerations like competition affect speed as is well known; it is probably fair to state that where shipowners have ordered relatively slow ships, they have often not been regarded as commercial successes. Although they may be satisfactory on owner-operator shuttle services, they lack the versatility required by tramp type owners who need vessels which appeal to a wide range of charterers. In the liner trades there is no doubt that speed sells in a competitive environment.

While recognising that the author is demonstrating a method rather than recommending estimating relationships, I feel that the formulations used for outfit weights and costs are inadequate to establish realistic derivatives. Apart from Sato, none of the expressions include depth/draft or block coefficient, yet both are implicit in calculation of equipment numeral, and have influence on items like anchors and cables, windlasses, rudder, internal hull access, paint and hull protection. I have found a better expression to be:

$$W_O \propto L^{0.8} B^{x} D^{0.3} C_B^{0.1}$$

where $x = 0.5$ for tankers and 0.6 for bulk carriers, where hatch covers are more significant items.

I welcome the honest statement quoted at the end of the Conclusions (Section 13) on page 24. As the author recognises, neither owner nor builder on his own has sufficient information to be able to design the optimal ship, which is a blend of features relating first costs, running costs and technical and operational performance. A proper dialogue between the parties concerned in a process of successive refinement of design can only be of benefit to all. This paper, and the author's earlier ones, have all contributed most encouragingly to increasing the understanding of the problems and their solutions.

MR. P.M. SWIFT (M.R.I.N.A.) The author is to be congratulated on a very fine and well presented paper. He has clearly stressed the need for a better understanding of the decision space in which today's designers, builders and owners operate. In recent optimization studies at the University of Michigan we have used screen displays of 2-dimensional decision space in order to obtain improved insight into the design relationships, the boundaries of the decision space, and the nature and effect of the various constraints placed on this space. Many of these constraints are artificial, since we either lack sufficient confidence to extend our design relationships beyond certain arbitrary limits, or they are present because of ignorance.

The author's work presents us with a useful method for the examination of those relationships which prove to be of greatest significance. I concur that there is an urgent need for systemmatic series resistance data for large block hull forms. Also we require research in the areas of higher beam-draught and length-depth ratios, lower length-beam ratios, etc. Further we must hope that industry will be more forthcoming with the necessary data required for the application of the new techniques.

Naturally the shipowner and shipbuilder is interested in absolute costs, but to obtain these it is necessary to have cost-parameter relationships and associated cost levels. Variations in cost levels can be readily handled by sensitivity studies, and it is therefore desirable to be able to study the effects of parameter variations. In this respect the paper has provided an excellent contribution.

MR. KOHEI OTA The method of analysis described in this paper is very unique and interesting. While it deserves more detailed examination than I have given it thus far, I would like to make these observations.

It is well recognised that standard ship systems are now part of the trend of generalisation by the principal shipbuilders in the world in order to save labour in design and site work.

Therefore, even if the variation of principal dimensions as a result of these calculations results in a lower shipbuilding cost, lower freight rate, and so forth, it is nevertheless actually difficult for the shipbuilders to accept the result promptly.

However, it appears that this method is effective in the determination of the particulars of vessels which will become popular in the future, though not necessarily popular at present.

CAPTAIN W.J. ROURKE, R.A.N. (F.R.I.N.A.) Mr. Fisher has given us an interesting extension of his earlier work in optimisation of ship design to achieve an appropriate minimum cost criterion.

Like the author, I tend to be wary of the approximations of marginal extensions to empirical formulations, and suggest as an example that it may not be appropriate to consider residual resistance to be proportional to the displacement which is proportional to the length. Many factors would contribute to a relationship in which the incremental resistance could be much less than incremental length and I believe there is empirical evidence available from the results of 'Jumboising' tankers to support this view.

I have a more fundamental problem which could be attributable to the limited time I have had to study the paper. In Mr. Fisher's earlier paper, recently published in the 'Naval Architect', he demonstrated how a global minimum of selected criterion could be established by a multi-variable search method. Now in this paper he takes a model ship and shows how certain small variations in parameters could lead to a significant reduction in required freight rate (RFR). Clearly the model ship used by the author can not have been an optimum ship or this reduction in RFR would not be achieved. It does not lie at the lowest point of a valley in the multidimensional space of the analysis.

My problem is that I see no way of determining where the model ship does lie, compared to the optimum. Mr. Fisher's marginal analysis would indicate that certain specified small changes in parameters would result in consequential changes to the required freight rates in a direction determined only by the magnitude and direction of the increments. But to me it seems that the direction of change in RFR depends upon whether the change leads the ship down the slope towards the optimum, or up the slope away from it, and that cannot be established unless it is known where the model lies initially on the slopes of the multidimensional space. The approach does not appear to deal with this problem.

MR. A.R. ASQUITH (M.R.I.N.A.) Cargo handling times with modern tankers and bulk carriers are so small these days that they effectively to not alter for up to 10% variation in physical parameters. Thus to use these as an optimisation hardly appears valid.

Are not the limiting features of docks, depth of water, technology and canals more over-riding than many of the desirable optimum parameters; and therefore in most cases would these not constitute the limiting factors of design?

AUTHOR'S REPLY

The wealth of information and thought contained in the discussions is most enthusiastically welcomed. It is with much pleasure that I undertake to reply to them.

Regarding the accuracy of the derivatives of the functions w.r.t. the design parameters, it is important to bear in mind that these are first approximations to the derivatives - something like the first term of a mathematical Taylor series. Nevertheless, accuracy should be maintained in accord with the information known on any particular aspect. I therefore take this opportunity to elaborate on several matters and to correct a few oversights brought to my attention by the discussions.

POWERING In Appendix II-E, the derivative of the frictional component of power w.r.t. C_B is stated to be nil. In fact, however, it is only Fisher's [1972]* earlier approximation to a wetted surface coefficient that has a zero derivative. The frictional power derivative should be 0.5.

The derivative of the residual component of power w.r.t. T (Appendix II-D) is given as (-1.2). But that does not account for the change of displacement. As in the length derivative, R_R per unit of displacement will be constant, thus changing that part of the power derivative to (-1.2 + 1.0) = (-0.2).

Dr. Buxton mentions the revised Mumford indices given by Moor and Small [1960]. There is additional information available from the work of Sabit [1971], which gives a 16-term expression for the B.S.R.A. residual resistance coefficients and a 4-term expression for the wetted

*The reference given as Fisher [1971a] should read: Fisher [1972]... The Naval Architect, R.I.N.A., No. 2, April, 1972.

surface coefficient. The coefficients for each of the terms are obtained by a regression analysis. Those expressions can be differentiated w.r.t. L, B, T and C_B, in order to obtain separate derivative coefficients for the residual and frictional power components.

Table D-I presents a summary of the derivative coefficients for power according to this present paper (as corrected), Sabit's [1971] expressions, and the revised Mumford indices. The values for Sabit's work use the following: L=325m., $^L/B=6.2$, $^B/T=2.5$, $C_B=0.8$, $V/\sqrt{L}=0.5$, and $R_F/R_R=1.95$. The resulting variations of 'a_p' for each parameter that appear in that table serve as the basis for a sensitivity study during the utilisation of these techniques.

Dr. Buxton's remarks that significantly higher derivatives for power w.r.t. C_B have been found for $C_B>0.85$ are a cause of concern, inasmuch as they indicate not merely a doubling of the expected values, but a change in the order of magnitude. This is not, however, wholly unexpected, as indicated in the fifth paragraph of Section 13, Conclusions.

We all recognise that a C_B of 0.85 is near the upper boundary of realistic values, but now we will have a better understanding of the exact mechanism of that boundary condition. The publication of the results of that extended B.S.R.A. series is anxiously awaited for that very reason.

Naturally, the alteration of numerical values of derivative coefficients will change some of the specific conclusions given in this paper arising from the application of these techniques to the example vessels, as mentioned by Dr. Buxton. The examples do remain valid, however, insofar as they demonstrate the potential uses of the techniques.

Table D-I

Coefficients for Powering Derivatives, 'a_p'

Parameter	L	B	D	C_B
Frictional Deriv. - Fisher	1.0	0.5	0.5	0.5
- Sabit	0.98	0.54	0.48	0.58
Residual Deriv. - Fisher	1.0	1.2	-0.2	1.0
- Sabit	1.29	0.42	0.29	0.32
Total Deriv. 'a_p' - Fisher	1.0	0.75	0.27	0.67
- Sabit	1.09	0.50	0.41	0.48
- Mumford		0.9	0.55	0.72

WEIGHTS In a similar manner, I would like to amend the value of 'b_w' for steam installations given in Appendix II. Mr. Sato is correct in his assertion that the values range from 0.40 to 0.45, rather than the previously stated values of 0.3 to 0.4. The error arose from a neglect of the negative sign in Sato's [1967] expression:

$$W_M = -0.326 \times 10^{-6}(S_N)^2 + 0.048(S_N) + 720.$$

Mr. Sato's remarks regarding steel weight estimates for tankers are most welcome. His presentation of a new approximation for the tanks section weight is regarded as being highly complimentary.

In order to shed brighter light on the steel weight estimates for tankers, the values obtained by Sato's method (W_{S-SATO}) and those obtained by the exponent method of Appendix I (W_{S-EXP}) have been compared to the "mean statistical values" for 40 tankers published by det Norske Veritas (W_{S-dNV}). The specific manner of calculation is given below:

$$W_{S-EXP} = W_S'\left(\frac{L}{L'}\right)^{\lambda a}\left(\frac{B}{B'}\right)^{\beta a}\left(\frac{D}{D'}\right)^{\delta a}\left(\frac{C_B}{C_B'}\right)^{\eta a}$$

in which $\lambda a = (\lambda + \lambda')/2$, etc.

$$W_{S-SATO} = W_{MID} + W_{ENDS},$$

in which W_{MID} is given in Mr. Sato's discussion, and W_{ENDS} is taken from Sato [1967]. The basis vessel (W_S', L', etc.) which is also used to derive a coefficient for the Sato expression, is marked with (*) in Table D-II, the comparison of predicted tanker steel weights for selected vessels. The weight of superstructures has not been included in W_{S-SATO} inasmuch as they are not included in the published values of W_{S-dNV}.

Table D-II (a)

Comparison of Predicted Tanker Steel Weights

LENGTH (m.)	L/B	L/D	C_B	W_{S-dNV}	W_{S-EXP} / W_{S-dNV}	W_{S-SATO} / W_{S-dNV}
260.0	6.500	13.000	0.822	15585.	0.989	1.093
260.0	6.500	10.000	0.822	18706.	0.992	1.101
260.0	5.778	13.000	0.822	17138.	0.989	1.098
260.0	5.778	10.000	0.822	20688.	0.993	1.080
260.0	5.000	13.000	0.822	19334.	0.989	1.110
260.0	5.000	10.000	0.822	23507.	0.995	1.062
300.0	6.667	12.500	0.829	24696.	0.999	1.072
300.0	6.667	10.000	0.829	29076.	0.999	1.076
300.0	6.000	12.500	0.829	26942.	0.998	1.073
300.0	6.000	10.000	0.829	31891.	0.999	1.056
300.0	5.455	12.500	0.829	29215.	0.997	1.076
300.0	5.455	10.000	0.829	34754.	0.999	1.041
300.0	5.000	12.500	0.829	31514.	0.997	1.082
300.0	5.000	10.000	0.829	37664.	0.998	1.032
380.0	6.909	13.103	0.846	50001.	1.006	1.047
380.0	6.909	10.857	0.846	58112.	1.002	1.016
380.0	6.909	10.000	0.846	62310.	1.000	1.016
380.0	6.230	13.103	0.846	54639.	1.004	1.049
380.0 *	6.230	10.857	0.846	63896.	1.000	* 1.000
380.0	6.230	10.000	0.846	68713.	0.998	0.993
380.0	5.672	13.103	0.846	59366.	1.001	1.053
380.0	5.672	10.857	0.846	69846.	0.997	0.988
380.0	5.672	10.000	0.846	75216.	0.996	0.975
380.0	5.205	13.103	0.846	64183.	0.999	1.058
380.0	5.205	10.857	0.846	75827.	0.995	0.982
380.0	5.205	10.000	0.846	81799.	0.994	0.963
460.0	6.866	12.778	0.850	96518.	1.004	1.010
460.0	6.866	11.795	0.850	103505.	1.005	0.985
460.0	6.866	10.222	0.850	117834.	1.005	0.964
460.0	6.301	12.778	0.850	104258.	1.002	1.009
460.0	6.301	11.795	0.850	112018.	1.003	0.979
460.0	6.301	10.222	0.850	127947.	1.004	0.947
460.0	5.823	12.778	0.850	112099.	1.001	1.009
460.0	5.823	11.795	0.850	120650.	1.002	0.975
460.0	5.823	10.222	0.850	138216.	1.003	0.934
460.0	5.412	12.778	0.850	120035.	1.000	1.012
460.0	5.412	11.795	0.850	129394.	1.001	0.973
460.0	5.412	10.222	0.850	148634.	1.001	0.925
460.0	5.055	12.778	0.850	128062.	0.998	1.016
460.0	5.055	11.795	0.850	138244.	0.999	0.973
460.0	5.055	10.222	0.850	159192.	1.000	0.918

Table D-II (b)

Comparison of Predicted Bulk Carrier Steel Weights

LENGTH (m.)	$\frac{L}{B}$	$\frac{L}{D}$	C_B	W_{S-dNV}	W_{S-EXP}	$\frac{W_{S-EXP}}{W_{S-dNV}}$
220.0	6.984	13.750	0.814	9587.	9540.	0.995
220.0	6.984	10.476	0.814	11555.	11508.	0.996
220.0	6.377	13.750	0.814	10365.	10316.	0.995
220.0	6.377	11.892	0.814	11577.	11525.	0.995
220.0	6.377	10.476	0.814	12493.	12444.	0.996
220.0	5.946	13.750	0.814	10989.	10938.	0.995
220.0	5.946	11.892	0.814	12274.	12220.	0.996
220.0	5.946	10.476	0.814	13245.	13194.	0.996
220.0	5.500	13.750	0.814	11712.	11658.	0.995
220.0	5.500	10.476	0.814	14117.	14063.	0.996
260.0	7.027	14.054	0.822	15771.	15730.	0.997
260.0	7.027	12.381	0.822	17444.	17417.	0.998
260.0	7.027	10.400	0.822	19434.	19417.	0.999
260.0	6.265	14.054	0.822	17400.	17358.	0.998
260.0	6.265	12.381	0.822	19246.	19219.	0.999
260.0	6.265	11.556	0.822	20164.	20143.	0.999
260.0	6.265	10.400	0.822	21441.	21427.	0.999
260.0	5.474	14.054	0.822	19446.	19401.	0.998
260.0	5.474	11.556	0.822	22535.	22514.	0.999
260.0	5.474	10.400	0.822	23962.	23949.	0.999
300.0	6.977	13.333	0.830	25748.	25735.	1.000
300.0	6.977	10.526	0.830	30163.	30175.	1.000
300.0	6.316	13.333	0.830	28040.	28029.	1.000
300.0	6.316	12.000	0.830	30331.	30330.	1.000
300.0	6.316	11.538	0.830	31122.	31127.	1.000
300.0	6.316	10.526	0.830	32848.	32865.	1.001
300.0	6.000	13.333	0.830	29268.	29259.	1.000
300.0 *	6.000	12.000	0.830	31660.	31660. *	1.000
300.0	6.000	11.538	0.830	32485.	32492.	1.000
300.0	6.000	10.526	0.830	34286.	34306.	1.001
300.0	5.505	13.333	0.830	31407.	31400.	1.000
300.0	5.505	10.526	0.830	36792.	36816.	1.001
340.0	6.800	13.600	0.838	37946.	37994.	1.001
340.0	6.800	10.462	0.838	45343.	45438.	1.002
340.0	6.239	13.600	0.838	40834.	40890.	1.001
340.0	6.239	10.462	0.838	48794.	48902.	1.002
340.0	5.965	13.600	0.838	42389.	42449.	1.001
340.0	5.965	11.930	0.838	46801.	46881.	1.002
340.0	5.965	11.724	0.838	47342.	47428.	1.002
340.0	5.965	10.462	0.838	50652.	50766.	1.002
340.0	5.528	13.600	0.838	45108.	45175.	1.001
340.0	5.528	10.462	0.838	53901.	54027.	1.002
380.0	6.972	13.333	0.846	53126.	53331.	1.004
380.0	6.972	10.556	0.846	62141.	62435.	1.005
380.0	6.179	13.333	0.846	58897.	59134.	1.004
380.0	6.179	11.875	0.846	64161.	64443.	1.004
380.0	6.179	11.692	0.846	64818.	65109.	1.004
380.0	6.179	10.556	0.846	68892.	69229.	1.005
380.0	5.547	13.333	0.846	64361.	64627.	1.004
380.0	5.547	10.556	0.846	75283.	75660.	1.005

It may be observed from that table that W_{S-EXP} does faithfully reproduce the given values of W_{S-dNV}, but that some variance is noted in values of W_{S-SATO}. That does not suggest that either one is wrong. All it merely suggests is that the data used by Mr. Sato in developing his expression is not the same as the "mean statistical values" of det Norske Veritas.

It is interesting to note that the C_B-dependency in Mr. Sato's expression has been dropped since his 1967 publication. His indication that he expects to publish new notes on his organisation's tanker design method is welcome news, since he does have access to a significant amount of data. Perhaps the C_B anomaly will be explained therein.

Both Mr. Sato and Dr. Buxton comment on the outfitting derivatives. Mr. Sato re-affirms his formulation for tankers:

$$W_o \propto [L \cdot (B + D)]^{0.75} \cdot [C_B]^{0.1}.$$

A summary of the values of 'a_o' is given in Table D-III. Considering Dr. Buxton's close agreement with Mr. Sato for those dealing with tankers, it appears prudent to accept the Buxton values for bulk carriers as being closer to the correct values than those previously stated in this paper.

<u>INVENTORY COSTS</u> Dr. Buxton has asked for discussion regarding the effect of inventory costs on optimal speeds. Although it does introduce new material to this paper, I shall use this reply as the vehicle for communicating it, inasmuch as it is directly relevant to the rest of the paper.

Table D-III

Coefficients for Outfitting Weight Derivatives, 'a_o'

($B/D \approx 1.9$)

Parameter	L	B	D	C_B
TANKERS				
Fisher	0.25	0.17	0.08	0.03
Sato	0.75	0.49	0.26	0.1
Buxton	0.8	0.5	0.3	0.1
BULK CARRIERS				
Fisher	0.75	0.75	-	-
Buxton	0.8	0.6	0.3	0.1

Table D-IV

Relative Incremental FREIGHT RATES, INVENTORY COSTS and TRANSPORT COSTS due to a 1% increase of speed for two example vessels, using CR = 0.2.

i_F	F_V	$\frac{\delta(FR)}{FR}$	$\frac{\delta(Q_{INV})}{Q_{INV}}$	$\frac{\delta(Q_{TR})}{Q_{TR}}$	$\frac{Q_{INV}}{Q_{TR}}$
TANKER					
0.1	10	1.77	0.88	1.72	0.063
0.1	25	1.77	0.88	1.64	0.143
0.2	10	1.77	0.88	1.67	0.118
0.2	25	1.77	0.88	1.55	0.250
ORE CARRIER					
0.1	10	1.78	0.72	1.76	0.035
0.1	25	1.78	0.72	1.72	0.082
0.2	10	1.78	0.72	1.73	0.067
0.2	25	1.78	0.72	1.67	0.152

The matter of inventory costs arising from long transit times can generally be viewed in two ways: (a) the absolute value of the inventory costs, or (b) the real cost of transport being the freight rate plus the inventory cost.

A major aspect of inventory costs involves consideration of cargo stock piling, arrival rates at the loading port, cargo removal rates at the discharge post, and the usage rates at the final destination. It is because of these complications that inventory costs had not previously been given consideration. But if their influence on optimal speed of vessel is sought, then the inventory costs associated with only the journey can be evaluated.

It is assumed that half of the voyage time is chargeable to these costs.

The following definitions are applicable:

i_F - equivalent annual interest rate assigned to the freight.

F_V - the freight value factor, being the ratio of the freight value (per ton) to the applicable freight rate.

Q_{INV} - the inventory cost per ton of freight per voyage.

The relationships are:

$$Q_{INV} = FR \cdot F_V \cdot i_F \cdot (T_S+T_C+T_F)/(2 \cdot 365)$$

$$T_o = N_V \cdot (T_S+T_C+T_F). \quad \text{(See App.IV)}$$

If $T_o \approx 365$, then

$$Q_{INV} \approx FR \cdot F_V \cdot i_F/(2N_V),$$

and
$$\frac{\partial(Q_{INV})}{\partial(V)} = - \frac{Q_{INV}}{N_V} \cdot \frac{\partial(N_V)}{\partial(V)}$$

If one is interested in the total cost of shipping each ton of freight, the following are applicable:

$$Q_{TR} = FR + Q_{INV},$$

and

$$\begin{pmatrix}\text{relative}\\ \text{incremental}\\ \text{trans. costs}\end{pmatrix} = \begin{pmatrix}\text{relative}\\ \text{incremental}\\ \text{freight rate}\end{pmatrix} - \left(\frac{Q_{INV}}{Q_{TR}}\right) \cdot \begin{pmatrix}\text{relative}\\ \text{change}\\ \text{of } N_V\end{pmatrix}$$

Thus, a new criterion is made available; namely, the total transport cost. If that is the applicable criterion, (as opposed to freight rate, capital cost per deadweight ton, etc.) then the relative incremental transport costs, appearing in Tabel D-IV can be used in the same manner as the freight rate was used in Section 12, Design Changes.

Of course, on the open charter market, where freight rates are equal due to effects of competition, then a charterer will choose on the basis of lowest inventory costs.

TO CAPTAIN ROURKE I am in thorough agreement with Captain Rourke's comment that the ships used as examples in this study are not optima for their respective situations. But I do feel that the approach of this paper, in contrast to his comments, does indeed demonstrate where the design lies relative to the optimum; although it cannot predict exactly how far away the present design is from that optimum. To demonstrate that, consider the following.

If the freight rate for the ore carrier is the criterion, Figure 8 can be used to show the apparent direction toward the optimum. Table D-V illustrates the rough calculation to determine the direction of the optimum, in which 'down' indicates the parameter should be decreased.

Captain Rourke also suggests that some empirical evidence regarding resistance may be available from jumboised vessels to support or verify some of the results of this paper. Unfortunately, such information was not available to the author. I do draw his attention, however, to a very interesting paper by Ramakrishnan [1964], and the discussion of that paper by Smettem, in which the matter of speed loss due to lengthening is never satisfactorily resolved.

But if some evidence as to the applicability of these techniques is sought, I draw the reader's attention to a recent article which has been made available to the author since preparing this paper in late 1971 and early 1972. Because it is complementary to this one, I would like to include a brief description of that paper by Heller [1972].

In that paper Dr. Heller applies the differential method to obtain the change of structural weight of a small ship arising from changes of the principal dimensions, from the point of view of longitudinal strength.

His procedure is to first determine the change in bending moment (BM) resulting from the change in dimension. Then the change of required section modulus (Z) consistent with the change of bending moment is examined. From the section modulus and the gross dimensions, the effect on moment of inertia (I) is obtained, from whence the change on the cross sectional area of steel (A) is derived. The correspondence between cross-sectional area (A) and weight being linear, the effect on weight

Table D-V

Determination of Directions Toward Optimum for the example Ore Carrier

Parameter	Relative Incremental FR = A	A / B	Apparent Direction Towards Optimum
L	1.22	1.4	down
B	0.88	1.0	level
D	0.32	0.4	up
C_B	0.25	0.3	up
V	1.78	2.0	down
	Σ = 4.45		
	avg. = 0.89 = B		

Table D-VI

Absolute and Relative Values of 'a_s' According to Two Techniques for a Tanker having L=325 m., L/B=6.2, L/D=11.8 and C_B=0.82.

Parameter	L	B	D	σ
Absolute Values				
Sato[1]	1.98	0.83	0.40	3.21
Fisher[2]	1.66	0.85	0.76	3.27
Relative Values				
Sato[1]	1.00	0.42	0.20	
Fisher[2]	1.00	0.51	0.46	

1-From discussion by Mr. S. Sato.
2-From Appendix I.

is thus calculated.

In the manner of this present paper, Dr. Heller's work is summarised by:

$$\frac{\partial(W_S)}{\partial(-)} = \frac{\partial(W_S)}{\partial(A)} \cdot \frac{\partial(A)}{\partial(I)} \cdot \frac{\partial(I)}{\partial(Z)} \cdot \frac{\partial(Z)}{\partial(M)} \cdot \frac{\partial(BM)}{\partial(\ -)} ,$$

in which this partial differential is applicable only for maintenance of longitudinal strength. Evidence is given by Dr. Heller demonstrating the accuracy of the technique when applied.

TO MR. ASQUITH Mr. Asquith is correct in his assertion that cargo handling times are quite small relative to an entire voyage time of several weeks. For rough considerations or for very preliminary work, assuming them to be constant is quite acceptable. But once the design effort reaches the near-final stage, the slight extra effort required to avoid the convenience of such an assumption would probably be repaid many times over. Because 'Murphy's Law' is universally applicable, it is highly likely that the effects of all such 'mild' assumptions are cumulatively detrimental.

In discussing 'assumptions', the content of a recent paper by Cheng [1972] is brought to the reader's attention, because it also pursues the influence of parameter variations on weights and volumes. It does appear to be more rigorously analytical than the present paper, but a number of the fundamental relationships are more coarse than those used here. As an example, Mr. Cheng states that "the weight of ship structures is assumed to be proportional to the enclosed hull volume." Thus all values of 'a_s' are essentially assumed to be 1.0; whereas Appendix I of this paper defines them with much greater accuracy.

Mr. Cheng goes on to assume that all other weights are either proportional to the total weight or to the total volume. Such assumptions are often reasonable for certain studies involving the first stages of design. But that is in contrast to the content of this paper, which seeks to employ analytical techniques for the <u>refinement</u> of designs, and therefore avoids such gross assumptions.

The entire matter of assumptions, of any nature and size, at any stage in the design process, is the one aspect of design that has probably been responsible for the greatest amounts of grief, despair and financial ruin. It should be realised that while a design problem may have many possible solutions, there is only one possible 'correct' approach: make not one single assumption about the structure of the problem nor about the form of the solution.

Mr. Asquith's second comment regarding the influence of boundary conditions on the design solution can never be over-stated. The last paragraph of Section 12 does briefly discuss the matter. The reader is referred to Part II of Fisher [1971b] for a more detailed discussion of boundary conditions.

<u>PROFESSOR BENFORD</u> has written to the Author apologising for not having been able to send a comprehensive written discussion, but in his letter did mention several items meriting inclusion and reply at this time.

Firstly, Professor Benford states that the title of the paper is confusing. "How much," he asks, "do parameters cost today?"

Secondly he writes, "The general method seems to be that used by George Manning [1956] in his book on ship design, and reflects the way most ships are actually designed: take an existing successful ship and modify its design a bit here and there. This is practical, useful, understandable and inhibiting to fast progress."

Finally Professor Benford comments, "Now if we only had all the cost estimating techniques and coefficients that we lack, we'd be in business."

The Author regards each of these comments stimulating, and will reply to them in full.

The absolute cost of a specified vessel is, of course, a function of the shipbuilder's backlog of orders, the prevailing national and international economic situations, the extent of the competition's inroads into the builder's traditional and planned market, and the rapidity with which the owner wishes to take delivery of the vessel from the builder.

In other words, there is no way to accurately define the absolute cost level of a vessel in a free or market economy. But the inescapable feature is that no matter where the vessel is constructed, regardless of competition and economic climates, the *relative* cost of each parameter is going to be the same for each vessel type, size and configuration.

For example, the values of 'a_s' give a clear and accurate indication of the relative cost of hull steel for each parameter. It is acknowledged that there is a minor difference of opinion on them between the Author and Mr. Sato regarding tankers, but that difference is small when contrasted with the differences between the parameters, as indicated in Table D-VI.

discussed here and in Dr. Manning's text is, in principle, true. It is at the appropriate stage of design, or in the type of situation most amenable to the particular technique.

TO MR. OTA The reply to Mr. Ota has been left for last because a thorough understanding of its content is of very great importance. In addition, his comments help substantiate the reply to Professor Benford's discussion.

In full accord with Mr. Ota's remarks, it is important to realise that if the application of any techniques to the ship design problem gives different answers than those already planned for, then the benefits of applying those techniques cannot be obtained for a substantial amount of time.

It is quite understandable, but nevertheless regrettable, that efficient ship construction facilities are not always the best for producing efficient ships because there is a great time lag between the realisation of what constitutes an efficient vessel, and the availability of facilities to build it.

In conclusion to my replies, the Author would like to express sincere thanks to the discussers on behalf of all the future readers of this paper. The stimulating remarks and comments have ensured that the entire document including discussions, will have greater potential benefit to our profession than could have been achieved otherwise.