ECONOMIC OPTIMISATION PROCEDURES IN PRELIMINARY SHIP DESIGN (APPLIED TO THE AUSTRALIAN ORE TRADE)

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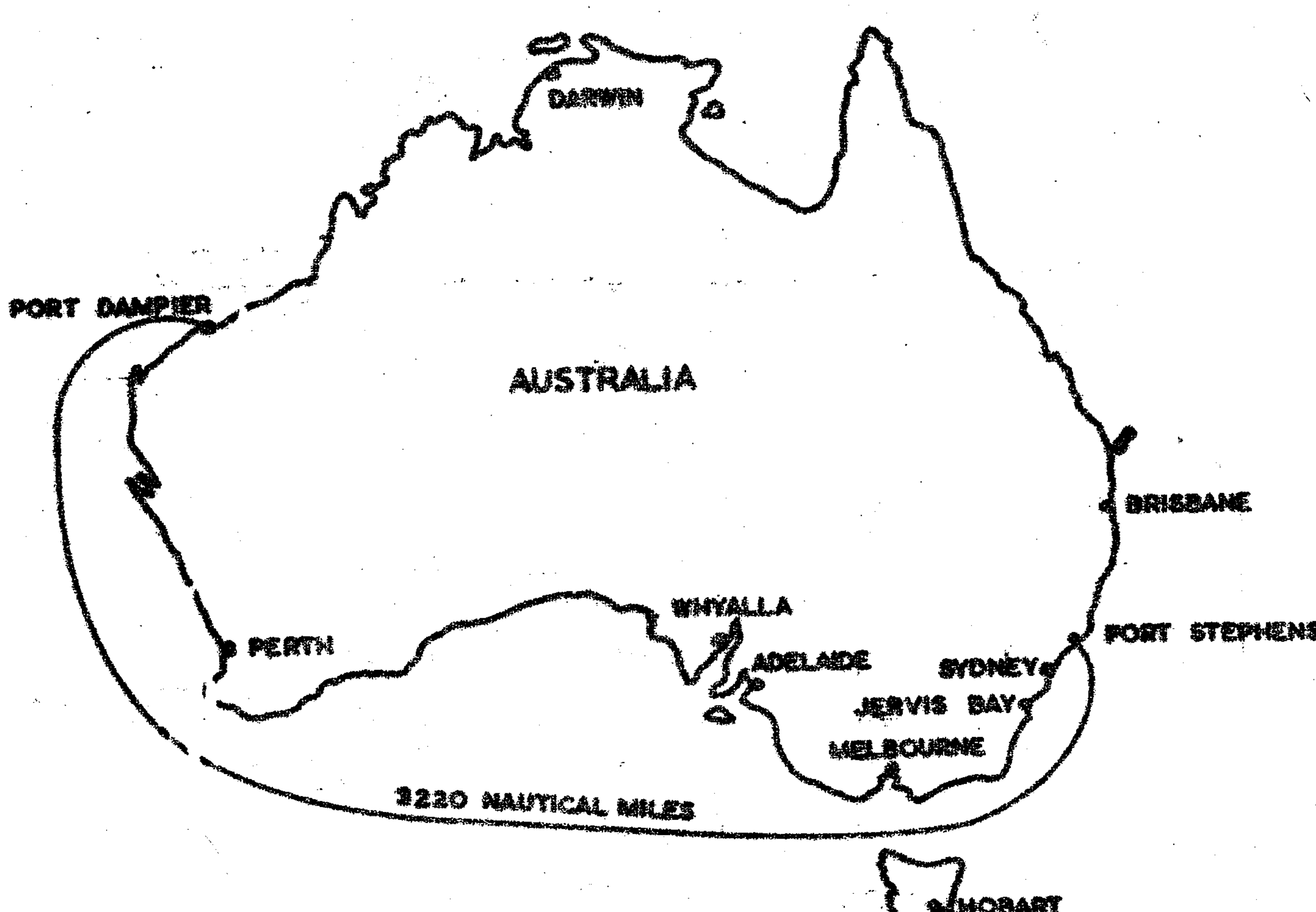
Summary

Large-volume, long-term contracts for the transportation of bulk cargoes, which have become the order of the day since the late 1960's, may be interpreted as high certainty cargo availability. That point of view can have a significant effect on the design of the fleet of vessels used to satisfy the contract of transport. Additionally, major port alterations or developments are required to effect those contracts.

Contrary to the contemporary trend that "bigger is better", this paper demonstrates that certain limits exist, unique to the conditions of each contract, which can be ascertained from the simultaneous optimisation of all parameters involved in the construction and operation of the fleet, as well as of the ports and associated facilities.

Techniques are demonstrated which can be used to find those optimum parameters. Using the example of the presently expanding Australian ore trade, optima are simultaneously found for the fleet size, principal characteristics of the vessels, expansion of shipyard facilities, port channel dredging depths and widths, and loading and discharging rates.

FIGURE 1
PORTS AND ROUTE



Introduction

In commenting on a paper by Goss (1965), Benford states that "naval architects and marine engineers have traditionally slighted or misued economics as a tool in ship design." In contrast to that, this paper presents and demonstrates techniques that enable ecomonic considerations to be the only ones that are used for decision-making in the choice of design parameters.

The thesis of this paper is that the only factors which need be considered in the preliminary design of a vessel are those factors which could have a measurable effect on the final decisions. The extent of these factors remains unknown, however, until a final design is decided upon. It is, therefore, encumbent upon the designer to account for all possibilities, ranging from considering draught restrictions to be only a form of economic penalty, to acceptance of triple-screw propulsion.*

Especially important is a clear understanding of the assumptions made in the design procedure. The number of assumptions made in design procedure is astounding when one counts them thoroughly. They range from reliance on the means of obtaining a power estimate, to approximating the economic life of the vessel.

The only correct method of design includes sensitivity tests on these assumptions and making a final choice based on the range of design parameters which may be considered "optimum" as a result of the sensitivity studies.

It is important that assumptions be as unrestrictive as possible. It is easy to say such things as "the optimum ratio of beam to draught is about 3."** It is totally unnecessary, however, to make such a judgement in a proper design procedure. In this paper, all dynamic and dimensional parameters are "free-floating." Everything from the length to the block coefficient to the speed are decided upon by economic criteria rather than conveniently expressed (and often misleading) geometric relationships.

* Recently it was announced that such an installation (72,000 BHP, triple-screw) would be made in a containership for East-Asiatic Co., Copenhagen.

** P.R.Salisbury, discussion of paper by Gilfillan (1969).

The proper choice of a design criterion has been notably lacking in the past published design procedures. That is, it has been assumed that one single design criterion suffices. In the case of merchant ship design, that criterion is, and rightly should be, an economic one. There is, however, a range of economic criteria, the field of which depends on the assumptions used (such as the proportion of capital borrowed from outside sources).

This paper presents a design method which utilises, extensively, computer assistance to assess a design problem from the point of view of a range of economic design criteria. As mentioned above, it incorporates as many factors as can be estimated or approximated; for certainly it is better to render some approximation to all factors than to disregard some of them entirely. The more coarse the approximation is, the more it should be subjected to a sensitivity study.

The major difference between this study and those of Gilfillan (1969), Murphy, et.al. (1965) and Kuniyasu, et.al. (1969) is the major one of "free-floating" dimensional parameters. Those three studies rely on a large number of permutations and combinations of physical variables (such as length), followed by the manual representation of a 4-to-7 dimensional space on a series of 2-dimensional graphs, in order to decide on the optimum.

That problem does not arise in the study by Mandel and Leopold (1966). Their study, however, utilises a random-search technique, which leaves one to question if all possible minima have been found. Also, that study limits the range of several parameters, such as B/T. Both of those problems are circumvented in this study.

Among the factors included in this paper are: the related shipyard expansion costs; the port preparation costs; and the construction of wharfage and discharge facilities suitable for the vessels of the chosen parameters.

The paper is divided into six general areas. The first main section is a statement of the problem which defines factors pertinent to the optimisation procedure. The second and third sections deal with economics. Firstly, general economic considerations are presented in section II, and the means of deciding upon the optimum design are given.

Section III deals with cost assessment for the ship as well as the shipyard and port.

Section IV is concerned with considerations of naval architecture and marine engineering which are pertinent to the design procedure. The fifth section deals with computer programmes and techniques, setting forth some of the criteria which should be used in deciding upon the type of computer assistance that should be rendered in a given situation.

As can be seen from the above, a proper design procedure necessitates a good understanding of the three areas of economics, naval architecture and techniques for design assessment, which are, in this situation, computer techniques.

Lastly, analyses of the optimum designs resulting from different choices of criteria as well as from the sensitivity studies. are presented in section VI.

I. Statement of Problem

It is easily noted from current issues of technical journals and trade magazines that the general sizes of ships and of operational contracts are increasing rapidly. The Australian press, in December 1969, stated that a contract had been signed between Japanese and Australian interests for the shipment of 100 million tons of high-grade iron-ore from Western Australia to Japan over a period of 15 years. The annual movement of crude oil on certain routes has been, for several years, several millions of tons. The associated costs are considerable, and the saving of only one cent per ton of cargo on a route could mean a savings of several hundred thousand dollars in the life of a contract of 10 or 15 years. With such sizeable sums of money involved, it becomes mandatory that the ship's major characteristics be chosen very carefully.

The situation with which this paper deals is a comparably large scale one. Briefly, a fleet of ships is to be designed and constructed in Australia for a coastal trade. The vessels are to carry iron-ore from the western part of the continent, where extremely large iron-ore deposits have recently been discovered, to the populous east coast of the continent where labour is available and where large reserves of coal are adjacent to the coast-line. The assumed purpose of this is to meet the increased demands for domestic consumption of steel as well as to begin large scale production of steel for export.

Recent newspaper reports have indicated the desirability of this exact development in an area known as Jervis Bay (see Figure 1). Avoiding that politically controversial problem, a different port on the east coast is chosen for this study which remains as the largest undeveloped potential sea port on the east coast of the continent. At present, Port Stephens is totally undeveloped except for a small tourist industry.

The design problem is to optimise the dimensions of the vessel accounting for the fact that Port Stephens will have to be dredged and developed in accordance with the size of the ships. This might be construed as a draught limitation on the vessel, but the only limitation is that of the cost of dredging the port to a sufficient depth. The preparation of wharfage and discharge and loading facilities for the bulk carriers is included in the study. (Refer to section III.2.)

Inasmuch as the trade is a coastal one, the Australian Government requires that the ships be constructed in the country. At present, the largest vessel that can be constructed at the Whyalla shipyard in South Australia is of a length of 750 ft. An estimate of the cost of constructing a new building dock for vessels larger than that has been developed with the assistance of that shipyard. It is assumed that the cost of construction at the shipyard would be borne by the owners of the ore carriers and four other interests equally. (See section III.3.)

The optimum vessel is to be decided upon by appropriate economic criteria as discussed in section II. The effect of including or excluding the port and shipyard development ccst is given in sensitivity studies reported in section VI.

At present loading facilities at Port Dampier are being developed for a loading rate of 7000 tons per hour. It is temporarily assumed that the discharge rate at Port Stephens will be 1500 tons per hour. A cost function for the ore discharge facilities has been estimated as a function of the unloading rate. (Refer section III.2.) A special study is made in section VI which allows the loading and discharging rate to be chosen by economic optimisation.

With all of these factors in mind, a fleet of vessels is to be designed according to the economic criteria discussed below which will deliver a total of 60 million tons of ore in a 15 year period. Ship construction takes place at the rate of one delivery per year. Thus the rate of ore delivery will approximate the usage rate at the new steel plant.

The route from Port Dampier to Port Stephens is around the South side of the continent avoiding the shallow reef area between the continent and New Guinea.

II. Economic Criteria

1. General Approach to Solution.

The broad approach to choosing the best vessel is quite easy to comprehend. Simply, it is to optimise a cost function which has been appropriately chosen. For comparison of alternatives, the net present value is usually accepted as the valid quantity to be optimised (Goss, 1967). In discussion of that paper, however, Benford states that he is of "the persuasion that there is no universally applicable criterion." For feasability and developmental studies, however, where interest rates and corporate taxes are known and taken into account, the required freight rate (RFR) is a valid index (Benford,1965). Thus, the optimisation procedure leads to a minimum cost of shipping each ton of cargo each year. The equation would be, in general,

RFR = F (Fleet size, ship dimensions, annual cargo movement, port facilities, union regulations, shipyard capacity, port preparation, etc.)

It should be noted that the above equation, if it could be written, would be a series of discontinuous smaller functions. (For instance, if power requirements go up, there will have to be a jump from one to two shafts.) With such an equation, a minimisation would still be quite difficult, due to the presence of over 20 variables.

As it shall be seen below, such an equation cannot be written explicitly. The RFR can, however, be obtained by a series of calculations, with some built-in self-correcting devices. In order to do that it is most important that all cost considerations be given as functions of the physical variables. If this can be accomplished prior to any decisions regarding the physical characteristics of the vessels, then it will be possible to evaluate the economic criterion function for any values of those variables.

Thus, by using computer-numerical, rather than analytical-mathematical techniques the "equation" can be minimised with respect to all the variables simultaneously, which is not necessarily at a point which is a minimum with respect to a single variable.

2. Specific Approach to Solution.

For this study, the RFR equation is the entire procedure incorporated into the flow-diagram of Figure 4 , Iterative Procedure for Dimensional Requirements. It should be noted that the block labeled "cost evaluation" includes all capital expenditures (shipyard expansion, dredging etc.) as well as the appropriate annual costs. The exact method employed is shown in Figure 2 , Rationalisation of Cost Assessments. The notation used in that figure is:

[CRF]	Capital Recovery Factor.
[SFF]	Sinking Fund Factor.
[UPWF]	Uniform Present Worth Factor.
[SPWF]	Single Present Worth Factor.

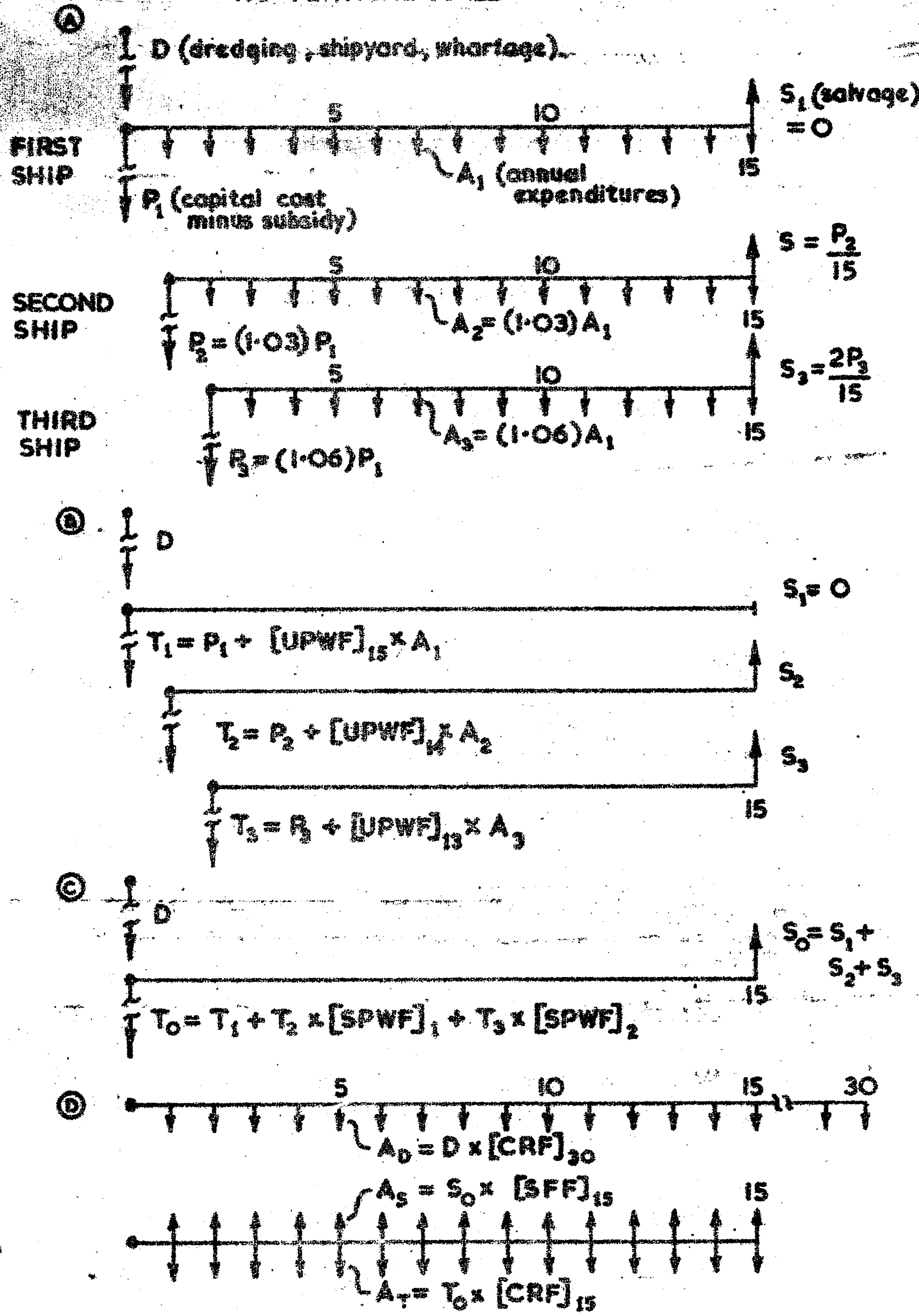
The subscripts refer to the number of years.

At the same time that an appropriate criterion is being chosen, it is necessary to decide upon an appropriate equivalent rate of interest that is to be used for the calculations. Without the proper choice, erroneous weighted values will be given to the initial and operating costs. As Benford (1968) points out, not only is the equivalent rate of interest important, but also the optimisation of the design depends on the corporate profits tax, the bank interest rate on borrowed capital, and the ratio of borrowed capital to owner's capital. All economic factors used in this study incorporate those effects. In Appendix I is shown a computer subroutine which calculates, using an iterative procedure, the equivalent before-tax economic functions accounting for the after-tax rate of interest, the corporate tax rate, the bank interest rate, and the ratio of borrowed capital to owner's capital.

The range of the RFR as the economic factor is determined by the costs that are included in its evaluation. Murphy, et.al. (1965) used only the ship construction cost in their economic criteria. More recent studies have widened the field included in the determination of the RFR by adding to it the time value of annual expenditures. Kuniyasu, et.al. (1969) limited their study, however, to three cases in which several of the dimensional parameters are fixed.

FIGURE 2

RATIONALISATION OF COST ASSESSMENTS
(EXAMPLE FOR THREE SHIPS)
NO VERTICAL SCALE



Ⓔ $\text{R.F.R.} = \dfrac{A_D + A_T - A_S}{\text{(average annual cargo)}}$

This study continues to widen the field by accounting for corporate taxes, bank interest and borrowed capital ratio. Additionally, the five-parameter* studies account for the possible port preparation, wharf construction, and shipyard expansion.

The seven-parameter studies widen the field more by including independently determined loading and discharging rates, limited only by the cost of purchasing the equipment to achieve those rates. Careful consideration of these factors, which are not an integral part of the vessel, reveals that their inclusion into the determination of the RFR is necessary to ascertain the real cost of moving the ore from port to port.

Equally, as will be seen in section VI, the inclusion of the economic impact on the ship design by the shore-side facilities can lead to lower costs in the final analysis.

Although the detailed study of the desirability of controllable pitch propellers is not wholly entered into in this paper, the well-founded detailed study by Ridley and Midttun (1970) is easily incorporated into an optimisation procedure such as this one. The important aspect to note, however, is this: a feasibility study for such a detail as that, or any other potential economically beneficial alteration, should not be carried out on a design which is "optimum" for fixed-pitch propellers. Rather, a new "optimum" should be found which utilises, from the start of the "search", the benefits of the new technological change. Then, the value of the function being minimised that results from those two different optima should be compared. An example of this is given in section VI.

Thamm (1970), in presenting a comparison of nuclear and conventional power plants for a bulk carrier, optimises only the power (and, subsequently, the speed) of a single design utilising either form of primary propulsion.

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* The five parameters represent independently determined: cargo capacity, length, beam, draught, and block coefficient.

The results of his study can be said to show trends only for that vessel of fixed principal characteristics. A more meaningful analysis would consist of fixing, for example, the annual required transport capacity. Then the minimum RFR for two vessels having optimised principal characteristics, one for nuclear power and the other for conventional power, would result in a valid comparison.

All capital costs related to the vessel are considered to be effected by straight-line depreciation for 15 years. Capital expenditures related to dredging, shipyard expansion, and port preparation are depreciated linearly for 30 years.

III. Cost Assessments

1. Port Dredging.

With the aid of the Maritime Services Board of N.S.W., an estimate of the cost of dredging Port Stephens as a function of the major dimensions of the vessel has been developed. The cost includes the dredging of a main channel 10,000 yards in length and of a depth of 110% of the draught. The width of the bottom of the channel is to be six times the beam of the ship with sides having a 1:4 slope, and a turning basin is to be included at diameter $2\frac{1}{2}$ times the length. It is assumed that the cost of this development will be shared equally by the developed steel industry with three other industries which would use the port. It is, however, assumed that the dredging will be to the specifications of the ore ships.

An estimate was made, considering the present bottom contours of the port, of $A15 million for dredging to a depth of 36ft. and a width of 600 ft., including a turning basin for a 600ft. ship. For ships requiring channels and turning basins of other dimensions, it is estimated that the cost of removal of additional material is $A1 per cubic yard. With this information a convenient estimate for the cost of dredging as a function of the vessels' principal dimensions, can be made.

2. Wharf and Discharge Facilities.

The cost of constructing a wharf appropriate for the given vessel is estimated in the following manner. The length of the berth should be 150ft. greater than the ship length. The cost is estimated at $A1500 per ft. of length at a 36ft. total depth, and $A2500 at a 45ft. depth, with linear interpolation and extrapolation assumed valid.

The cost of discharge facilities was unavailable to the author, but consistent with previously mentioned necessities of approximating rather than neglecting ,the ore discharge facility is estimated to cost $A300,000 plus $A500,000 per 1,000 tons per hour discharge rate. The loading facilities are estimated at $A200,000 + $A200,000 per 1000 tons per hour.

Sensitivity studies in Section VI are used to demonstrate what the "optimum" loading and discharging facilities are, when they are not assumed constant at 7000 and 1500, respectively.

3. Shipyard Expansion.

Although a general cost function of the size of a graving dock is a most desirable item for this study, it was unavailable in the preferred form. As a result of a study performed for the Whyalla shipyard, a detailed estimate revealed that it would cost $A12 million to establish a graving dock to accommodate the construction of a vessel of 150,000 DWT.
The result of that study produced the following approximate criteria for estimating the cost as a function of the size of the vessel to be constructed therein.

(i) If the L.B.P. is less than 750ft., a new construction is unnecessary.

(ii) If construction is necessary, the costs of cranes, electrics, etc. is $A6 million regardless of the size of the vessel to be constructed therein.

(iii) The cost of pilings, tracks, etc. is proportional to $A3 million times the ratio of the L.B.P./950 (in which the 950 is the assumed length of 150,000 DWT vessel on which cost analyses are based).

(iv) Excavation costs including concrete, pumps,etc. is equal to $A3 million times the ratio of the product of the length x beam x draught divided by the product of the dimensions for 150,000 DWT vessel (950 x 145 x 52.5).

4. General Construction Costs.

The cost for constructing bulk carriers is based on detailed cost estimates published in special surveys of "The Motor Ship" for the past several years. Those estimates are for the total construction of a 72,500 DWT bulk carrier.

Based on that information and similar information from previous issues for a 23,100 DWT bulk carrier, the cost of constructing vessels in the U.K. is obtained with sufficient accuracy. The cost of machinery has been obtained from information supplied by a Northern European manufacturer of large-bore slow-speed diesels. The figures supplied by that manufacturer are pertinent for a shipment from the point of manufacture.

The major problem encountered at this point is to ascertain the cost of ship and engine construction in Australia relative to that of the U.K., and the country of the engine manufacturer. A study performed by Chapman (1969) indicates that the ratio of Australian to British shipbuilding costs for tankers has been measured at values between 1.8 and 2.1 for several selected situations. Inasmuch as ship construction in Australia is subsidised to the extent of reducing the owner's cost to the equivalent British cost, it might be appropriate to use the subsidy ratio as a guide. At the time of writing, that ratio stands at 1/3. Recently, however, a large number of hearings have been held to ascertain whether that ratio should be altered. It is the author's opinion that such a full-scale hearing, having obtained both confidential and public information, would be a better guide than the small amount of information obtained by the author. The conclusions of the board have not, however, yet been released to the public at the time of writing. Lacking in further guidelines but feeling that the present ratio of 3/2 is too low, the author has used a slightly modified ratio of 1.55 with reluctance.

Confidential information received by the author indicates a similar situation for the construction of main propulsion units. The sole manufacturer of such engines in Australia is the Commonwealth Government Engine Works, a licensee of the Northern European manufacturer from whom information was obtained. Again, for lack of sufficient justification the same ratio has been used to estimate the cost of engine construction.

5. Detailed Construction Costs.

The cost for construction in the U.K. in 1969 is given by the following. The cost of steel construction including labour varies linearly from approximately £91 per ton at 6,000 tons of steel to £83 per ton at 12,000 tons of steel.

The cost per ton of outfitting is independent of size at approximately £697 per ton of outfitting. That outfitting is for a basic complement of 32 men. Additional outfitting cost for a crew larger than 32 is estimated by £32,000 $(N-32)^{0.56}$ (Ref:Buxton, 1967) Miscellaneous costs including owners' costs are assessed at £30 per ton of lightship. These costs refer to British construction.

The cost of main engines is given as a function of engine size in Table I . From the "motor ship" surveys it has been determined that, for bulk carriers employing slow-speed diesel engines for main propulsion, the total cost of machinery, including hull engineering, is 2.28 times the cost of the main engine.

6. Multiple Construction and Subsidy.

Benefits accrued from multiple ship construction are given by Couch (1963). Based on his work, the average cost for ships constructed in Australia is estimated by:

$$\text{Average Cost} = \frac{\text{First Cost}}{(\text{N-ships})^{0.09}} .$$

McNeal (1969) suggests that a more refined approach be taken to the calculation of multiple construction benefits. Briefly, he points out that there are different "learning" rates for labor, materials and overhead. Moreover, during the construction of a fleet of vessels, the "purchase" of those three commodities occurs at different times over differing intervals. Inasmuch as such learning rates are highly dependent on the managerial history of the shipyard, as well as its total productivity, it is believed that the application of McNeal's method would introduce unrealistic accuracy into this study.

Table 1

Marine Diesel Engines

Max. Cont. BHP_{met} (÷ 1000)	No. of Shafts	Cylinders per Engine	Mach'y Space Length (meters)	Total Mach'y Weight (metric ton)	Main Engine Cost* (U.S. $1000)	Cylinder Bore (cm.)	Total Crew
10.0	1	5	22.2	760	596	76	41
12.0	1	6	23.5	880	718	76	41
14.0	1	7	25.0	1010	819	76	41
16.0	1	8	26.4	1130	930	76	41
17.4	1	6	26.9	1210	920	90	41
20.3	1	7	28.8	1380	1060	90	41
23.2	1	8	30.7	1550	1200	90	41
26.1	1	9	32.6	1720	1340	90	42
29.0	1	10	34.5	1880	1480	90	42
32.0	1	8	36.3	2160	1674	105	42
36.0	1	9	38.2	2425	1860	105	42
40.0	1	10	40.1	2685	2047	105	43
44.0	1	11	42.0	2940	2234	105	43
48.0	1	12	43.9	3165	2420	105	43
52.2	2	9	32.6	3450	2680	90	53
58.0	2	10	34.5	3760	2960	90	53
64.0	2	8	36.3	4320	3348	105	53
72.0	2	9	38.2	4900	3720	105	53
80.0	2	10	40.1	5370	4094	105	55
88.0	2	11	42.0	5890	4468	105	55
96.0	2	12	43.9	6330	4840	105	55

*ex. Northern Europe, 1970

Bore (cm.)	Fuel Rate** (lb./SHP/hr.)	R.P.M.
76	0.357	122
90	0.357	122
105	0.355	108

**Calorific value 17000 BTU/lb.

For that same reason, the constant 0.09 is taken as a localised approximation to Couch's 0.097.

The construction subsidy for this study is based on this average construction cost taking into account the fact that the basic construction costs for vessels increase arithmetically at the rate of 3% per year.

The exact manner that would be employed by the Australian Shipbuilding Board to ascertain the subsidy is unclear at the time of writing. It is believed, however, that the above method of approximating the subsidy is a reasonably representative one.

7. Annual Operating Costs.

As in the situation for construction, it is assumed that the annual operating costs for each vessel will be proportional to the costs for the first vessel but will increase by the same percentage that the construction costs increase. For example, the third ship constructed in the fleet will have annual operating costs of 106% of the first ship constructed, inasmuch as its completion date will be two years later. The detailed annual operating costs are obtained from information given by Benford (1965) and Gilfillan (1969). Those costs are listed in Appendix II. The appropriateness of these costs is studied in section VI where sensitivity studies are performed for several variations of annual costs.

It should be noted that crew costs are expected to rise geometrically with an annual real growth rate of 3%, whereas all other costs are expected to rise arithmetically (ref: Goss, discussion of paper by Gilfillan, 1969). Also, mid-life values of annual costs are used for all other categories.

Insurance costs were ascertained from the Australian representative of Lloyds. Insurance rates are considered to remain constant throughout the life of the vessel since the premium per unit value will rise with the age of the vessel, but the value will decrease. This presupposes a good maintenance history by the shipowner.

It should be noted that for large ships there is considerable debate as to proper insurance premiums. It was with reluctance that figures for insurance premiums were given as a function of the deadweight. It is believed, by the underwriters, that the rates should be a function of the vessel's dimensions, rather than its cubic capacity. Such formulations, however, have not yet been adequately tested to guarantee their validity. Insurance costs are subjected to sensitivity studies in section VI.

8. Salvage and Resale Value.

As mentioned in section I, the design problem centres on a 15 year contract. Costs are minimised, based on the assumption that the fleet would be sold off at the end of that 15 year contract. Whether this is, in fact, an exact method is doubtful. It does, however, assign appropriate costs and returns to the life of the contract. The salvage value of the first ship is considered to be zero at the end of this 15 year life. The salvage value of the second ship is approximated by 1/15 of its initial cost; the third vessel at 2/15, etc. Again, the accuracy of these estimates are subject to sensitivity studies in section VI.

IV. Naval Architecture.

In this section, will be set forth the considerations, assumptions and criteria necessary for the complete design that falls in the domain of the naval architect.

In a number of instances it has been assumed that certain relationships are valid over a range which is much wider than can be properly substantiated. This is of concern only if the final designs are outside the range for which the validity of the relationships can be established. It is necessary, however, that such quantitative values be available to the computer programmes, in order to avoid putting artifical and unnecessary boundaries on the possible designs. For instance, it is recognised that the powering estimates will be low for higher speeds ($V/\sqrt{L} > 0.75$). If the final optimum design requires such high speeds, then more work should be done towards developing better estimates of high-speed full-form hull powering requirements, for it would appear, then, that it is an economical region in which to operate ships.

With these considerations in mind, the relationships and assumptions that have been utilised in the design processes are given in the following sections.

1. Voyage Information.

Given the number of vessels in the fleet and the cargo capacity of the vessel, the speeds required for the loaded and ballasted voyage are calculated from the required total cargo movement in the 15 year contract over the distance of 3220 nautical miles. This design programme assumes that ballast speeds are 15% greater than the loaded design speed. It is calculated using the following additional estimates.

(i) 3 hours are lost to manoeuvring upon each entry to or exit from a port.

(ii) Each vessel is out of service 15 days in its first year, and is out of service one additional day per year thereafter.

(iii) 8% of the time at sea (loaded and ballasted) is lost to bad weather.

(iv) Bunkering takes place while the vessel is unloading at Port Stephens.

(v) The total number of round trip voyages available from the fleet over the 15 years is based on the delivery rate of one vessel per year.

2. Stability.

As will be noted in flow diagrams (Figure 4), the computer programmes alter the beam of the proposed vessel until the GM is at least 6% of the beam. The general assumption regarding the vertical centre of gravity is that its position is 57% of the depth above the keel. (This figure is subject to sensitivity studies in section VI.) Other necessary relationships are given as follows.

(i) The prismatic coefficient is written by

$$C_P = 0.04 + 0.96C_B$$

(ii) The water-plane coefficient is a function of the prismatic coefficient and the number of propellers. They are considered as a pair of straight-line functions given as follows:

Single screw $C_p < 0.85$: $C_w = 0.878C_p + 0.164$

$C_p > 0.85$: $C_w = 0.600C_p + 0.400$

Twin screw $C_p < 0.80$: $C_w = 0.745C_p + 0.264$

$C_p > 0.80$: $C_w = 0.700C_p + 0.300$

(iii) The vertical centre of buoyancy is estimated from

$$KB = T\cdot|0.71 - 0.21(CB/CW)|$$

(iv) The position of the metacentre requiring an estimate of the water-plane inertia is given by the following two relationships:

$$C_i = 0.1385C_w - 0.0552$$

$$BM = (C_i/C_B) \cdot (B^2/T)$$

The above relationships are derived from Wright (1969) and Nevitt.

3. Freeboard.

A computer subroutine has been written which estimates the required basic minimum summer freeboard for bulk carriers including all corrections according to the 1966 load line convention. The subroutine is shown in AppendixIII. According to Murray-Smith (1969) it is difficult to assign basic minimum freeboards for bulk carriers according to the 1966 convention without detailed design of the vessel. Inasmuch as they are likely to be "fairly close to the basic freeboards agreed for tankers in the 1930 convention", they are utilised in this study. It is assumed that the designed bulk carriers have no sheer. The required freeboard is compared, in the computer programme, to the freeboard arrived at from volumetric requirements, and the larger of the two is used.

4. Weights.

The estimate of weights is divided into the categories of steel, outfitting and machinery including hull engineering. The machinery weights are obtained from information supplied by the diesel manufacturer and is contained in Table I.

The weight of steel is estimated from three methods, the average of which is used. The three methods are given in detail in Appendix IV. The first two methods require a detailed weight estimate for a specified vessel. That weight is projected to other vessels by differing degrees of reliance upon the dimensions of the new vessel. The first method derives the steel weight from an estimate of the area of longitudinal steel at midships. The second method uses a cubic number coefficient approach.

The third method is based on the equation of Murray (1965) that uses a corrected initial coefficient. The closeness by which each method predicts the steel weight, is shown in Table II.

It may be noted that vessel "A" is the one on which detailed cost estimates are based; vessel B is the one on which weight estimates for the first two methods are based; and vessel C is the smaller vessel on which the linearly varying steel cost estimate is based.

Table 2

Weight Comparisons
for Steel and Outfitting

Vessel A: 760' x 104' x 59' x 43' x 0.82

Vessel B: 795' x 105' x 61' x 44.5' x 0.84

Vessel C: 562' x 71.8' x 48' x 34.3' x 0.75

Vessel	A	B	C
Steel Wt., Method 1*	11,181	12,484	4,330
Method 2*	11,180	12,366	4,317
Method 3*	11,115	12,367	4,798
Average	11,159	12,405	4,482
True Value	11,180	N.A.	4,500
Outfitting Wt.	1,480	1,522	925
True Value	1,480	N.A.	950

(N.A. = Not Available)

* Method 1: Area of Midship steel.
Method 2: Cubic Number Coefficient.
Method 3: Murray's Equation.

The outfitting weight is based on a square number method also given in Appendix IV.

The deadweight is taken as the weight of the cargo, the weight of fresh water and miscellaneous weights (estimated at 300 tons), plus 60% of the weight of the fuel. The 60% factor is derived from considering the ship to be fully bunkered at the beginning of its ballasted voyage and to not consume the 10% fuel margin.

The lightship weight is taken to be 103% of the combination of the steel, outfitting and machinery weights.

5. Lengths.

The following relationships have been used in this study.

(i) The LWL is 103% of LBP.

(ii) The forepeak length is taken to be $5\frac{1}{2}$% of LBP.

(iii) The afterpeak length is $3\frac{1}{2}$% of LBP (These two figures are based on data presented by Gilfillan (1969)).

(iv) The superstructure length is the sum of the forepeak, afterpeak and machinery space lengths.

6. Powering.

The required shaft horsepower is estimated from a series of equations which have been derived from the work of Gertler and Taylor. The equations and the computer subroutine incorporating them are given in Appendix V . In order to demonstrate that the resultant values of the residual resistance coefficient are close approximations to those set forth by Gertler, Table III is presented.

From that table it can be observed that the derived equations give lower values at the higher speeds. As will be seen in section VI, that discrepancy is of little consequence since the optimum designs fall in the range of lower speeds where the accuracy is much greater.

Frictional resistance is estimated from the ITTC correlation line with an additional allowance of 0.004. The wetted surface is estimated from Saunders' graphs at $C_M = 0.993$ All other assumptions are apparent in Appendix V , and agree with the machinery requirements as set forth in sub-section 7.

Table 3

Comparison of Residual Resistance Coefficients

C_R: G = Gertler-Taylor
A = Approximation for this study

$\frac{B}{T}$	C_P	*$C_{VOL} \times 10^3$	$C_R \times 10^3$ @ $V_K/\sqrt{LWL}$							
			0.5		0.6		0.7		0.8	
			C_{R-G}	C_{R-A}	C_{R-G}	C_{R-A}	C_{R-G}	C_{R-A}	C_{R-G}	C_{R-A}
3.00	.70	5.	.60	.62	0.63	.72	0.88	.94	1.31	1.39
		6.	.67	.67	0.72	.77	0.97	.99	1.38	1.44
		7.	.73	.72	0.82	0.82	1.04	1.04	1.49	1.49
	.75	5.	.62	.66	0.74	0.81	1.11	1.13	2.00	1.73
		6.	.69	.71	0.82	0.86	1.20	1.18	2.10	1.78
		7.	.73	.76	0.92	0.91	1.25	1.23	2.20	1.83
	.80	5.	.68	.72	0.97	0.94	1.48	1.39	2.82	2.17
		6.	.73	.77	1.02	0.99	1.52	1.44	2.94	2.22
		7.	.78	.82	1.06	1.04	1.57	1.49	3.03	2.27
2.25	.75	5.	.48	.47	0.58	0.62	0.99	0.94	1.61	1.54
		6.	.55	.52	0.67	0.67	1.08	0.99	1.73	1.59
		7.	.62	.57	0.72	0.72	1.15	1.04	1.80	1.64
	.80	5.	.51	.53	0.75	0.75	1.50	1.20	2.09	1.98
		6.	.58	.58	0.81	0.80	1.62	1.25	–	2.03
		7.	.64	.63	0.88	0.85	1.73	1.30	3.00	2.08
3.75	.75	5.	.82	.75	0.85	0.90	1.12	1.22	1.85	1.82
		6.	.88	.80	0.89	0.95	1.22	1.27	1.95	1.87
		7.	.95	.85	0.97	1.00	1.30	1.32	2.05	1.92
	.80	5.	.84	.81	0.97	1.03	1.50	1.48	2.69	2.26
		6.	.90	.86	1.05	1.08	1.59	1.53	2.82	2.31
		7.	.96	.91	1.12	1.13	1.67	1.58	3.02	2.36

$$* C_{VOL} = \frac{\text{Displaced Volume}}{(L.W.L.)^3}$$

7. Machinery.

The machinery used for this study is a series of large-bore diesel engines from a single manufacturer. The series of engines available are given in Table I .

Essentially, the use of a series of discrete sized engines means that the next larger sized engine is used for intermediate values of SHP. The engine chosen is one having a maximum continuous rating of 120% of the trial SHP, which is derived as in the above section. Also, then, the machinery weights, the engine room length, and the number of crew are a series of step functions.

For this study the number of crew has been estimated in accord with the machinery requirements, since that plays the largest role in the determination of the manning requirements for a vessel. The sizes of the crew are also presented in Table I .

The effect of using a controllable pitch propeller instead of a fixed pitch propeller has the following effects as summarised by Ridley and Midttun (1970).

(i) Manoeuvering time is reduced by one third.

(ii) Machinery maintenance and repair costs are reduced by one fourth.

(iii) The net added capital machinery cost is $50,000 per vessel.

V. Computer Techniques and Programmes.

1. General Problem.

From the point of view of seeking an optimum set of principal characteristics, resulting in a minimum RFR, the mathematical behaviour of the general "equation" for RFR should be considered.

Firstly, the problem is non-linear; not a simple non-linear problem, but one which cannot even be approximated by a series of linear segments. "Highly non-linear" would be an appropriate term to use. In order to understand that, one should ask, of every factor: what is the relationship between the RFR and that factor (which might be, for example, the design speed of the ship). Since it cannot be written in the form:

$$RFR = a_1 V_k + a_o ,$$

it is non-linear. Nor can it even be approximated by a function like

$$RFR = \sum_{i=0}^{i=N} a_i (V_k)^i , \quad N \approx 25.$$

Therefore, to seek its minimum value is a task beyond ordinary analytical mathematical techniques.

Secondly, it is such an irregular type of function that ordinary numerical techniques, such as those utilising graphical assistance, are inadequate. The solution is, therefore, obtained by turning to numerical techniques of higher order which search for the optimum. This is complicated by the presence, in the five (or more) dimensional space, of a large number of crests and valleys, occurring from such considerations as a number of discrete power-plant sizes. It is important, therefore, to be able to find the global minimum, and not merely a local minimum.

Nowacki (1969) discusses the relative benefits and shortcomings of each of eleven recognised classes of techniques. The one chosen for this study is characterised as a multivariate direct search.

Nowacki considers it to be the most efficient class of technique that does not require a derivative of the function (RFR) for which the minimum is sought.

There are available about a dozen such direct search methods, of which one need be chosen. Box (1966) examined four of them, and tested each for efficiency and failure rate for each of two, three, five, ten and twenty dimensional spaces. As a result of that study, the method of Nelder and Mead (1965) was chosen for utilisation in this design optimisation.

The number of trials required by such direct search methods (i.e., the efficiency) is a function of the accuracy desired to satisfy a problem. Additionally, it is also dependent on the type and internal accumulative accuracy of the computer. Box's study involved three different types of computers, which substantially aided in the selection of the method.

One short-coming of all available techniques is that the parameters to be optimised cannot be discrete values. Thus, whilst one of the parameters in this study is the number of ships in the fleet, that parameter could not be included in the optimisation programme.* The minimum RFR was obtained, therefore, for several values of the fleet size.

The accuracy criterion is stated for an N-dimensional optimisation as:

$$\sum_{i=1}^{N} \frac{(R_i - \bar{R})^2}{N} \leq (ACC)^2 ,$$

in which R_i is an ascertained value of the RFR, $\bar{R}$ is the mean value of the lowest N values of RFR, and ACC has a specified numerical value. For these studies, ACC = 0.002.

Nelder and Mead's method is constructed in such a manner that the final values of the optimised parameters are those corresponding to the minimum value of the function, and not merely the last one to be evaluated (which falls into the N cases) which satisfies the accuracy criterion.

(* It is awkward to construct and operate 2.79 ships.)

2. Specific Application of Minimisation Technique.

In this study, the minimisation technique of Nelder and Mead has been used with five, six, and seven parameters. For most of the sensitivity studies, the five parameters were:

(i) The cargo capacity of each vessel.

(ii) The difference between the LBP and a mean statistical value approximation given by:

$$LBP_O = 18.3 \times (DWT).^{1/3} \; *$$

(iii) The difference between the C_B and a mean statistical value approximation given by:

$$C_{B-O} = 0.968 - 0.269 \times V_k / \sqrt{LBP} .$$

(iv) The length/beam ratio.

(v) The beam/depth ratio.

The input information consists of a first estimate of these five parameters, which are given by the vector of five components: (100, 20, 0.03, 7.00, 1.67). Also, an incremental vector for those same parameters is given by: (20, 5, 0.005, 0.3, 0.02). In the course of operation, the optimisation programme alters those values in such a manner to give the final values for a minimum RFR. An example of final values of those two vectors is: (106.46, 12.063, 0.0328, 7.6976, 1.6184) and (0.77, 0.413, 0.0007, 0.0248, 0.0065).

In the six-parameter study, the additional vectorial components were estimates, leading to final values, of the discharge rate of cargo, in thousands of tons per hour. The initial values of the components in the two vectors were 1.5 and 0.2. This change in the programme itself consisted of altering only 5 statements (out of about 1000).

The seventh variable introduced was the loading rate of cargo, for which the corresponding initial values were 7.0 and 0.2 for the seventh component of the two vectors. For this last situation, the programme searched for values of each of those seven parameters that resulted in a minimum RFR. Consequently, the principal characteristics of the vessel, as well as the loading and discharge rates,

* Units of long tons and feet.

were all determined independently, avoiding the need to use such fixed relationships as: beam = 0.146 x LBP - 3.4 (Gilfillan, 1969).

The reason for using the five-parameter minimisation for most instances, and using the six and seven-parameter optimisation for few, rests on the low credibility of the cost estimates of the loading and discharge facilities. Because those figures are the least reliable in this study, they were used as static, rather than optimised, parameters in most sensitivity studies.

The average number of trials involved for the five-parameter studies was 66 of which 44% were improvements (lower values of RFR) on the previous minimum. For the six and seven-parameter studies the average numbers of trials were 81 and 83, respectively.

3. Programme Details.

In order to guarantee a reliable, well-tested programme, a series of sub-programmes were developed, each of which were tested prior to use in the main programme. In Table IV are listed the more important ones, with a brief description of their use.

A second advantage to the use of semi-independent sub-programmes is their potential interchangeability. The sub-programme MCHNRY could be easily exchanged for a comparable one which is based on either a conventional steam turbine main propulsion plant, a nuclear-power plant, or a medium speed diesel primary propulsion system. New optima could be determined readily for each type of plant, assuring valid comparisons between the several types of propulsion machinery installations.

The general lay-out of the programme is given in Figure 3 . The box labelled "Iterative procedure to satisfy dimensional requirements" is a substantial part of the programme itself. It is shown in Figure 4. Numerous flow diagram insets can be given which make up that iterative procedure. Figure 5 is but one example, included here in order to demonstrate the type of flow diagram sub-structure that is required prior to writing a programme.

To assure that a global minimum was found, several optimisation trials were started at an initial cargo load of 300 kton.*

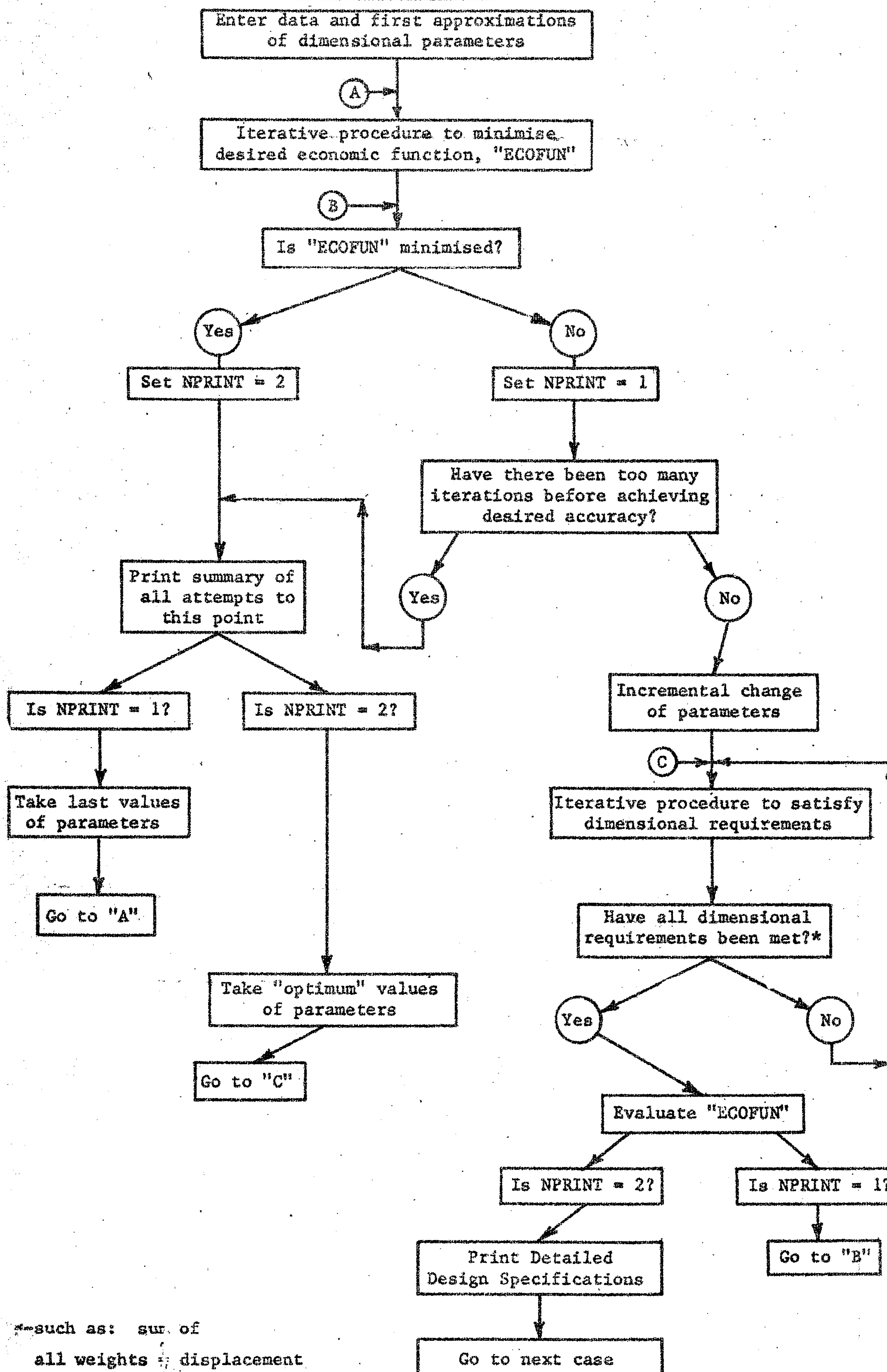
* kton = kilo-tons.

Table IV

Sub-programmes used in RFR Minimisation

NAME	PURPOSE
FUNMIN	Minimises an unconstrained function of N variables by method of Nelder and Mead (1965).
ECOFAC	Computes the before-tax economic factors CRF, SFF and SPWF for a given after-tax rate of interest, a given bank interest rate, and a specified borrowed-capital ratio.
FREBRD	Uses the 1966 Load Line Convention to determine the basic minimum summer freeboard for bulk carriers.
POWER	Calculates the design shaft horsepower for a bulk carrier of specified dimensions, accounting for the possibility of twin-screw propulsion.
MCHNRY	Returns the characteristics of a machinery plant utilising large-bore, slow-speed diesels, based on a given required maximum continuous SHP.
HULL	Calculates the weight and cost of steel and outfitting for a bulk carrier, using methods described elsewhere in this paper.
STBLTY	Computes the approximate stability factors for a bulk carrier of specified characteristics.
VOYAGE	Calculates the times and speeds involved in each voyage of a vessel carrying a specified amount of cargo, such that a given total amount will be carried by the fleet in NY years. Assumes vessels are added to the fleet at rate one per year.
DREDGE	Calculates the cost of dredging Port Stephens to accommodate a vessel of specified characteristics; calculates cost of preparing one wharf for same size vessel; computes cost of loading and discharging facilities; and calculates the cost of constructing a graving dock at Whyalla to suit vessel's dimensions.

Figure 3
Overall Flow Diagram



*such as: sum of all weights = displacement

Figure 4

Flow Diagram for Iterative Procedure
to satisfy Dimensional Requirements

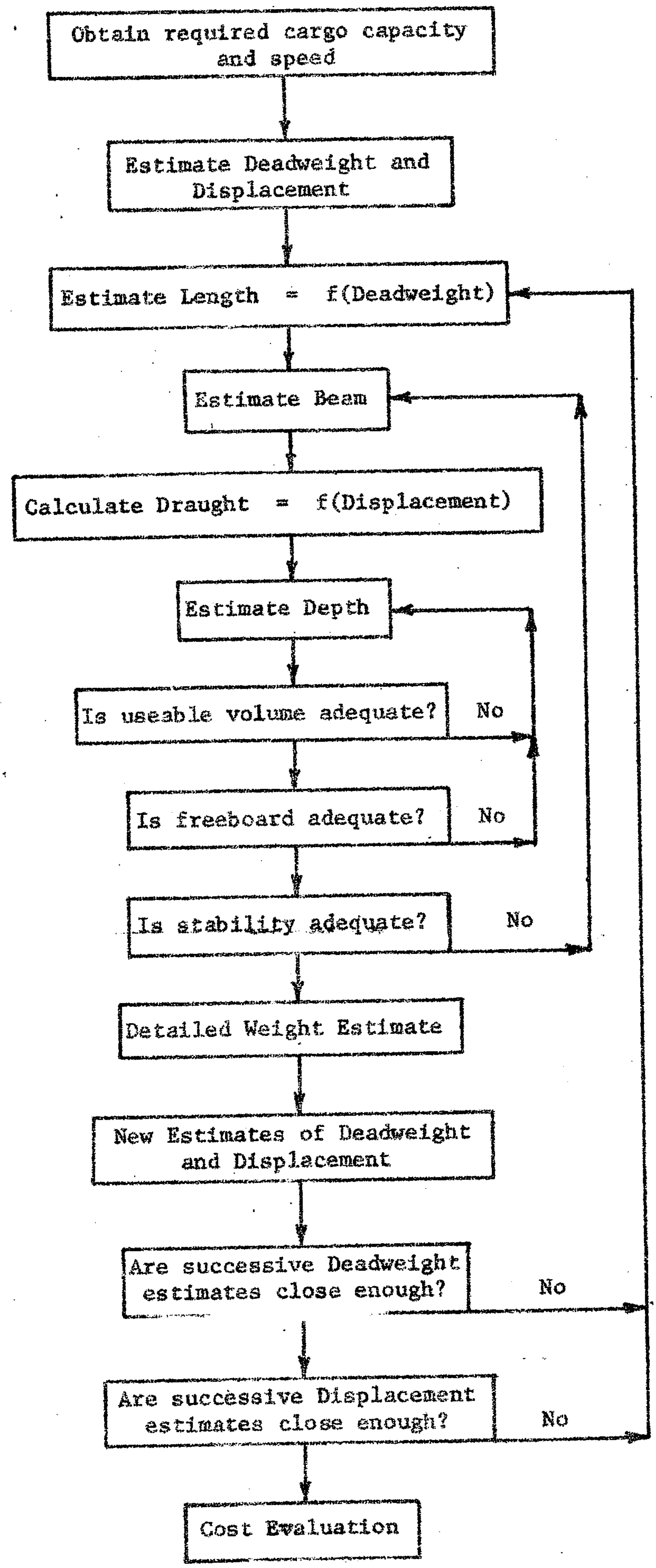
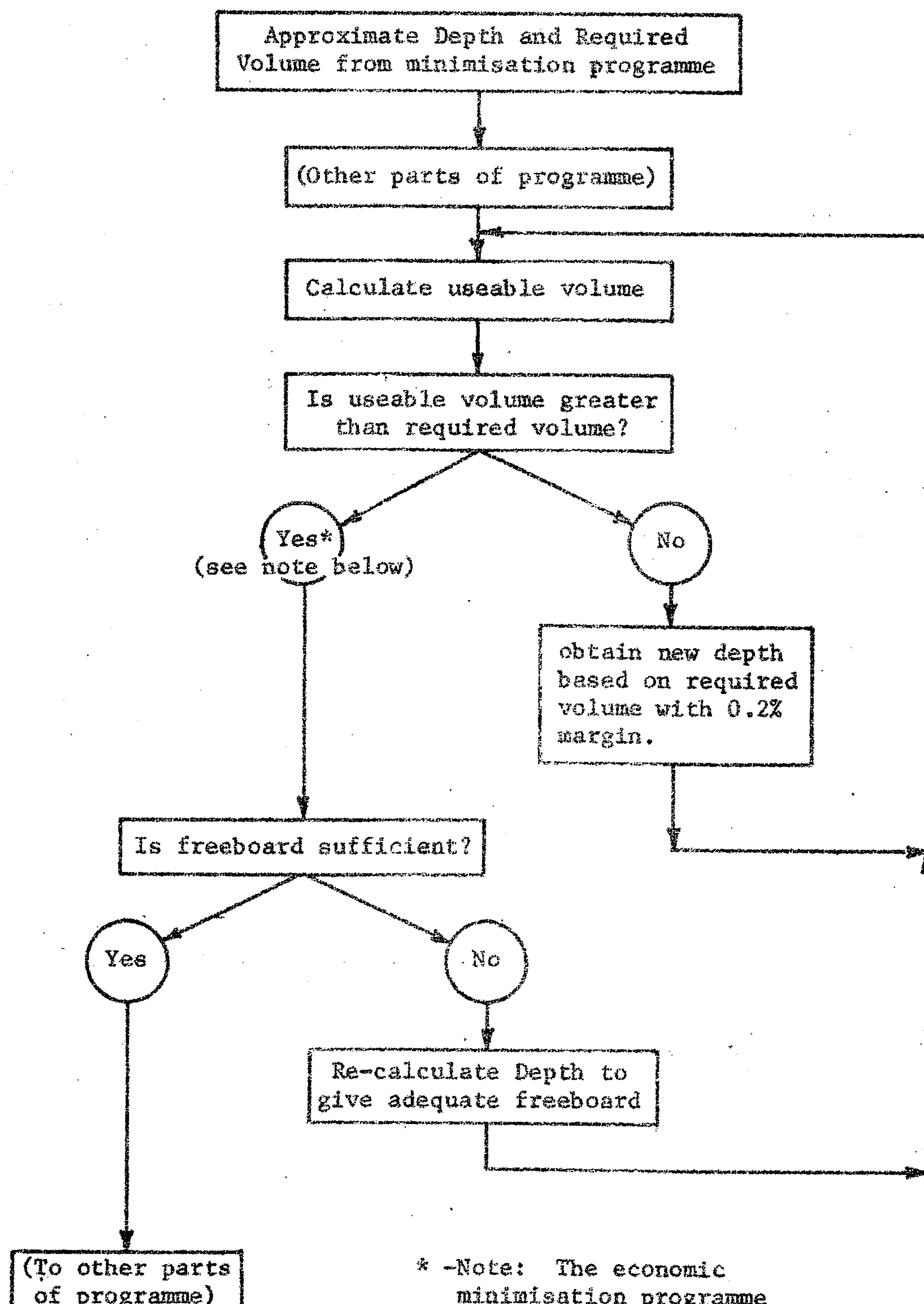


Figure 5

Flow Diagram Inset for
Calculation of Depth



* -Note: The economic minimisation programme ensures that the useable volume will not be significantly larger than the required volume.

The summary output indicates that the search swept from 320 kton down to 51 kton, with the length going below the critical 750' for which no shipyard expansion is needed. In all instances, within the required accuracy, the same minimum was found as for the 100 kton starting point.

Table 5

Principal Design - Variation of Fleet Size
(Fixed loading and discharge rates)

N-ships	RFR	DWT	LBP	L/B	B/T	V_K
2	2.6168	147.8	983	7.59	2.31	14.4
3	2.4994	104.6	879	7.70	2.29	13.0
4	2.5302	73.9	784	7.70	2.26	13.8
5	2.5691	58.4	732	7.72	2.27	14.3

Table 6

Optimisation of Cargo-Discharge Rate
(with Loading Rate constant at 7000 t./hr.)

N-ships	Discharge Rate	RFR	DWT	LBP	L/B	B/T	V_K
2	2980	2.4684	136.4	957	7.65	2.28	14.1
3	3080	2.4190	95.6	851	7.59	2.30	13.3
4	2450	2.4869	70.6	761	7.52	2.27	13.9
5	2000	2.5146	60.4	734	7.62	2.29	13.5

Table 7

Simultaneous Optimisation of Cargo-Discharge
and Cargo-Load Rates

N-ships	Discharge Rate	Load Rate	RFR	DWT	LBP	L/B	B/T	V_K
2	3.31	5.91	2.4614	142.6	969	7.70	2.26	13.4
3	3.10	7.85	2.4103	94.2	849	7.65	2.26	13.4
4	2.53	6.40	2.4921	71.2	766	7.56	2.27	13.8
5	2.11	6.99	2.5199	60.3	739	7.60	2.34	13.5

VI. Analyses and Sensitivity Studies.

In the next ten sub-sections are presented the results of the computer-aided economic optimisation procedures applied to the preliminary design of ore carriers under the previously described circumstances of operation and evaluation. Sub-sections 1, 2 and 3 may be considered to state the characteristics of the optimum design for the five, six and seven-parameter RFR-minimisation procedures. The other sub-sections, with the exception of 10, essentially demonstrate the sensitivity of the optimum design to variations of pertinent economic assumptions and approximations. In some instances, the choice of principal characteristics is unaffected by moderate variations of cost factors. Such conclusions are not general, however . They pertain only to the particular circumstances stated earlier in this paper. The important point is the realisation that similar sensitivity studies of economic influences should be made prior to the choosing of design specifications. With the type of analysis presented herein being used in everyday practice, any such generalisations are totally unnecessary.

Sub-section 10 is essentially an economic feasibility study for the installation of controllable pitch propellers on the vessels.

1. Principal Design (Five Parameters).

With the discharge and loading rates fixed at 1500 and 7000 tons/hr., the optimum designs for 2-5 ships in the fleet were ascertained to be those appearing in Table V . It appears, then, that the best size fleet is that of three vessels, with the ships being considerably larger than any previously planned for the Australian Trade. The detailed design specifications for that ship which shall henceforth be referred to as the principal design, are shown in Figure 6 . It is characterised by a high block coefficient, a low speed-length ratio (0.44), and being a relatively long and narrow vessel. This is most likely the result of influence by the dredging and shipyard expansion costs.

In order to demonstrate the course followed by the minimisation procedure, a sample of part of the summary output is shown in Figure 7 .

Figure 6

DESIGN 83 CODE 1 NOPT 101 STARTING POINT 100

	(FT.)		(L.T./1000)
L.B.P.......	878.5	DISPL.......	124.89
BEAM.......	114.1	D.W.T......	104.61
DEPTH......	70.4	CARGO......	103.63
DRAUGHT....	49.9	LIGHTSHIP..	20.28
FREEBOARD..	20.5	STEEL......	16.72
HLD.LNGTH..	711.2	MACHINERY..	1.19
		OUTFIT.....	1.78
CB.........	0.875	FUEL OIL...	1.12
CP.........	0.880	FRESH WATER	0.30
CM.........	0.994		
LBP/B......	7.700		(KNOTS)
B/T........	2.286	SERV. SPEED	12.95
B/D........	1.621	BLST. SPEED	14.89
LBP/T......	17.600		
		S.H.P......	14300.
G.M........	7.29	MAX. S.H.P.	17160.
KG.........	40.12	FUEL RATE *	0.357
BM.........	21.85	SHAFTS.....	1.
KB.........	25.55	CYL/ENG....	6.
KM.........	47.41	BORE (CM)..	90.
		(*-LB/SHP/HR)	
NO. OF SHIPS..	3.		
PORT-TO-PORT..	3220.	(DAYS PER ROUND TRIP)	
LOAD RATE **..	7.00	LOADED.....	10.36
UNLOAD RATE **	1.50	BALLASTED..	9.01
TRIPS/YEAR....	13.78	WEATHER....	1.55
(** -1000 L.T./HR)		LOADING....	0.62
		UNLOADING..	2.88
STOWAGE FACTOR	22.00	TOTAL......	24.92
FREEBOARD CODE	1.		

* * * CAPITAL COSTS * * * (FIRST YEAR ONLY)		* * * ANNUAL COSTS * * * (FIRST VESSEL)	(U.S. $1000)
SHIP CONSTRUCTION		CREW........	445.
	(U.S. $1000)	FUEL........	274.
MACHNRY....	3251.	MAINT. REPAIR	192.
STEEL......	4714.	INSURANCE....	437.
OUTFIT.....	5024.	PORT	74.
MISC.......	2265.	STORES SUPPLS	22
TOTAL......	15255.	TOTAL	1446.
SHIPYARD EXPANSION COST.......	2409.	EQUIVALENT ANNUAL COSTS	
PORT DREDGING COST.......	12676.	DRDG + WHRF..	2144.
		SHIPYARD.....	281.
WHARF CONSTRUCTION		FLEET CONSTR.	3728.
COST.......	5[illegible]96.	FLEET SALVAGE	-55.
		OPERATION....	3900.
TOTAL FIRST YEAR		TOTAL........	9998.
CAPITAL....	30178.		
		INTEREST RATES	
AVERAGE CONST. COST		AFTER TAX....	0.0900
FOR FLEET..	14095.	BANK LOAN....	0.0700
AVERAGE CONST. COST		TAX RATE.....	0.4250
SUBSIDY....	4[illegible]98.	LOAN RATIO...	0.8000
		CREW.........	41.
R.F.R......	2.4994		

Figure 7

3 SHIPS....OPTION 101 KARGO= 100

	R.F.R.	SUBSIDY	CAPITAL	ANNUAL	CARGO	L.B.P.	BEAM	DRAUGHT	DEPTH	C(B)	KNOTS	G.M.	S.H.P.
1	2.6464	5199.	31285.	1514.	120.0	924.9	132.1	46.5	79.1	0.899	11.15	10.02	10918.
2	2.6303	5246.	29369.	1563.	100.0	877.4	125.3	44.8	75.1	0.876	13.43	9.54	16729.
3	2.6222	5210.	29292.	1562.	100.0	872.4	124.6	44.9	74.6	0.881	13.43	9.40	16927.
4	2.5494	4936.	29319.	1508.	100.0	872.3	119.5	46.8	71.6	0.876	13.43	8.74	16197.
5	2.5769	5045.	29056.	1538.	100.0	872.4	124.6	45.1	73.7	0.876	13.43	9.91	16601.
6	2.5796	5049.	29075.	1541.	100.0	872.4	124.6	45.1	74.6	0.876	13.43	9.41	16603.
7	2.7542	5455.	28299.	1751.	80.0	814.8	114.4	44.7	68.2	0.841	16.89	8.75	28248.
8	2.6005	5102.	30152.	1514.	110.0	899.9	128.0	45.9	76.6	0.889	12.18	9.69	13358.
9	2.5804	5050.	29746.	1513.	104.0	878.6	123.2	46.4	73.4	0.883	12.90	9.29	15036.
10	2.5487	4926.	29797.	1489.	105.6	885.9	123.3	46.8	73.3	0.879	12.70	9.38	14197.
11	2.5690	4965.	31056.	1457.	111.2	899.0	122.0	48.9	72.0	0.877	12.05	9.49	12071.
12	2.5588	4956.	28777.	1541.	93.8	851.7	118.0	46.3	70.1	0.865	14.34	9.04	18696.
13	2.5846	5073.	29007.	1546.	95.8	863.3	120.8	45.7	71.9	0.865	14.04	9.23	17855.
14	2.5704	5017.	29474.	1516.	101.9	874.9	122.6	46.2	73.0	0.879	13.17	9.27	15675.
15	2.5411	4908.	29507.	1494.	100.6	870.8	118.7	47.3	70.1	0.874	13.36	9.20	15799.
16	2.5232	4796.	30086.	1465.	101.1	869.2	113.3	49.7	70.1	0.873	13.28	7.18	15210.
17	2.5248	4815.	29955.	1469.	101.0	869.5	114.4	49.2	69.6	0.873	13.30	7.81	15313.
18	2.5122	[illegible]	29713.	1471.	98.7	864.8	113.0	49.3	69.3	0.868	13.62	7.46	16020.
19	3.0232	6229.	29477.	1941.	95.4	855.4	159.3	37.3	112.9	0.857	14.10	11.89	23749.
20	2.5309	4797.	30938.	1459.	[illegible]	892.1	115.1	50.5	71.4	0.882	12.33	7.11	12779.
21	2.7300	5496.	29881.	1638.	106.0	880.6	[illegible]	[illegible]	92.3	0.875	12.65	9.03	15369.
22	2.5448	4908.	29768.	1488.	101.5	874.4	117.6	47.9	71.1	0.876	13.23	8.18	15370.
23	2.9427	6036.	29370.	1866.	98.3	862.8	156.1	38.1	107.1	0.870	13.60	12.09	21437.
24	2.5604	4965.	30147.	[illegible]	103.9	880.0	118.9	48.1	71.7	0.877	12.91	8.34	14499.
25	2.4998	4699.	30187.	1446.	103.7	878.7	114.1	49.9	70.4	0.875	12.94	7.29	14280.
71	2.5393	4855.	30490.	1459.	103.6	878.4	114.1	49.9	70.4	0.875	12.95	7.28	14312.
72	2.5392	4855.	30483.	1459.	103.6	878.3	114.1	49.9	70.4	0.875	12.96	7.30	14321.
73	2.5392	4855.	30485.	1459.	103.6	878.3	114.1	49.9	70.4	0.875	12.96	7.29	14319.
74	2.5393	4856.	30485.	1459.	103.6	878.4	114.1	49.9	70.4	0.875	12.95	7.30	14315.
75	2.5393	4855.	30489.	1459.	103.6	878.4	114.1	49.9	70.4	0.875	12.95	7.29	14313.
76	2.5395	4856.	30491.	1459.	103.6	878.5	114.1	49.9	70.4	0.875	12.95	7.29	14305.
77	2.4994	4698.	30179.	1446.	103.6	878.5	114.1	49.9	70.4	0.875	12.95	7.29	14299.
78	2.4995	4698.	30180.	1446.	103.6	878.5	114.1	49.9	70.4	0.875	12.95	7.29	14296.
79	2.5396	4856.	30493.	1459.	103.6	878.5	114.1	49.9	70.4	0.875	12.95	7.30	14300.
80	2.4994	4698.	30178.	1446.	103.6	878.5	114.1	49.9	70.4	0.875	12.95	7.29	14300.
81	2.4995	4698.	30183.	1446.	103.7	878.6	114.1	49.9	70.4	0.875	12.95	7.28	14291.
82	2.4997	4699.	30188.	1445.	103.7	878.6	114.1	49.9	70.4	0.875	12.94	7.28	14281.

The 80th design is seen to be the optimum, but evaluations of designs 77, 78, 80, 81 and 82 were required to satisfy the convergence/ accuracy criterion.

It is interesting to note that if the maximum SHP(17160) were 1.0 horsepower greater, the next larger size engine would be required. Thus, the principal design is utilising the engine to its fullest extent.*

Several sums on Figure 6 initially appear incorrect without the following three notes.

(i) The fuel weight is the total carried during the return ballasted voyage, whilst the deadweight includes only 60% of the fuel weight, which is on board at the outset of the loaded voyage.

(ii) The lightship weight includes a three per cent margin.

(iii) The total voyage time includes manoeuvering time (0.5 day), not shown in that figure.

There are many interesting facets to the design optimisation. One example follows.

For the situation of four vessels in the fleet, the optimum LBP is above the maximum allowed without shipyard expansion. The summary sheet for that procedure indicates that a more highly powered vessel having LBP < 750' was evaluated. With LBP = 740, L/B = 7.40, B/T = 2.34, carrying 60.5 kton of cargo, the consequent RFR was 2.6987, well above the minimum for a four-ship fleet of 2.5302. The added capital and annual costs for a 23,350 SHP plant (versus 14,260) apparently exceed the effect of lack of the shipyard expansion cost.

2. Principal Design (Six Parameters).

Table VIshows the optima for the situation where the loading rate is fixed at 7000 tons/hr., and the discharge rate is allowed to "float". For all fleet sizes, the RFR is lower than the corresponding situations having a fixed discharge rate. Moreover, the principal characteristics of the optimum vessels for each fleet size are measurably different.

* Recall that 1.0 British h.p. = 1.014 metric h.p.

From that table, it appears that, under the circumstances of a fixed loading rate of 7000 tons/hr., a fleet of three vessels of 95,600 DWT is optimum, with an unloading facility capable of handling 3080 tons/hr.

3. Principal Design (Seven Parameters).

For the situation having both the loading and discharging rates among the parameters to be optimised, the RFR is found to be lower for all fleet sizes than in the case of a fixed loading rate. From TableVII it should be noted, also, that the principal characteristics are different, although not greatly so, due to the fact that 7000 tons/hr., is quite close to the optimum loading rate.

Overall, comparing the five-parameter study to the seven, a net savings over 15 years amounting to $US5.35 million* could be effected by using a combination of ships and facilities that have been chosen together, rather than using an optimised vessel with arbitrarily chosen shore-side facilities.

Based on the previously discussed cost relationships, the optimum fleet size is three vessels, of 94,200 DWT, and loading and discharge rates of 7850 and 3100 tons/hr., respectively. Different cost assessments for the facilities are expected to lead to different optima.

4. Sensitivity of Interest Rate.

The owner's after-tax interest rate was subjected to variations, consisting of 7, 9, 11 and 13 per cent. The upper part of Table VIII indicates the optima for each rate, whilst the lower portion contains other interesting designs, which are optima for their corresponding fleet size. It is notable that somewhere between 9% and 11%, the extra capital for shipyard expansion becomes significant to the extent that the optimum length drops below the critical 750', and consequently the fleet size becomes five. The progression of the RFR, at 9% and 11% interest, may be noted from that table for 3,4 and 5 vessels in the fleet. Recalling that 80% of the capital is borrowed, it becomes more significant that

---

* $(2.4994 - 2.4103) \times 60 \times 10^6 = 5.35 \times 10^6$

Table 8

Variation of After-Tax Equivalent Interest Rate

Option	i_a	N-ships	RFR	DWT	LBP	L/B	B/T	V_K
102	7%	3	2.2277	104.6	879	7.70	2.29	13.0
101	9%	3	2.4994	"	"	"	"	"
103	11%	5	2.7414	57.6	728	7.72	2.25	14.5
104	13%	5	2.8969	62.2	743	7.60	2.33	13.4
(103	11%	3	2.7834	99.1	862	7.69	2.28	13.7)
(103	11%	4	2.7611	74.6	786	7.70	2.28	13.7)
(104	13%	3	3.0674	99.1	864	7.72	2.27	13.7)
(104	13%	4	2.9892	73.9	785	7.71	2.27	13.8)

Table 9

Variation of Relative Fuel Costs

Option	Relative Cost	N-ships	RFR	DWT	LBP	L/B	B/T	V_K
101	100%	3	2.4994	104.6	879	7.70	2.29	13.0
133	115%	3	2.5365	98.1	861	7.71	2.26	13.8
134	130%	3	2.5579	105.6	881	7.70	2.29	12.8

Table 10

Variation of Relative Insurance Costs

Option	Relative Cost	N-ships	RFR	DWT	LBP	L/B	B/T	V_K
101	100%	3	2.4994	104.6	879	7.70	2.29	13.0
135	120%	3	2.5584	104.6	879	7.70	2.29	13.0
136	140%	3	2.6204	98.8	861	7.71	2.26	13.8

the owner's required rate of return should exert such considerable impact on the choice of the optimum fleet size and cargo capacity of each vessel.

5. Sensitivity of Construction Cost Estimate.

For relative construction costs of 90,100 and 110 per cent, the optimum design was consistently the principal design for a 3-ship fleet. Only the RFR showed variation, being 2.3803, 2.4994 and 2.6186 for those three relative values, respectively. It is suspected that the other capital costs heavily influence the choice, and thus it would be particularly dangerous to generalise for the situation in which there is only light capital investment in facilities.

6. Annual Cost Growth-Rate Variations.

As set out in section III, it has been assumed that annual costs associated with later-built vessels would grow at a 3% arithmetic rate compared with the first-built vessel.* The optimum was determined also for growth rates of 1.5% and 0.0%. In all situations, again, the 3-ship fleet of the principal design was found to be the optimum. For the three growth rates, in decreasing order, the values of the RFR were 2.4994, 2.4865, and 2.4736.

7. Sensitivity of Fuel Costs.

Fuel prices were varied from 100% to 130% relative cost, for which the optima were found to be those in Table IX . The optima corresponding to 100% and 130% use the same engines; whilst the smaller vessel which is the optimum for the 115% relative fuel cost utilises the next larger size engine at 99.35% of its rating. Considering the instability of fuel prices, due to political controversies, it is realised that fuel-cost sensitivity studies should have an important role in the final choice of principal characteristics.

---

* i.e., the annual costs associated with the third ship would be 106% of those for the first.

8. Relative Insurance Cost Variations.

Shown in Table X are the optima for variations of the relative insurance costs. Briefly, it is noted that whilst the optimum may be "nested" in a valley for some variation of insurance costs, ultimately smaller, but faster ships become the optima. This constitutes a play-off between two annual cost factors: insurance and fuel.

9. Capital Cost Variations.

Because there are significant political and corporate decisions behind the potential acceptance of capital investment in shipyard expansion and dredging, a number of trials have been run that exclude some of the major capital investments in facilities. In all instances, however, the wharf preparation is included, along with the costs of loading and discharging facilities at the fixed rates of 7000 and 1500 tons/hr. Under the conditions of Part A of Table XI it is found that two large vessels form an optimum fleet when major capital facilities are not included in the determination of the RFR. Parts B and C confirm that as well. The designs at the bottom of Parts A and C, shown for comparison purposes, are optima for their associated fleet size, which is not optimum.

10. Controllable Pitch Propeller Study.

The designs that result in minimised RFR's utilising a controllable pitch propeller (CPP) were computed in accord with the advantages and disadvantages given in a previous section. The results are shown in Table XII. With a CPP, for a 3-ship fleet, the principal characteristics for the minimum RFR show that a slightly larger vessel is chosen. That choice lowers the RFR from 2.4994 to 2.4953. A small difference of RFR, but a 15 year savings of nearly a quarter million dollars (U.S.).

But by using the 4-ship fleet of 71,100 DWT, a total savings of over half a million dollars in the 15 years is realised.

Table 11

Miscellaneous Capital Cost Variations

A - without construction subsidy benefit
with and without (shipyard + dredging) capital outlay

Option		N-ships	RFR	DWT	LBP	L/B	B/T	V_K
125	with	3	2.9400	104.6	879	7.70	2.29	13.0
126	without	2	2.3933	171.8	1032	7.79	2.25	12.3
(125	with	2	3.0282	162.6	1012	7.65	2.31	13.0)
(126	without	3	2.5057	105.9	878	7.68	2.30	12.8)

B - without construction subsidy benefit
without (shipyard + dredging) capital outlay at
60% and 100% relative construction cost.

126	100%	2	2.3933	171.8	1032	7.79	2.25	12.3
119	60%	2	1.7581	183.3	1060	7.87	2.27	11.5

C - without construction subsidy benefit
without shipyard expansion capital outlay at
60% relative cost
with and without dredging capital outlay.

118	with	3	2.2165	105.0	877	7.63	2.32	12.9
119	without	2	1.7581	183.3	1060	7.87	2.27	11.5
(118	with	2	2.3081	162.1	1013	7.68	2.30	13.1)
(119	without	3	1.8407	132.5	931	7.63	2.31	10.1)

Table 12

Controllable Pitch Propeller Study

Option	Prop.	N-ships	RFR	DWT	LBP	L/B	B/T	V_K
101	FPP	3	2.4994	104.6	879	7.70	2.29	13.0
146	CPP	4	2.4906	71.1	775.2	7.68	2.26	14.0
(146	CPP	3	2.4953	110.6	893.8	7.65	2.32	12.0)

It can be easily seen that, accepting the cost influence of a CPP as set forth by Ridley and Midttun (1970), its most successful utilisation depends not only on its installation, but on applying it to a vessel which is optimised with it as an integral part from the outset.

11. Summary of Analyses.

Although a number of sensitivity studies have been carried out in the previous sections, there remains a greater number which should be pursued as well. As mentioned in section V, the basic advantages of different available machinery plants should be studied as a matter of course prior to choosing one. Large-bore, slow-speed diesels from different manufacturers may show distinct differences, as much as the possible use of medium-speed diesels. For countries having the appropriate technology available, oil and nuclear steam installations should be investigated also.

Bargaining with unions over manning requirements could be aided by a sensitivity study dealing with the effect of the crew number. Argument for special tax reliefs or subsidies due to political decisions regarding capital facilities can readily be substantiated by selected studies. For example, if a governmental agency decided that the port dredging should be limited, the effect on the RFR or the rate of return to the owner, compared with the true optimum, could be readily ascertained.

Even without political interference, the final decision regarding choice of fleet size and principal characteristics of the vessels remains a matter of judgement. But with the assistance of numerous feasibility and sensitivity studies, in which true optima are compared, the bases for decisions is much more substantial than it could have been previously.

Only optimisation studies as those conducted herein could reveal that a CPP installation on a 4-ship fleet of 71,100 DWT could be far better than a FPP installation on an optimised 3-ship fleet of 104,600 DWT.

Once the techniques for optimisation are understood by, and available to, the prospective shipowner, the matter of design is merely a matter of up-dating the cost assessments and physical relationships for various factors. Admittedly, the optimisation programmes for non-bulk trades is not as straight-forward as used in this display of techniques. Nonetheless, sufficient motivation on the part of the shipowners, and the availability of essential figures from shipyards, engine manufacturers, and suppliers of major components of ships, will result in the development and use of such techniques to the ultimate benefit of all.

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Appendix 1

```
C
C     SUBROUTINE ECOFAC        (ECONOMIC FACTORS)
C
C     PURPOSE
C        COMPUTES THE BEFORE-TAX CAPITAL RECOVERY FACTOR (CRF), THE
C        BEFORE-TAX SINKING FUND FACTOR (SFF), AND THE BEFORE-TAX SINGLE
C        PAYMENT PRESENT WORTH FACTOR (SPWF) FOR A GIVEN AFTER-TAX RATE
C        OF INTEREST, A GIVEN BANK INTEREST RATE, AND A SPECIFIED BOR-
C        ROWING RATIO.  IF THE TAX RATE IS SPECIFIED AS 0.0 IT COMPUTES
C        AFTER-TAX FACTORS.
C
C     USAGE
C
C        CALL ECOFAC(CRF,SFF,SPWF,NY,XI,XT,BI,BRATIO)
C
C     DESCRIPTION OF PARAMETERS
C        CRF - OUTPUT CAPITAL RECOVERY FACTOR
C        SFF - OUTPUT SINKING FUND FACTOR
C        SPWF - OUTPUT SINGLE PRESENT WORTH FACTOR
C        NY - INPUT NUMBER OF YEARS
C        XI - INPUT AFTER-TAX INTEREST RATE, AS 0.075
C        XT - INPUT TAX RATE, AS 0.333
C        BI - BORROWED MONEY INTEREST RATE, AS 0.06
C        BRATIO - RATIO OF BORROWED MONEY TO PRINCIPAL INVESTMENT, AS 0.
C
C     REFERENCE
C        BENFORD, MEASURES OF MERIT FOR SHIP DESIGN, UNIV. OF MICHIGAN
C        REPORT 007, FEB 1968
C
C     *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
C
      SUBROUTINE ECOFAC(CRF,SFF,SPWF,NY,XI,XT,BI,BRATIO)
      FACT = (1.0 + XI)**NY
      CRF = XI*FACT/(FACT - 1.0)
      SFF = XI/(FACT - 1.0)
      SPWF = 1.0/FACT
      IF (XT .LE. 0.0) GO TO 40
      XFACT = (1.0 + BI)**NY
      BCRCRF = BI*XFACT/(XFACT - 1.0)
C
C     FIND BEFORE-TAX CRF
      YN = NY
      CRFB = (CRF - XT/YN - XT*BRATIO*(BORCRF - 1./YN))/(1. - XT)
C
C     FIND EQUIVALENT BEFORE-TAX INTEREST RATE USING A NEWTON-RAPHSON
C        METHOD
      NTIMES = 0
      QI = XI
   20 NTIMES = NTIMES + 1
      IF (NTIMES .GT. 10) GO TO 42
      FCT = 1.0 + QI
      FCTN = FCT**NY
      U = QI*FCTN
      DU = FCTN + YN*QI*FCTN/FCT
      V = FCTN - 1.0
      DV = YN*FCTN/FCT
      F = CRFB - U/V
      FPRM = (U*DV - V*DU)/(V**2)
      G = ABS(F)
      IF (G .LE. 0.00001)GO TO 30
      QI = QI-F/FPRM
      GO TO 20
C
C     NOW CALCULATE  BEFORE-TAX FACTORS
   30 SFF = QI/(FCTN-1.0)
      SPWF = 1.0/FCTN
      CRF = CRFB
      GO TO 42
   40 CONTINUE
      QI = 0.0
      NTIMES = 0
   42 CONTINUE
      RETURN
      END
```

Appendix II

Annual Costs - First Ship Only

(expressed in U.S. dollars)

1. Crew Costs

Allow five crew for every four aboard the vessel, thus accounting for paid vacations. With Nc the number of crew aboard the vessel, the first year annual cost in U.S. dollars is given by:

$$\$_{C1} = 15000 \left(\frac{4}{5} Nc\right)^{0.8} + 650\ Nc$$

(ref. Benford, 1965)

Assuming a real economic growth rate of 3%, and allowing for crew costs to rise geometrically at the rate, the equivalent annual crew cost may be given by the following:

$$\$_{C} = \$_{C1} \frac{\left[r - r\left(\frac{1+g}{1+r}\right)^{n}\right]}{(r-g)\left[1 - (1+r)^{-n}\right]}$$

in which g = the real economic growth rate.

r = rate of discount being employed.

n = assumed ship's life.

(ref. Goss, 1969)

2. Fuel Costs

East coast Australia price is, at the time of writing, \$US19.50/ton of bunker oil. In this study, an extra margin of six percent is added to the fuel consummed to allow for the consumption of lubricating oil. Port fuel is considered to be equal to the extra margin provided by assuming the same ballasted power requirements as the loaded requirements.

3. Port Expenses.

Pilotage is \$US274 per entry or exit from a port, \$US1096 per round trip.

Light dues are assessed at the rate of \$US0.014 per gross ton per port per year (two ports). Gross tonnage is estimated, based on existing Australian bulk carriers, as:

$$G.R.T. = 0.86 \left(\frac{L \times B \times D}{100}\right) .$$

Dock usage is given by \$US0.0197 per gross ton per day loading or discharging.

4. Maintenance and Repair.

Mid-life hull maintenance and repair costs are given as:

$$\$hull = 8000 \left(\frac{L \times B \times D}{100,000}\right)^{\frac{2}{3}} .$$

(ref. Benford, 1965, and Gilfillan, 1969)

The engine manufacturer gives an estimate of \$US2.50 per horsepower per year for engine maintenance and repair, which is multiplied by 1.55 for Australian conditions.

5. Stores and Supplies.

Being a function of the number of crew, N_C, the annual cost is given by:

$$\$_{S-S} = 78 \left(\frac{N_C}{10}\right)^4$$

(ref. Benford,1965, and Gilfillan, 1969)

6. Insurance.

For ore-ships operating around the Australian coast by an experienced operator, the cost of protection and indemnity insurance is given as a function of the deadweight. For thousands of tons and thousands of U.S. dollars,

$$\$_{P,I} = 16.5 + \frac{3}{20} DWT.$$

The cost of hull insurance for the same operation has been given at four values of deadweight, with straight line interpolation used. Expressed as a percent of the construction cost, the annual premiums are given below:

DWT	PERCENT
50,000	1.875
70,000	2.05
90,000	2.40
110,000	2.75

Appendix 3

```
C
C     SUBROUTINE  FREBRD
C
C     PURPOSE -
C        * * * USES THE 1966 LOAD LINE CONVENTION * * *
C        TO DETERMINE THE BASIC MINIMUM SUMMER FREEBOARD FOR BULK CARRIERS
C        INCLUDING ALL CORRECTIONS ACCORDING TO THE INTERNATIONAL CONVEN-
C        TION -- TO COMPARE IT TO THE PREVIOUSLY CALCULATED FREEBOARD
C        BASED ON VOLUMETRIC REQUIREMENTS -- AND TO RETURN A VALUE WHICH
C        IS THE LARGER OF THE TWO
C
C     ASSUMPTIONS -
C        NO SHEER
C        C(BLOCK) OF SECTION BETWEEN DESIGN DRAUGHT AND 0.85 X DEPTH IS
C           APPROXIMATED BY (CB + 2.0)/3.0
C        L.W.L. = 1.03 X L.B.P.
C
C     USAGE -
C        CALL FREBRD(DLBP,DLSS,DB,DD,DT,CB,NFBD)
C
C     DESCRIPTION OF PARAMETERS -
C        DLBP  - LENGTH BETWEEN PERPENDICULARS
C        DLSS  - LENGTH OF SUPERSTRUCTURES
C        DB    - BEAM, FEET
C        DD    - DEPTH, FEET    (INPUT AND OUTPUT)
C        DT    - DRAUGHT
C        CB    - BLOCK COEFFICIENT
C        NFBD  - (OUTPUT)     = 1 IF DEPTH IS DETERMINED BY VOLUMETRIC
C                                 REQUIREMENTS
C                             = 2 IF DEPTH IS DETERMINED BY FREEBOARD
C                                 REQUIREMENTS
C
C     NOTES -
C        ACCORDING TO THE FIRST REFERENCE (BELOW), IT IS DIFFICULT TO
C        ASSIGN BASIC MINIMUM FREEBOARDS FOR BULK CARRIERS WITHOUT A
C        DETAILED DESIGN OF THE VESSEL. INASMUCH AS THEY ARE LIKELY TO
C        BE 'FAIRLY CLOSE TO THE BASIC FREEBOARDS AGREED FOR TANKERS
C        IN THE 1930 CONVENTION,' THOSE ARE UTILISED IN THIS SUBROUTINE.
C        * * THERE IS NO CAMBER CORRECTION  ACCORDING TO THE 1966 CONV.
C
C     REFERENCES -
C        MURRAY-SMITH, TRANS. R.I.N.A. VOL. 111, JAN. 1969
C        GILFILLAN, TRANS. R.I.N.A. VOL.111, JAN. 1969
C
C     *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*
C
      SUBROUTINE FREBRD(DLBP,DLSS,DB,DD,DT,CB,NFBD)
      DIMENSION DL(82), FBD(82), XBD(42), YBD(40)
C
C     ASSIGN ARRAY OF BASIC MINIMUM UNCORRECTED SUMMER FREEBOARDS
      DATA XBD/21.5,23.1,24.7,26.3,28.0,29.7,31.5,33.3,35.2,37.1,39.1,
     1 41.1, 43.1, 45.1, 47.1, 49.2, 51.3, 53.5, 55.7, 57.9, 60.2,
     2 62.5, 64.9,67.4,69.9, 72.5, 75.1, 77.7, 80.2, 82.7, 85.1, 87.5,
     3 89.8, 92.1, 94.3, 96.5, 98.6, 100.7, 102.7, 104.6, 106.5, 108.4/
      DATA YBD/110.1,111.7,113.1,114.5,115.9,117.3,118.6,119.9,121.2,
     1 122.5, 123.7, 124.9, 126.1, 127.3, 128.5, 129.6, 130.7, 131.8,
     2 132.9, 134.0, 135.1, 136.2, 137.2, 138.2, 139.2, 140.1, 141.0,
     3 141.9, 142.8, 143.7, 144.5, 145.3, 146.1, 146.9, 147.7, 148.5,
     4 149.2, 149.8, 150.4, 151.0/
      DO 2 JX = 1,42
      FBD(JX) = XBD(JX)
    2 CONTINUE
      DO 3 JY = 43,82
      KY = JY - 42
      FBD(JY) = YBD(KY)
    3 CONTINUE
      DLWL = 1.03 * DLBP
      DO 5 J = 19,100
      XJ = J
      NJ = J - 18
      DL(NJ) = 10.0*XJ
    5 CONTINUE
```

Appendix 3 (cont'd.)

```
C
C     SUPERSTRUCTURE DEDUCTIONS
      R = DLSS/DLWL
      IF (R .GT. 0.30) GO TO 10
      SSDED = 42.0*0.7*R
      GO TO 50
   10 IF (R .GT. 0.50) GO TO 20
      SSDED = 42.0 *(R-0.09)
      GO TO 50
   20 IF (R .GT. 0.70) GO TO 30
      SSDED = 42.0*1.1*(R-0.1273)
      GO TO 50
   30 SSDED = 42.0*1.233*(R-0.1892)
   50 CONTINUE
C
C     SHEER CORRECTION
      SHEER = 0.0
      SHRSTD = 79.95 + 0.7995*DLWL
      SHRCOR = (SHRSTD - SHEER)*(0.75-R/2.0)/16.0
C
C     NOMINAL FREEBOARD FROM TABLES
      I = 1
   55 IF (DLWL .LE. DL(I)) GO TO 58
      I = I + 1
      IF (I .GE. 82) GO TO 57
      GO TO 55
   57 TFBD = 151.0 + 0.6*(DLWL-1000.0)/10.0
      GO TO 60
   58 II = I - 1
      IF (I .GT. 1) GO TO 59
      I = 2
   59 TFBD = FBD(II) + (DLWL-DL(II))*0.1*(FBD(I)-FBD(II))
   60 CONTINUE
C
C     FIND C(PRISM) AND C(W.P.)
      CP = 0.04 + 0.96*CB
      IF (CP .GE. 0.85) GO TO 110
      CW = 0.878*CP + 0.164
      GO TO 112
  110 CW = 0.600*CP + 0.400
  112 AWP = CW*DB*DLWL
C
C     FIND THE VOLUME UP TO 0.85 X DEPTH
      D85 = 0.85*CD
      VOL = CB*DLBP*DB*DT
      VOL = VOL + (D85 - DT)*AWP*(2.0 + CB)/3.0
      CBX = VOL/(DLWL*DB*D85)
C
C     CB CORRECTION    (FINENESS CORRECTION)
      IF (CBX .LE. 0.68) GO TO 114
      CBCOR =(CBX + 0.68)/1.36
      GO TO 116
  114 CBCOR = 1.0
  116 CTFBD = TFBD*CBCOR
C
C     FREEBOARD WITHOUT DEPTH CORRECTION
      FBD1 = CTFBD - SSDED + SHRCOR
C
C     LENGTH-DEPTH RATIO  CORRECTION, DERIVED BY GILFILLAN
      DX = 1.333*(DT + FBD1/12.0 - DLWL/60.0)
C     ABOVE ASSUMES L.W.L. GREATER THAN 390 FT.
C
C
C     FIND THE LARGER OF DX AND DD
      DC = DX
      DE = DD
      IF (DD .GE. DX) GO TO 78
      DD = DX
      NFBD = 2
      GO TO 79
   78 NFBD = 1
   79 CONTINUE
      RETURN
      END
```

Appendix IV

Steel and Outfitting Weight Estimates

Method 1: Steel Weight from Area of Midship Steel.

(subscript "O" indicates particulars of vessel having known weights.) From Crouch (1963), Gilfillan (1969).

$$\log_{10}(\log_{10}(A)) = 0.1512 \log_{10}(L) + 0.0862 \log_{10}(B) - 0.0204 \log_{10}(D) + 0.0121 \log_{10}(T) - 0.0095.$$

(A = area of longitudinal material at midships.)

$$Ws = Ws_o \cdot \left(\frac{L}{Lo}\right) \cdot \left(\frac{A}{Ao}\right)$$

Method 2: Steel Weight from Cubic Number Method. From Gilfillan (1969).

$$Ws = Ws_o \cdot \left(\frac{L\ B\ D}{Lo\ Bo\ Do}\right) \cdot \left(\frac{1 + 0.5\ C_b}{1 + 0.5\ Cbo}\right) \left(\frac{L / D}{Lo/Do}\right)^{\frac{1}{2}}.$$

Method 3: Steel Weight from Murray's Equation. From Murray (1965)

$$W_s = 1.05 \cdot L^{1.65} (B + D + T/2)\ (0.5C_b + 0.4)/800.$$

Outfitting Weight: by Square Number Method.

$$WO = WO_o \cdot \left(\frac{1}{4} + \frac{3}{4}\ \frac{L\ B}{LoBo}\right).$$

Appendix 5

```
C
C      SUBROUTINE POWER
C
C      PURPOSE -
C         TO CALCULATE THE DESIGN SHAFT HORSEPOWER FOR A BULK CARRIER OF
C         SPECIFIED DIMENSIONS, ACCOUNTING FOR THE POSSIBILITY OF TWIN
C         SCREW PROPULSION
C
C      ASSUMPTIONS -
C         C(PRISM.) = 0.04 + 0.96*CB
C         I.T.T.C. FRICTION LINE USED WITH ADDITIONAL CORRELATION
C            ALLOWANCE OF  0.0004
C         CONDITIONS OF 68-DEGREE F. SALT WATER
C         MAXIMUM HORSEPOWER   = 1.2 X DESIGN H.P.
C         MAXIMUM DESIGN S.H.P. PER SHAFT = 48,000
C         TWIN SCREW PROPULSIVE EFFICIENCY IS 10 PERCENT LESS THAN
C            SINGLE SCREW
C
C      USAGE -
C         CALL POWER(DLBP,DB,DT,CB,VSL,SHP)
C
C      DESCRIPTION OF PARAMETERS -
C         DLBP   - LENGTH BETWEEN PERPENDICULARS, FT.
C         DB     - BEAM
C         DT     - DRAUGHT
C         CB     - BLOCK COEFFICIENT
C         VSL    - VESSEL SPEED IN KNOTS WHEN FULLY LOADED
C         SHP    - DESIGN SHAFT HORSEPOWER
C
C      REFERENCES -
C         GERTLER, REANALYSIS OF TAYLOR SERIES
C         SAUNDERS, HYDRODYNAMICS IN SHIP DESIGN, VOL. II
C         FISHER, PRELIMINARY DESIGN GRAPHS FOR TANKERS
C
C      *-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-*-
C
       SUBROUTINE POWER(DLBP,DB,DT,CB,VSL,SHP)
       DATA A1/-1.010/,A2/11.04/,A3/-10.37/
       DATA B1/-1.866/,B2/12.99/,B3/-12.23/
       DATA RHO/1.9982/,XNU/1.1342E-05/
       VOL = DLBP*DB*DT*CB
       DLWL = 1.03*DLBP
       CVOL = VOL/(DLWL**3)
       SLR = VSL/SQRT(DLWL)
       CP = 0.04 + 0.96*CB
       VFPS = VSL*1.6889
       RN = VFPS*DLBP/XNU
C
C      CALCULATE WETTED SURFACE
       RBT = DB/DT
       CS = 2.65+((RBT-2.65)**2)*0.05/(0.51**2)
       WS = CS*SQRT(VOL*DLBP)
       DENOM = 0.5*RHO*WS*VFPS*VFPS
C
```

Appendix 5 (cont'd.)

```
C     CALCULATE FRICTIONAL RESISTANCE COEFFICIENT
      RNL = ALOG10(RN)
      CF = 0.075/((RNL-2.0)**2) + 0.0004
C
C     CALCULATE RESIDUAL RESISTANCE COEFFICIENT
      SLX = SLR + (CP-0.7)
      CR3 = -1.83 + SLX*(14.02-SLX*(27.0-SLX*18.32))
      IF (RBT .GE. 3.0) GO TO 10
      CR = CR3 - 0.19*(3.0-RBT)/0.75
      GO TO 15
   10 CR = CR3 + 0.09*(RBT-3.0)/0.75
   15 CONTINUE
      CR = CR + 0.5*(CVOL-7.0E-03)*100.0
      CR = CR/1000.0
C
C     CALCULATE E.H.P.
      RTOT = (CF + CR)*DENOM
      EHP = RTOT*VSL/326.0
C
C     CALCULATE PROPULSIVE EFFICIENCY FOR SINGLE SCREW
      CPX = CP
      IF (CP .GT. 0.7) GO TO 20
      CP = 0.7
   20 A = A1 + A2*SLR + A3*SLR*SLR
      B = B1 + B2*SLR + B3*SLR*SLR
      PE = A - B*CP
      CP = CPX
C
C
C     CALCULATE MAXIMUM HORSEPOWER
      SHP = EHP/PE
      SHPMAX = 1.2*SHP
C
C     CHECK TO SEE IF TWIN SCREW REQUIRED
      IF (SHPMAX .LE. 48000.0) GO TO 30
      PE = 0.9*PE
      SHP = EHP/PE
      SHPMAX = 1.2*SHP
   30 CONTINUE
C
      RETURN
      END
```

SUPPLEMENT

ECONOMIC OPTIMISATION PROCEDURES IN PRELIMINARY SHIP DESIGN (APPLIED TO THE AUSTRALIAN ORE TRADE)

by K.W.Fisher

Department of Mechanical Engineering
The University of Sydney

WRITTEN DISCUSSIONS

and

AUTHOR'S REPLY

October, 1970.

HORST NOWACKI, ASSOCIATE PROFESSOR, DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING, THE UNIVERSITY OF MICHIGAN, ANN ARBOR.

My discussion will concentrate on some aspects of optimization procedures applied to ship design.

Mr. Fisher's paper presents further evidence that our profession is beginning to view ship design consistently as an economic optimization problem. This should be to nobody's surprise: Design presents choice, choice calls for optimization, optimization requires rational decision criteria, which must be in accord with the ship owner's economic motivation.

The tools of optimization are presented to us readily from other fields of application where the mathematical theory of optimization has reached great refinement. I therefore agree with the author when he turns away from simply simulating the conventional design procedure, and instead adopts a general purpose direct search optimization method. His choice of the Nelder-Mead algorithm seems rather fortunate in view of its favorable efficiency.

The paper recognizes ship design as an optimization problem with constraints. While such conventional ship design constraints as building dock and channel dimension limits are indeed more adequately treated as cost penalties, there remain such restricting factors as freeboard, stability, strength, volume capacity, etc. In the treatment of these constraints I would advocate a different course than the author.

It seems that his design procedure alternates between one step in which the design variables are reset by the search algorithm, and another where these variables are readjusted if any constraints are violated. Consequently, one is running the risk of spoiling the basic efficiency of the algorithm when constraints are encountered and, in the worst case, of ruining its convergence. However, this is unnecessary since other search algorithms exist in which the constraints are treated flexibly and without loss of rigor, for example the SUMT method (Sequential Unconstrained Minimization Technique.).

I want to close with a few specific questions:

* The paper mentions the possibility of several crests and valleys in the measure of merit function due to step function inputs. Is there any actual indication of multimodality?

* Has the measure of merit function been studied and perhaps displayed in the vicinity of the optimum? Which constraints are governing the design?

My compliments to Mr. Fisher for his original work in this important area.

PROFESSOR HARRY BENFORD, DEPARTMENT OF NAVAL ARCHITECTURE AND MARINE ENGINEERING, UNIVERSITY OF MICHIGAN.

Mr. Fisher's marine transport study is the first I have seen that has been broad enough to include not only the ships and terminals, but the shipbuilding facilities as well. This breadth of scope is appropriate to the problem he has undertaken to solve, and one that should be used more often in the future.

There is one minor dissent I want to register. In his introduction, Mr. Fisher states that his paper presents "techniques that enable economic considerations to be the only ones that are used for decision-making in the choice of design parameters". As enthusiastic as I am about the subject, I have never proposed complete reliance on economics in decision-making. There are always important intangible considerations that must also be brought to bear. Let the computer produce a [illegible] of feasible solutions, and prices, but let some man make the [illegible]

Computer programs such as the one Mr. Fisher has presented here can be subjected to never-ending refinements and improvements. In further phases of development, I urge him to consider two or three modifications; and I suggest that he do so before going further in the design and construction of the proposed fleet.

To begin with, I question the recommended value of the block coefficient, which I infer from Figure 6 to be 0.875. I further infer from paragraph V-2 (111), that Mr. Fisher may have arbitrarily chained block coefficient to speed-length ratio by a variation on the old Alexander formula. If that is so, then he has introduced an unnecessary shackle in violation of the free-floating precepts of his own introduction. Worse yet, he may have used the Alexander formula in a low-speed range where the formual was never meant to apply. In any event, the proposed value seems likely to lead to unacceptable propeller vibrations. The entire topic demands further explanation, or further study, or both.

The surprisingly low beam-draft ratio of the recommended ship also deserves further thought. I presume it is a logical outcome of the dredging relationships used in the algorithm. Increasing the draft by one foot would add about twice as much deadweight as increasing the beam by a like amount and would require considerably less dredging - at least under the assumption that any increase in beam will require a six-fold increase in dredged channel width. I should expect, however, that there must be many miles of shoal area in which a wider ship with less draft could operate without benefit of dredging. If that is the case, then greater beam and less draft would obviously become appropriate. Perhaps the algorithm needs further refinement.

Finally, let me suggest a simplification: forget all those ramifications about owner's equity vs borrowed funds; they simply confuse economics (which you want to optimize) with finances (which is the business manager's internal problem). Normally, the design that promises the best overall economics (i.e. to both bank and owner) will also be the best from the point of view of the owner alone. There are exceptional cases where that would not be true, but they are exceptional.

Mr. Fisher has made an excellent start. I hope he will keep up the good work, and that he will continue to receive cooperation and support in gathering cost data from all segments of the Australian marine industry.

PROFESSOR P.T. FINK, UNIVERSITY OF NEW SOUTH WALES.

I congratulate Mr. Fisher on his effective demonstration of the possible use of optimising procedures in preliminary ship design, and the paper is a fine systems study. Even though estimates are made of the effect of including extensions at a particular shipyard, I believe we still have a sub-system study here. Benford's dictum that one man's system is another man's sub-system applies here - as it does always.

My own reaction to the figures would be to go for a fleet of two large ships without bothering to extend the facilities of the shipyard. I would prefer the ship to be welded together from two pieces made at existing facilities. At the same time, Table 8 seems to show that bulk carriers with deadweight in the 50,000-60,000 ton range, as now used on the Australian Coast, give a fine return on capital! If yard extensions were to be gone ahead with, one would have to have a sensitivity analysis on the effect of changing capital costs in the yards, since extimates provided by the yard would have to be treated with great reserve.

When looked at from the point of view of the whole of the local shipbuilding industry, delivery times of one year and fleet dimensions as low as those quoted remind one very much of the ineffective state of the industry as is, rather than of the future one would have to anticipate if we are to retain any measure of competitiveness with the shipbuilding process abroad.

Surely an academic study should now be made combining total ship-system design possibilities with appropriate models for the Australian coastal trade in the next decade or more, admitting all the uncertainties inevitable in such as extrapolation, and - perhaps daringly - including various fractions of our expected overseas trade. We should also follow recent initiatives in the United States and sponsor feasibility studies to evolve a few basic designs which might then be made in adequate numbers to lead to reductions in the capital cost of ships. Although the 'standard' design idea appears to be anathema to the conventional ship owner, it seems to be the case that significant differences can be built into basic ship designs without very appreciably increasing their costs. There seems to be no other way to obtain multiple production with its corresponding cost reductions and enhanced prospects for local survival and perhaps even export. At that stage we could use the combined computer model to provide evidence on the advisability of shipyard extensions.

Among specific questions I have are the following.

The replacement of the fixed pitch propeller by controllable pitch propellers (Table 12) appears to call for a very different fleet while yielding a one cent improvement in required freight rate. Could the speaker attempt a qualitative explanation? Also, if a small increase in return on capital leads to such dramatic reductions in size of ships as indicated in Table 8, the general conclusion that 'bigger is better' appears to be unfounded and existing facilities would seem to be adequate without further expansion. Both these immediate conclusions run counter to general experience and therefore cast some doubt on the applicability of Mr. Fisher's seemingly excellent procedures. In his attempts to sell the technique, he will have to devise means of bridging these and similar gaps between logical deduction and experience.

R.J. STACEY, WHYALLA SHIPBUILDING AND ENGINEERING WORKS, SOUTH AUST.

Shipbuilders invariably think of optimizing the design of a ship as the means by which the building cost is reduced to a minimum. Mr. Fisher shows very clearly in his paper the fallacy of such thinking applied to the overall economy of transportation.

My first reaction to the result shown for his principal design was that the vessel is obviously too long and narrow, perhaps as a result of using such a simple powering estimation that the greater efficiencies of modern full formed ships were placed at a disadvantage. However, to illustrate the factors involved I have made estimates for the principal cost effects for Mr. Fisher's principal design having a L/B ratio of 7.70, with a vessel of similar desplacement with an L/B ratio of 6.5 at the same draft.

1. STEEL COST:

Principal Design	Alternative Design.
878.5' X 114.1'	808' X 124.2'
W_s = 16,720T.	W_s = 15,200T.
Difference in steel weight	= 1,520T.
Cost/vessel	= $270,000 (U.K. cost).
∴ 3 vessels cost	= $810,000 less

2. PORT DREDGING:

Channel width increased by 6 X 10'

$\therefore$ cost = 10,000 yds. X $\frac{55'}{3}$ X $\frac{60'}{3}$ X $1

= $3,660,000 extra divided by four parties.

= $ 915,000 extra.

3. WHARF:

70.5' X $3,060 = $216,000 less.

4. **SHIPYARD EXPANSION:**

Length $\frac{70.5 \times \$3M}{950}$ = \$222,000 less, divided by five parties = \$44,400 less.

5. As the same displacement has been used for comparing the steel weights, a slight reduction in C_B may be made to give corresponding deadweights, i.e. $C_B = .867$.

With this lower C_B and taking into account the speed assumptions for loaded and ballast condition, it would be surprising if the same speed could not be achieved for the relative designs, with the same machiney cost.

The cost summary is then:

	(a) 878.5' X 114.1'	(b) 808' X 124.2'
Steel cost	+ 810,000 (1)	
Dredging		+ 915,000 (2)
Wharf	+ 216,000 (3)	
S.Y. Expansion	44,400	
	1,070,400	

1. I feel that the construction cost of steelwork (after subsidy) is closer to \$300/ton, which makes an even greater difference to the comparison.

2. The assumption that channel width requires to be 6 times the beam of the ship requires investigation. In my opinion the main danger lies in the ship's heading turning off the channel heading, and so increasing its effective width, making it possible to run aground. For the case in point the effective width of both vessels is 241 ft. when their heading is 9° off channel heading. Above this deviation it is obvious the longer vessel is more likely to run aground.

3. Wharf cost presumed to be wholly to account of steel industry as statement to contrary could not be found in paper.

It will be seen that up to \$52,000 additional can be spent on greater machinery power for the shorter vessel before the two designs cost the same. As notes (1) and (2) above both tend to favour the shorter and wider ship, I would welcome Mr. Fisher's comments.

In regard to the method of optimizing vessel dimensions, Mr. Fisher is to be recommended, however I feel that the basis for the input data requires careful checking to ensure the right answer is obtained.

A.R.L. Tait, Bureau Veritas, Australia.

Firstly, Mr. Fisher's refreshing and clear presentation made this paper most enjoyable; Mr. Fisher is therefore to be congratulated not only for the importance of his thesis, but for the able and interesting way in which he delivered his lecture, and it is to be hoped that he will find time to give us more like this one.

Despite my own enthusiasm for the paper, I would like to offer a word of caution on the use of dollar as the prime mover, activator or reason for the exercise. I would consider the dollar to take a secondary place and only agree that it should be considered as a catalyst in the operation which, though it should not remain quite unaltered as in a simple chemical equation and should deserve some enrichment, the too strong a use of this motivation does tend to confuse the results to the exclusion of many other commendable features; e.g. safety, aesthetics, long time visionary planning ideas, possible fields of progress, to name but a few.

If we strike out the S (= SAFETY) with two vertical strokes we get the "$" sign but at no time should S be relegated to playing a secondary consideration when dealing with ships and the sea, thus I would have liked to have seen S for the second lecture slide with $ as the third.

As far as Classification Societies are concerned, of course they are primarily concerned with Safety of the ship's structure and this important fact must never be lost sight of. Even so, it should not be said that Classification Societies ignore costs entirely and in Bureau Veritas some extensive computer research programmes have been made, paying very close attention to the fact that a slight increase in scantlings particularly on large vessels means a great loss in overall deadweight.

With increasing sizes of vessels, no longer is the common method of extrapolation of physical dimensions or components possible if adequate strength is to be maintained without a severe weight penalty; I refer therefore to a paper entitled "THE SAFETY OF TANKERS" given by Mr. J. Engerrand and Mr. Y. Hervo of Bureau Veritas in January/February 1970, which outlines a little of our society's thinking in this regard and its efforts to overcome the necessity for meeting safety and yet assist in keeping costs within more reasonable proportions. Other studies are currently being made and an Advisory Service with utilisation of the computer for quick results is available, which will enable the Naval Architect and Engineer to obtain the best of safe scantlings to put forward in his proposed design or designs to the prospective owner. Would perhaps some of the steel weight considerations for the larger vessels have to be reviewed in the programmes in the light of more recent thinking in the Classification Societies?

Going back to the particular case mentioned in the paper of a voyage along the Australian coastline, it would appear that the two ship types can be envisaged giving 3 of about 100,000 tons deadweight or 5 of about half that size with a possible 9% financial return in the case of the larger ships and 11% return in the case of the smaller ones, but with a higher required freight rate of some 9% greater increase in fact for the smaller ones. This surprisingly, at first sight, would seem to the dollar motivated thinker to provide an obvious choice of a 2% extra return with the smaller vessels and particularly if an owner having built in Australia he would not expect to have the fear of outside competition and could charge his own freight rate.

Against this, from Australia's point of view, would be the cost of greater freight rates for the transport of the goods, bigger labour force and associated problems, the loss of the development of a shipyard and a harbour. One would expect that the Shipbuilding Board would certainly not allow such vessels to be subsidised if the overall concept did not benefit the community and industry as a whole. The tool of optimisation thus does give the Shipbuilding Board a much greater overall picture for several choices of design, provided the dollar concept is kept in its right perspective, as it would seem to have such a marked effect on possible design but not be entirely conclusive, and should not be followed blindly.

As an aside, there is of course a well-known company which transports as well as processes its own ores in Australia and such a company might even feel that though they would be getting a larger return from the point of view of running costs, they would be rather reluctant to pay associated higher freight rates. These operators might also consider the port development an advantage when re-shipping the finished products.

Another point of hesitation before choosing too small a vessel in this exercise is that in the case of future expanding demand, perhaps many small vessels would be required and would take too long to produce and larger vessels would be needed anyway. I would like therefore to ask whether in the optimisation programme it would be possible to introduce a realistic projected economic expansion factor? (It has been possible to place an economic growth rate factor on crew costs and costs for later built vessels).

Since the study in the paper dealt with an Australian vessel, would the study of a vessel capable of a double duty - Japan-Australia and Australian Coast - necessarily result in a vessel that was unsuitable for later use on the Australian Coast voyage only? Such a vessel might be worth a study from the Australian Shipping Industry's point of view, as it might be useful to use Australian ships to export the raw materials until a greater content can be processed in Australia itself. Such a ship might also have a better world-wide resale value at the end of its supposed 15 years life.

Finally, it seems that Naval Architects and Engineers must no longer be purely technical in their outlook, but must learn to assess the influence of ever-pressing monetary considerations, but nevertheless be strong enough to resist being completely swayed into decisions purely for financial reasons.

Captain W.J. Rourke, Royal Australain Navy.

Mr. Fisher has prepared a most interesting paper on "Economic Optimisation Procedures in Preliminary Ship Design". It is so comprehensive that it presents some difficulties in ready assimilation. The reader would be helped by some more detailed explanation of procedures, and a key that explained all the symbols used.

This discussion will look at the problem specified, the general method of solution, the particular algorithms used and finally at the conclusions of the design study.

The author has chosen for his problem a particular shipping route with a specific quantity of cargo to be carried in a given time. For any particular discrete number of ships there is therefore a unique relationship between cargo capcaity and speed. This may not be a logical constraint. The ship with the least freight rate might not fit into any of these unique relationships, but may still be preferred even though the ship moved all the ore in 12 years rather then 15, or every few years ran an occasional voyage on charter. In other directions the approach is appropriately broad and demonstrates clearly that it is not sufficient to optimise one parameter at a time, nor is it sufficient to optimise the ship as a whole if the ship is an integral part of a more comprehensive transport process.

The general method of solution must be the key part of the paper and I suggest the author could have provided us with more explanation of his choice of parameters and his method of mathematical manipulation. He lists his five principal parameters as:

(1) Cargo capacity;

(2) The differences between LBP, and LBP as a function of DWT.

(3) The differences between C_B, and C_B as a function of design speed and LBP;

(4) Length/beam ratio.

and (5) Beam/depth ratio.

Would Mr. Fisher tell us why he chose the particular parameters listed, and what the effects are of having variables (2) and (3) partly dependent upon (1). In the iterative procedure detailed in Fig. 4 the author appears to use a series of the fixed relationships whose use he sets out to avoid.

The author has calculated those values of the parameters that lead to a minimum required freight rate, by the technique of Nelder and Mead. He says he was able to calculate a minimum after an average of only 66 trials. To calculate for each of four values of five parameters requires 1024 calculations and 66 trials corresponds to about three values of two parameters and two of three others. I would like to be convinced this established a global minimum.

Mr. Fisher provided us with two mathematical references and I have made what I could of them. It appears to me that Nelder and Mead start at a point in n-dimensional space and then take a series of steps down the slope, reversing direction should they overrun a valley to the rise on the other side. This to me may find a local minimum, but may fail even to explore some other area with another local minimum, that could provide the least value. I note that Box says "the method.... performed well in two dimensions, and also to a lesser extent in three dimensions, but for more dimensions it was progressivly less successful". Would the author explain how he can be confident a true minimum is found so quickly, and in what way the method is superior to Mandels experimental random technique. I would also like his comment on the cost saving of an "efficient" programme compared to one that looks at tens of thousands of notional ships.

I would now like to discuss some of the particular algorithms used in detailed calculations; the relationships appear open to some argument:

(a) The ship lifetime chosen of only fifteen years seems unusually short and to use a salvage value directly proportional to unexpired life seems an over-simplification. It is suggested a life of 20-25 years, and a sliding scale depreciation may be more appropriate.

(b) The device of taking a function for British construction costs, and converting it to a function for Australian construction costs by multiplying it by an average cost ratio, appears of doubtful valifity. The proportion of steel cost in ship cost increases with ship size. The Australian/British steel cost ratio is about 1 : 1 and the labour cost ratio about 2 : 1 or more. So the ratio of Australian to British costs should decrease with ship size. It is not clear how the author converts the notional building cost, to the subsidised cost to the owner.

In estimating the benefits of multiple construction the author uses the equation :

$$\text{Average cost} = \frac{\text{First Cost}}{(\text{N ships})^{0.09}}$$

and attributes this to the work of Couch. But Couch (1963) derived an exponent of 0.097 for general cargo ships built in the US. and the translation to 0.09 for bulk cargo ships built in Australia needs some justification other than approximation.

The authors expression for residual resistance appears to produce resistance coefficients with variations of about 10% from Gertler-Taylor. Is it not practicable to use a more accurate derivation of these figures?

The statement about rising costs on page 15 of the paper appears to mean that in the same year the annual operating costs of the ship just completed will be higher then those of its predecessor built two or three years before. No justification for such an assumption is given. The author does not state whether he has modified Benfords crew cost relationship to reflect the pay scales on the Australian coast.

(If the expression quoted applies to the Australian coast, then some of us here are in the wrong business).

In discussing sensitivity to interest rates in section VI-4 the author notes that 80% of the capital was borrowed. I believe it difficult conceptually to assign a value to use of shareholders funds other then the market rate of capital over the appropriate term and would like Mr. Fisher to discuss how he has combined the costs of borrowed capital and the costs of internal capital.

The auther points out that he has conducted a restricted optimisation by confining his attention to slow speed diesel engines, and suggests that countries with the proper technology should investigate oil fired and nuclear steam installations. Nuclear plant is not yet likely to produce a low freight rate and gas turbines may be a more competitive contender. Of course countries do not have to make an engine to put it in their ships, and most Australian built ships use engines from overseas.

The summary of the analysis shows the optimum fleet to be:

(a) 3 ships of fixed pitch propellers of 104,600 DWT and speed of 13 knots,
or
(b) 4 ships with controllable pitch propellers of 71,100 DWT and speed of 14 knots;

or if interest rates rise to 11%

(c) 5 ships of 57,600 DWT and speed of 14.5 knots.

Just what do these results show? Perhaps they demonstrate that the problem is unusual and that the solution has marked discontinuities. So we come back to whether or not the problem is the right one to be solving. It appears that in restricting the ships to a closed system of ore transport in fixed quantities in a fixed time, the solution has been artificially constrained. It is suggested that the problem should be widened to allow for greater variations in work load.

There is much in this paper that is arguable and perhaps for that reason it is particularly stimulating. The techniques of design optimisation that Mr. Fisher has outlined can be applied to all types of ships; war ships as well as merchantmen. Australia has been slow in applying such techniques to preliminary design and Mr. Fisher will have done us a considerable service if his work accelerates acceptance of such new approaches to the design of ships.

<u>MR. E.S. CLARKE</u> (General Manager, Australian Shipbuilding Board)

Professor Fink has explained the technique of getting ships built in Australia under the subsidy scheme. The object of the scheme is to offer the ship to the owner at a price which he would pay for the ship built in UK and delivered to Australia. However, the subsidy cannot exceed 33-1/3% of the Australian construction cost.

Therefore, I am not quite clear why the paper introduced the concept of shipyard expansion and so on into the analysis, for the reason that the price to the owner would be equated to the British price in which those cost elements would probably not be found because of existing facilities.

The point made earlier in the discussion, that there is a selling problem here is an important one. I think, if I may say so, that you brushed it off a bit as a secondary problem. I suggest that it is not much use devising an optimisation technique like this unless it can be "sold" to the owners who have to finance the construction of a ship that will operate profitably.

(9) TO (11)

I think the summary of the object of the exercise on page 32 is good, i.e. the final choice of ship "remains a matter of judgement", but an optimisation technique should help in making the choice.

This is in line with the point that Professor Benford made that finally, in the face of some such analysis as this, some man or board has to make a desicion as to the ship that has to be built. He may have quite non-economic or not easily analysible considerations influencing the making of such decisions on a ship such as uncertain diversions of the ship to other trades, or its use in export trades and so on. But it seems to me that the sort of exercise we have heard about will form a very good basis of such decisions. It might be worth considering, towards selling it to the owners, to demonstrate its relevence by carrying out exercises on ships that have been considered and built to determine how such ships measure up in terms of optimisation technique.

Author's Reply

Professor Nowacki's comments on the incorporation of constraints in the computer programmes are entirely in agreement with mine. Specifically, some of the basic efficiency of the optimisation technique has been lost by the manner in which the constraints have been handled.

However, Professor Benford answered that in his comment about refinements and improvements in computer programmes. It is prefered to think of the material presented as a display of techniques, using a number of building blocks, having potential interchangeability with others for greater refinements or genuine changes. This is consistent with the second paragraph of section V.3. As Figure 3 indicates, the minimisation sub-programme is one of those building blocks which may be exchanged for the S.U.M.T. or other method.

In answer to Professor Nowacki's specific questions, no evidence of any local valleys other than the global one found. However, the author remains unconvinced on this matter, as only a limited number of trials were conducted.

The measure of merit function (RFR) has not been displayed in the vicinity of the optimum due to page space considerations. However, it is opined that if the RFR is displayed, it should be in "spaces" of the economic environment, such as that of the sensitivity studies (section VI), and not in the relatively un-important "spaces" of length-to-beam ratio, speed-length ratio, etc., except for the purpose of demonstrating errors in pre-judged decisions. Further, the sensitivity studies indicate that dredging costs are the primary constraint, while shipyard expansion is the secondary one.

While Professor Benford's introduction of intangible considerations into the design problem deserves much more attention than has been given to them, the author feels that this might be an area in which significant re-thinking must be done. Being a firm believer in rational decisions, the author is led to the conclusion that the most rational decision is the one having the least non-reliance on the economics involved. If a ship owner is willing to put a price on some intangible considerations, then the price he is paying for them can be ascertained by completing the economic optimisation without those factors in the first place. A decision can then be made on a firmer foundation.

Both Professor Benford and Captain Rourke appear to misinterpret the use of the formulae in section V-2. Those are used only as a first approximation to the primary design parameters, in order to speed-up the optimisation process. Thereafter, the relationship between, say, the length and deadweight is only an economic one. The difference between the LBP and the mean statistical value as a function of deadweight, which is then known at the conclusion of the optimisation, merely indicates where the design stands relative to current practice.

Regarding Professor Benford's comments on the high block coefficients, while it is agreed that it seems very high, it may be attributable to two factors. One is the inadequate amount of information known on powering of ships of such high block coefficients, and the other is an oversight regarding the voyage information. As far as the inadequate information relating to the powering of ships is concerned however, it should be noted that this ship's speed-length ratio is just over 0.4, and therefore most of its resistance by far is purely frictional resistance. The oversight is that while assigning 8% of the time at sea to lost time due to bad weather, it is now suggested that should have been coupled with the block coefficient, where perhaps for a block coefficient of 0.8 it would be 8% of the time and for a block coefficient of say 0.5 it might be 5% of the time at sea lost to bad weather. This would be a slight penalty for higher block coefficient as it correctly should be.

Professor Benford's comments on the dredging aspect of the problem might properly come within the "refinement" category of programming. Further to the point is the fact that, at present, only pleasure craft of extremely shallow draught can navigate Port Stephens.

The suggestions that the relative shares of equity be neglected cannot receive agreement from the author. For only a little extra computer time, the exact sensitivity of the optimum design to the relative portions of ownership and loans can be ascertained. Thus the designer need not be concerned with the "exceptional cases" of which Professor Benford speaks.

The suggestion that half-ship sub-assemblies be used as an economic alternative to shipyard expansion, as Professor Fink indicates, is altogether reasonable. If the costs associated with such a construction procedure could be determined as general functions of the physical dimensions, it would be very easy to incorporate them into the programmes, thus searching for the optimum design to be produced by that method. That would result in a most interesting comparison, indicating the overall worth of shipyard expansion.

In reply to his specific questions centred on Tables 12 and 8, it can only be re-stated (section IV-7) that there are a number of step-function costs and physical relationships. This state of affairs results in a very irregular set of contours in the multi-dimensional RFR-space. Additionally, the basic requirements that the fleet size be an integer number of vessels causes further irregularities of the contours in the RFR-space. Perhaps a very fine sensitivity study would reveal those contours, and therefore satisfy Professor Fink. Such additional studies must await the sponsorship to which he alludes, but the source of which he refers to as a vague "we". That study is of the type mentioned in the above reply to Professor Nowacki's discussion.

The optimum design, it must be realised, is going to be a function of the total environment in which the design occurs; environment being defined in economic as well as physical terms. In that light, Professor Fink's summary regarding pre-conceived notions is not at all inconsistent with the author's second paragraph of the initial summary.

The author is in complete agreement with Mr. Stacey's cautionary statement regarding input data. There is much work to be done yet in those areas, the accomplishment of which requires a greater amount of data being released by shipyards, engine builders, and classification societies. His figure of Aust$300/ton for steelwork is not consistent with the author's, (Aust$240), pointing up the communications problem to an even greater extent.

Mr. Stacey's comment on channel width is of concern. However, the author was consistent with the recommendations of local authorities.

Mr. Stacey is correct, generally, in his diagnosis of costs. According to the required power estimating procedure, for vessels of his suggested dimensions, the horsepower is 17,270 (British), slightly above the 17,160 (British) which is the power required for the given vessel, as well as being the maximum of the 6-cylinder, 90cm. engine. Thus, the next larger size engine is needed (7 x 90cm), costing $140,000 additional per vessel (Table 1), this being a sum beyond his calculated $52,000.

Although the method of power estimating requires refinement, use of the same method demonstrates that the optimum has been chosen correctly, insofar as the input information is correct.

Mr. Tait's question regarding steel weight serves to emphasize the very point made in reply to Mr. Stacey's comments on costs of steel work, calling for closer cooperation by all involved to estimate such quantities in preliminary design studies. His comments regarding safety are well received, as seen by the author's own written discussion on Professor J.F.C. Conn's paper, "Mammoth Ships" (I.E.S.S., 1970). It is necessary to include in cost-optimisation procedures the effects of insuring maximum safety and minimal damage arising from possible accident. Assistance toward the implementation of this must be forth-coming from organizations responsible for that aspect of ship design.

Concepts along the lines of projected economic expansion factors, if suitably defined, are easily incorporated into optimisation procedures. Indeed, this could lead, with added complications, to open-ended studies, which are not chosen for a fixed period of time. Perhaps that is what Mr. Tait had in mind.

The matter of double-duty vessels at first appears to be not inconsistent with Captain Rourke's comments on chartering for 3 of 15 years. The study would lead to a vessel with slightly higher RFR's, since it would have to fall within additional constraints. It could well be a price worth paying, however, with the price being readily ascertained.

While several other aspects of Captain Rourke's discussion have been included above, there remain several important ones. His comments on the possibility of doing all the movement of cargo in, say, 12 years rather than 15 has opened up new worlds to the author. Perhaps one of the free-floating variables should be the number of years over which the contract should be fulfilled, with an upper limit of say, 15. The author regards that as potentially the most significant aspect of all the written discussion, and shall endeavor to explore the matter in future studies which will be reported in the literature.

It appears obvious to the author that the first several comparably-oriented papers appearing in the literature will have to be ones of an educating nature. However, it is felt that detailed explanations regarding the mechanism by which the optimum of five parameters can be chosen after only 66 trials, as requested by Captain Rourke, are significantly beyond the intended scope of this paper. As mentioned in the reply to the discussion of Professor Nowacki (who is pursuing comparable studies at the University of Michigan), the use of the technique in the form of a building block in the procedures is all that need be comprehended by those who are not themselves going to write programmes. Further elucidation in another field of application may be available from the recent paper: "Multivariable Search and its Application to Aircraft Design Optimisation," Stepniewski and Kalmbach, The Aeronautical Journal, Royal Aeronautical Society, May 1970.

Journals on computer techniques are best referred to for such queries.

In response to the inquiry into the cost of using "inefficient" programmes, it is pointed out that each optimisation required about 66 design evaluations. If, instead, 10,000 design evaluations were conducted, the required computer time would be only slightly less than 10,000/66 times the time now required. It should be realised, too, that only four different values of each of seven independent parameters requires 16,384 trials. The author believes that at least 8 different values of each (over 2 million trials) would be necessary to have the same reliability as the present method. At this point, also, the limitations of the random search technique become obvious, with the reliability going down quickly as the number of independent parameters parameters goes up.

The method of Nelder and Mead was chosen for this study, not only for its efficiency, which decreases slightly with increasing numbers of variables, but for its consistently high reliability. Perhaps the S.U.M.T. or other methods, all of which are being tried out at various research centres, will ultimately prove to be the most satisfactory. In any case, the use of a general direct search technique is the important point.

The matter of combining costs of borrowed capital with that from loans, in reply to Captain Rourke's question, is explained in the reference: Benford (1968).

The author's final comment is in reply to Captain Rourke's query regarding costs. The figures presented herein are modified from Benford's, but require collaboration and/or correction from industrial sources in Australia.

The author is sincerely grateful to all of those who have contributed to the discussion of the paper. As seen in the reply to the discussions, much has been learned by the author from it. Equally, it ensures that the paper is complete and comprehendable in the R.I.N.A. Transactions.