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OPTIMISATION CONCEPTS IN SHIP DESIGN

K.W. FISHER

DEPARTMENT OF MECHANICAL ENGINEERING
THE UNIVERSITY OF SYDNEY

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by K. W. Fisher*

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Since 1965, the application of general computer-aided optimisation techniques to various areas of ship design has been utilised with increasing success. Often, the technique has been used for structural design, in which the optimised parameters have been a combination of stiffener and frame section moduli and spacings or plating thicknesses. A number of studies have also included as optimised parameters one or two subdivision dimensions. More recently, in addition to structural work, the principal ship dimensions have been subjects of optimisation studies.

The number of simultaneously optimised parameters has grown from 4 to 12, and with that growth have come a number of problems arising from a basic re-thinking of the design process in order to take advantage of the benefits of design optimisation. The first-encountered of these problems has been the necessity of a mathematical-type rigorousness being used in both the definition of the system to be optimised, and the criterion which is used to judge the relative merits of alternate possibilities.

Quite rapidly, too, the problem of an "acceptable" range of parameter values has been found to require mathematical definition, rather than the "considered judgement" of experienced naval architects. But the most significant problem associated with the concept of optimisation in ship design is that of the planning necessary for the simultaneous, rather than sequential, decision-making for all the relevant parameters.

*Department of Mechanical Engineering, University of Sydney.

Practitioners of those optimisations have found that a basic re-education of their associates is fundamental to the blending of good naval architectural practice with appropriate computer optimisation techniques in order to achieve acceptable and highly-regarded designs, rather than contemptuous remarks about how the "computer made a mistake."

The first part of this paper discusses a number of those problems associated with design optimisation, drawing on over 20 reported ship design optimisation studies for elaboration and examples. The second part of this paper, using VLCC's as an example, proposes the thesis that it is possible to simultaneously optimise over 40 parameters associated with principal hull dimensions, subdivision configuration, and major structural scantlings, subject to all relevant constraints. As a prelude to such a "total optimisation", the entire subdivision configuration of a 400,000 DWT tanker, involving 20 parameters, and subject to the new IMCO regulations, is designed by use of a general optimisation procedure.

1. INTRODUCTION.

The 'design problem' for tankers is probably one of the simplest total problems likely to be encountered by practioners of naval architecture. The word 'total' is used to indicate the finished product - a separate entity, capable of satisfying performance requirements by itself.

It is only quite recent that the design of such a large object has been contemplated as a single process involving simultaneous decisions, rather than a series of processes requiring sequential decisions. The prime reason for this late development of the design concept has been the inability to cope with all the implications and ramifications simultaneously. That inability, itself, is now being overcome largely due to two not wholly unrelated advances.

The first is the economic motivation to examine the various aspects of ship design in a more 'scientific' manner than has previously been done. It has taken the dispensers of research funds a considerable time to learn that scientifically rigorous research in all areas of ship design does, generally, have a good economic rate of return associated with it. As will be seen by the end of this paper, while practitioners of ship design have begun to view the design process as a group of simultaneous decisions, designers are still a long way from being able to adequately cope with the entire process; thus pointing out that continued research funding will still be quite useful and will continue to show a good return.

The second reason for the only-recent development of the total design concept is, of course, computers. They have been useful not only in aiding the more rigorous scientific approach to segments of the design problem, but have also meant that larger numbers of simultaneous decision-consequences could be studied. In further sections of this paper, examples will be given demonstrating the growing size of the fraction of the design problem that is being simultaneously handled by the aid of the computers.

Because this generalised approach to design is relatively new, it is being applied first to the simplest transport problem, that arising from the carriage of bulk homogeneous materials. The problems arising from the application of that same approach to non-homogeneous cargo transport mechanisms are, perhaps, only doubly complex when compared to tankers and bulk carriers. It is not, to be sure, a new order of magnitude. This is evidenced by the fact that although reports on the applications of the new techniques to tankers [Mandel, 1966] [Nowacki, 1970] and bulk carriers [Fisher, 1972a] appeared first, work is being pursued on the comparable application to vessel types as container ships [Erichsen, 1972]. Two summaries of an integrated approach to design are given by Vahl [1972] and Nowacki [1972]. An excellent description of one entire system for technical evaluation of a design is presented by Yuille [1970].

All of this is, of course, entirely consistent with the statement made by Professor Benford ten years ago in his discussion of the paper by Evans [1963]:

> We are steadily approaching the day when major decisions in preliminary design will be made on a rational basis with all conflicting requirements properly integrated.

Nachtsheim [1970] points out that the introduction of the automobile did far more than merely replace the horse, to the extent that "it has dramatically affected our entire way of life," having been the start of a new system. He then goes on to ask:

> Is there an incipient "system" lying beneath the bits and pieces now available or ultimately available to our industry from computers which offers orders of magnitude improvement to the industry?

While it is yet impossible to fully answer that question, this paper attempts, in part, to develop the guidelines for the affirmative answer from the designer's point of view, in the context of optimisation. The discussions of previous works are presented as evidence that the "bits and pieces" will indeed prove to be the tips of the iceberg of that new ship design system.

2. CRITERIA

> The first essential in any technique, be it computer or any other, is for management to take a good hard look at itself and its problems and to be quite sure that it knows where it wants to go, and how it intends to get there. [Steward, 1965]

Prior to a proper discussion regarding the development of optimisation applications in ship design, regard is given to the calculable object function that is to be optimised.

The works of Benford [1963, 1967a, 1967b, 1970], Goss [1965, 1967] and Steward [1965], collectively demonstrate the desirability of regarding the ship design problem from the point of view of ensuring the commercial, and not merely the technical, success of the vessel. Individually, those papers illustrate several avenues of approach to that consideration, including the shipbuilder's requirements. Under almost all circumstances, the economic aspects will dominate the design decision-making process, and the mentioned papers give illustration of that point. There are occasionally exceptions, however, an example of which is given at the end of this section.

Essentially, the value of the object function determines the relative merit of the design, differentiating a "good' design from a "better" one. The determination of the absolute merit is much more subjective than a group of calculable functions, which are collectively referred to as 'criteria'.

A discussion on the approach to that subjective decision, incorporating probabalistic-type studies, is given by Fisher [1971]. The need for such an approach is emphasized in the discussion of the Benford [1963] paper by the economist-turned-businessman, G.F. Bain:

> The heart of the matter of engineering economics is uncertainty...[One] should beware of falling into the error of assuming that these formulas will always give precise answers relevant to the real world. Precise figures, yes. But no engineer should become enamoured of precision when dealing with economic concepts.

It being firmly established that, in general, the final criterion to be optimised is an economic one, the questions arise: which economic criterion?...covering how much of the system? A general view of the requirements for answering those questions is given by Woodward [1968], in which the ship is considered the essential core of the system.

In contrast, but also complementary to that view, Nachtsheim [1972] discusses the system - less the ship.* Mr. Nachtsheim's paper is a stimulating one, urging naval architects to strive toward designs that approach the ill-defined elusive goal of "lower costs". But that paper fails to emphasize that as a criterion, the matter of "whose" costs are to be lowered often defies rational judgement. Consider the following quasi-mathematical formulation.

The general transport system consists of numerous components, each of which are probably owned by different interests; operated by further different organisations; and subject to widely differing rules and regulations. Whose costs are to be optimised? The individual owners, the different operators, or the system user?

It is a rare mathematical problem that has a co-incidence of boundary conditions. And yet, it is precisely that type of unique solution that is desired when the component-owner's costs are to be minimised by the same solution which optimises the sub-system operator's costs, all within the constraints of certain rules and regulations.

The mathematical improbability of finding a satisfactory solution is highlighted when it is realized that the same solution must be that dual optimum solution of all individually considered components in the system.

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*part of this section is taken from the present author's discussion of the paper referred to in the text.

It is easily comprehended that the sum of the optimised partial costs is going to be greater than the optimised whole. What leverage is available to cause the individual sub-system owners and operators to allow their solution to be dictated by the overall optimum solution? Who will exert that leverage? To be sure, that overall optimum will render some of the components less profitable by present standards, if not redundant, when contrasted with a series of sub-system optima.

The movement of borax, described by Nachtsheim [1972], is an acceptable example. It is pointed out that in moving the borax to a Californian port from inland, the former system consisted of using 50-lb. sacks, regular box-type rail carriages, and conventional conference-operated ships to move the sacks to Northern Europe. Now the system utilises 100-ton hopper carriages, a special bulk shipment port facility, and a unique bulk vessel under charter. What has happned by that change?

The product of the sack-maker has become redundant by the change from usage of 50 lb. sacks to 100 ton hopper cars and dry-bulk ships. The capital outlay of the railroads has increased. The conference shipping lines have lost an important customer. The port authorities were called on to provide new bulk terminals, while suffering decreased use of the conventional facilities. The profit of the labour component is substantially curtailed.

By whose criteria is the solution an improvement? Who has gained by the consideration of the total system, and not individual components? Perhaps by the judgement of technologically oriented people involved and the overseas customer it is a superior system. But by the judgement of the port authorities, railroads, sack-maker and those concerned with un-employment, it is not an entirely satisfactory solution.

This example serves to illustrate a very important aspect that must be given far greater consideration than previous authors have implied. Namely, the boundaries of the transport system must be clearly stated - perhaps in mathematical terms - before attempts are made to achieve a more optimum solution. Without doubt, Professor Benford's Universal Dictum is applicable: one man's system is another man's subsystem.

It is also probable that the best choice of criterion changes with the passing of certain events. This is illustrated by another example on a far smaller scale, in which the entire 'system' is a series of hatch covers for a large bulk carrier.

Suppose a fixed-price construction contract has been let to the shipyard by the vessel's owner. The owner would prefer at this stage to have the lightest possible hatch covers, since every ton of lightship weight is one less revenue-earning ton of deadweight. The shipyard, however, would like to supply the least-cost hatch covers, since every dollar saved in the construction is a dollar profit.

Are the two criteria compatible? Will the same design satisfy both parties? S.R. Heller's discussion of the Evans [1963] paper would indicate that the two optima are most likely not identical. In that discussion, Capt. Heller shows that the minimum-weight transverse frame spacing of a conventional vessel may vary by 10-35 percent of the minimum-cost spacing.

The above comments all demonstrate that the seemingly simple task of choosing an appropriate criterion is, in fact, anything but simple. A final illustration of that point is given in Appendix I.

The use of a weight-optimisation study, as in the hatch cover example above, is not always the end of the process. Such studies having a least-weight criterion are quite necessary in the continuing maturation of the general design solution.

The reason for that requirement is recognition of the desirability of first firmly establishing the feasibility of achieving weight optimisations prior to later including them as a component of the larger economic optimisation. The tanker subdivision optimisation reported later in this paper constitutes one of those feasibility studies, using a weight criterion of limited scope.

3. CONSTRAINTS AND PENALTY FUNCTIONS

The use of the words "internal" and "external" constraints in the following sections should not be confused with the "interior" and "exterior" penalty functions.

Firstly; "constraints" are the upper, lower or integer limits on certain parameters in the acceptable solution. Violation of a constraint causes the solution to be unacceptable. For example, if the midship section modulus (Z) is less than that minimum value required by a classification society, (Z_{MIN}) then the design (solution) is unacceptable because the constraint ($Z \geq Z_{MIN}$) is violated. That is an example of an 'external' constraint, because it is imposed regardless of the mechanism used to find an optimum solution.

An 'internal' constraint might be stated as: the widths of the wing tanks (of a tanker) plus the width of the adjacent centre-line tank must be equal to the beam of the vessel. It is considered 'internal' because the possibility of violating that constraint arises only from the manner of solution; and it may not arise if a different technique was being employed. In the summary of constraints:

(a) INTERNAL CONSTRAINTS are those arising from the necessity of physical compatibility of the various components.

(b) EXTERNAL CONSTRAINTS arise from considerations of environmental factors, operational and construction limitations, strength requirements, and the regulations of outside authorities.

In contrast to constraints, a "penalty function" is a mathematical formulation that essentially alters the topography of the solution-space in order to assist the optimisation process toward finding an acceptable solution. Examples of several different types of penalty functions are best explained graphically, as in Figure 1 , which is for a 1-variable constraint. If g(x) is the penalty function, then it is applied in this manner:

$$F(x) = F_0(x) \cdot (1+g),$$

in which $F_0(x)$ is the unconstrained object function. In this paper, a stepped exterior penalty function is used for all non-integer constraints, as in Figure 1 (D).

FIGURE 1

Illustrations of Penalty Functions

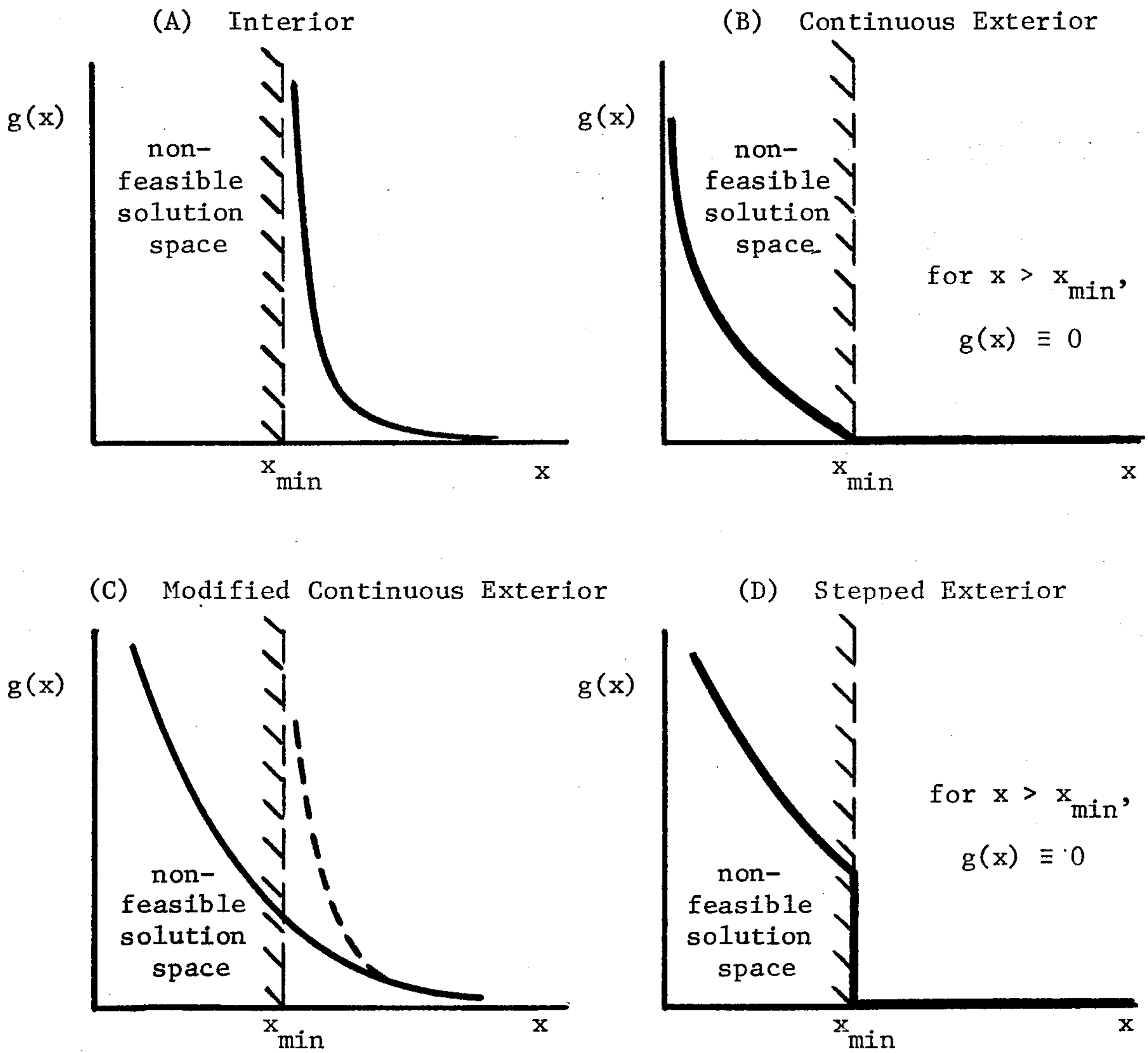
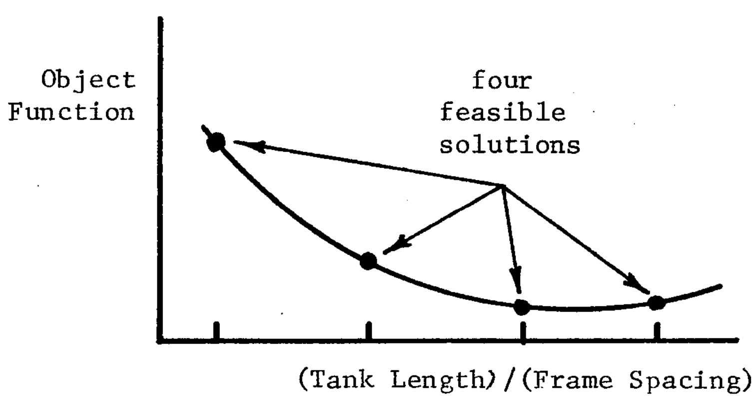


FIGURE 2

Illustration of Integer Constraint



It may be noted that interior penalty functions are ill-defined or undefined outside feasible spaces; and thus their use requires a non-optimum but feasible set of variables at the start of the optimisation program. Often, the determination of that feasible, non-optimum solution is a lengthy and arduous process.

4. LOCAL AND GLOBAL MINIMA

The presence of multiple local minima in the topographical solution-space is usually detectable from the construction of the problem or from the use of integer-constraints. In the bulk-carrier study by Fisher [1972a], for example, the presence of local minima was suggested by the use of discrete-size slow-speed diesel engines for propulsion. Thus the unaltered topography itself may have at least as many local minima as discrete size power plants. Illustration of that point is given in Appendix I.

In the case of using a steam turbine power plant for a vessel, for which continuously varying weight and cost functions are applicable, a local minimum would occur at the point of stepping from one to two shafts. If the solution was found to be optimum for a power plant well-away from that critical size, then it would appear advisable to seek the other local minimum in order to gain confidence as to the global nature of the first-found solution.

The application of integer-type constraints is also the source of production of multiple local optima. The requirement that a tank length be an integer number of frame spacings, when optimising the internal configuration of a vessel, is an acceptable example. Figure 2 shows an object function of the (tank length)/(frame spacing). From the construction point of view, only four points are feasible solutions, the remainder of the unconstrained curve being an "illegal" solution. Thus while an unconstrained object function may have a unique global minimum, the topographical alteration arising from the application of an integer or stepped penalty function will apparently have several local minima.

In the tanker subdivision optimisation presented in this paper, integer-type restrictions arise from three requirements, and a series of steps in the object function lead to similar integer-type restrictions.

The steps in the object function (total weight of subdivision bulkheads) appear as the bulkheads are brought closer together by the optimisation procedure. When two bulkheads are more than, say, 0.1m apart, they both contribute to the weight. At some point in their closer approach to each other, however, they must be considered as the same bulkhead. That process leads to a stepped, rather than continuous object function.

For the study reported in this paper, the effect of those local minima being present was avoided by a very slight program alteration. Namely, the program was established in such a manner so as to optimise for the specified number of bulkheads. The local minima were identified by systematically altering the number of centre tank and wing tank subdivision bulkheads.

5. FLEXIBILITY OF RESTRICTIONS

The three integer-type restrictions, mentioned in the previous section, which arise in this subdivision optimisation study, originate in the problem statement itself. Specifically they deal with the requirements of a shipyard, and the ability to safely and accurately construct the vessel.

(i) The transverse bulkheads must be positioned on deep web frames, which are uniformly spaced throughout the total cargo section length, L_{TOT}.

(ii) The longitudinal bulkheads must be positioned an integer multiple of 5cm apart.

(iii) The deepweb frame spacing must be an integer multiple of 5cm, and still fit an integer number of times into L_{TOT}.

At this point it becomes apparent that recognition of the origin of those integer restrictions can make the problem far simpler to optimise by the creation of a larger number of possible combinations. That is achieved by a realistic amount of flexibility.

If the total length of cargo tanks, L_{TOT}, is 305m (as it is for this study) then for deep web frame spaces between 3.5m and 6.5m, there are only two (5.00 and 6.10) which are simultaneously an integer multiple of 5cm and integrally divisible into L_{TOT}. However, if L_{TOT} is specified as 305.0 ± 2.0m, then 48 different feasible frame spaces are acceptable, and 13 are unacceptable.

The effect of this is to increase the number of valleys that may lead to local minima; but at the same time reduce the heights of the crests between them so as to reduce considerably the probability of the optimisation scheme becoming "bogged down" in one of them. That situation is obviated by an appropriate choice of step sizes for the optimisation search itself.

Another example of flexibility incorporated into the study is that of the slop tank capacity, which was specified as a nominal 2.5 percent of the total cargo capacity. As there is no firm rule regarding the capacity, it is allowed to vary by ±0.5 percent in order to more easily fit the required volume into two tanks, for which both the length and width were subject to integer-type restrictions.

The containership optimisation study by Erichsen [1972] is the basis of a further example of the room for flexibility in constraints. In that study, a solution is first demonstrated using a non-integer number of vessels, but with the constraint that the vessels be identical. However, once the integer-type solution is required, the addition of integer restrictions is not the only step necessary. The constraint of identicality of ships should have been removed at the same time, but with economic benefits available if certain design parameters of the vessels are the same. What is accomplished by that action may be seen in the following.

Suppose the optimum non-integer solution calls for 2.8 vessels capable of transporting 2400 standard 20 ft. containers. The addition of the integer constraint coupled with the removal of the identicality constraint then results in an optimum of, say, two vessels having a 2650-container capacity, and one of a 1900-container capacity.

The solution, in brief, might be to begin construction of the first 2650 capacity vessel; and before it is necessary to devote funds to the development of the third vessel (1900 capacity), situations will have changed, as well as having new and different peripheral data. Then a new optimisation scheme will show that, with one 2650-capacity vessel about to enter service, and with another's construction just beginning, the third vessel should almost surely be somewhat different from the 1900-capacity envisaged in the previous optimisation.

This example illustrates the necessity of maintaining maximum flexibility and minimum commitment when dealing with constraints, while assigning proper economic penalties to non-identicality.

The concept of flexibility through continuous re-assessment of the 'optimum', based on up-dated information and data, for use in the construction of a fleet of vessels, is parallel to the philosophy expressed by Benford [1972], which is applicable to the demise and/or replacement of a fleet.

6. OPTIMISATION STUDIES

The purpose of this section is to present a summary of several reported parametric and optimisation studies that deal with some aspect of ship design, in order to indicate the existing scope of abilities. The parametric-variation studies are, of course, the forerunners of the optimisation studies. A self-explanatory summary of them is shown in Table 1. Inasmuch as there are often considerable delays in the publication

TABLE 1

PARAMETRIC STUDIES IN SHIP DESIGN

Source	No. of Independent Parameters						Notes
	principal characteristics	pltg thicknesses or widths	stiffener sections	stiffener frame spcg.	subdivision positions	others	
Evans [1963]	4	-	-	1	-	1	General Cargo ship midship structures.
Murphy [1965]	6	-	-	-	-	-	General Cargo ship overall costs
Chapman [1966]	4	-	-	2	-	1	General Cargo ship structural weights.
Buxton [1966]	4	2	2	2	2	-	Tanker midship structure, includes effects of different stiffener arrangements.
Johnsen [1966/7]	2	-	2	4	2	2	Tanker and Bulk Carrier Structures, includes effects of different steel types.
Gilfillan [1966]	4	-	-	-	-	-	Bulk Carrier overall costs
Kuniyasu [1969]	5	-	-	-	-	-	Bulk/Ore Carrier overall costs
Aldwinckle [1969]	5	-	-	-	-	-	Bulk Carrier Longitudinal steelweights
Gilfillan [1969]	4	-	-	-	-	-	Bulk Carrier operational studies
Talbot [1971]	2	-	-	-	-	2	Tug and barge transportation studies

of reports, the dates cannot be safely used as an indication of the progress made when they are within one or two years of each other. Thus there is no precise order to that summary.

While the purposes of some parametric studies (e.g. Buxton, 1966) are to develop a more comprehensive understanding of the relative importance of the pertinent parameters, others (e.g. Talbot, 1971) are for the purpose of finding an optimum combination of parameters through a semi-manual procedure. It is therefore difficult to say whether some studies should properly be called "optimisations" or "parametric variations". That problem is of little consequence, however, and is mentioned only as background to the presentation of Tables 1 and 2.

The second of those tables is a comparable summary of reported optimisation studies, in which the total number of simultaneously optimised variables is noted, along with the number of constraints. In addition to those variables, there are frequently one or two other variables which are "controlled", rather than "free". For example, Moe [1969] controlled the number of longitudinal stringers in the tanker structure; Lorentz [1970] controlled the number of transverse subdivision bulkheads; and Fisher [1972a] controlled the number of vessels in the fleet.

In order to give greater depth to the content of Table 2, brief descriptions of five of the reported optimisations are given in the following sub-sections. Careful consideration should be given to the applicable constraints, especially in the study by Lorentz [1970], the constraints of which represent the most comprehensive set of restrictions in the studies reported.

TABLE 2

OPTIMISATION STUDIES IN SHIP DESIGN

Source	No. of Independent Parameters							Constraints		Notes
	Total	principal characteristics	pltg thicknesses or widths	stiffener sections	stiffener of frame spcg.	subdivision positions	others	Internal	External	
Mandel [1966]	5	5	-	-	-	-	-	8	4	Tanker design, using a random search technique.
Kavlie [1966]	10	-	6	2	2	-	-	8	16	deck structure of car carrier.
Moe [1968]	6	-	2	2	2	-	-	2	15	Tanker midship structure longitudinal material only.
Moe [1969]	12	-	3	2	6	1	-	10	19	Tanker structure, transverse and longitudinal material.
Lorentz [1970]	8	-	-	-	-	8	-	8	18	Tanker subdivision with overall strength requirements.
Gisvold [1970]	11	-	4	3	3	-	1	7	20	corrugated transverse bulkheads for tankers.
Lutkus [1970]	4	3	-	-	-	-	1	12	4	trawler design, using two sequential optimisations.
Nowacki [1970]	5	5	-	-	-	-	-	9	4	Tanker design, with fixed draughts.
Lund [1971]	10	-	10	-	-	-	-	10	4	Tanker deep web frame structure.
Fisher [1972a]	7	5	-	-	-	-	2	8	4	bulk carrier and port facilities design
Erichsen [1972]	8	6	-	-	-	-	2	12	4	containership and port facilities (cranes) design.
This paper	23	-	-	-	1	21	1	4	12	Tanker subdivision with IMCO design constraints.

6.1 DESIGN OF DECKS IN CAR CARRIER

The use of optimisation procedures for the minimum-cost design of three decks and the double bottom of a car carrier is reported by Kavlie [1966]. A total of 10 non-integer variables were simultaneously optimised, subject to 16 external and 8 internal constraints. The total number of evaluations required varied between 20 and 50 n^2, when n is the number of free variables.

The optimisation was performed simultaneously for the double bottom plus only three of the 9 decks since they were the only ones involved in the vessel's longitudinal strength. The other decks were cost-optimised individually, thus being a three-variable optimisation for each of those structures.

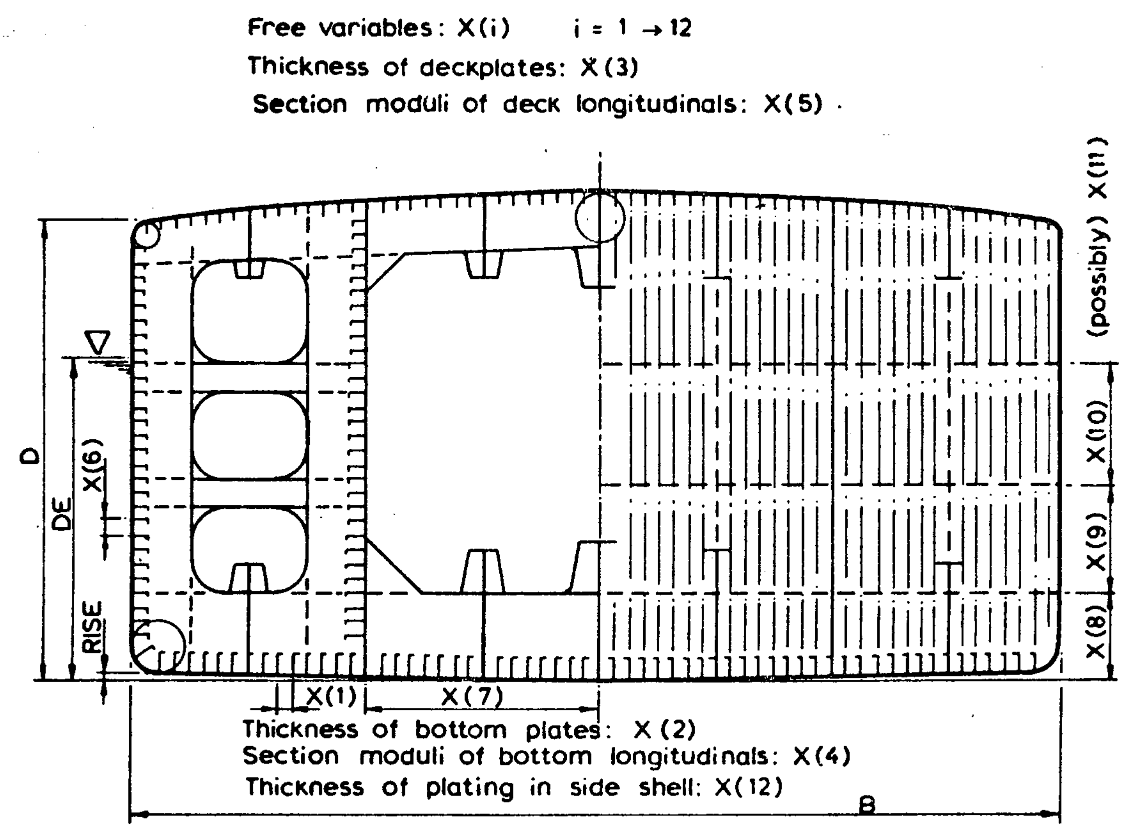
The external constraints arose from the Rules of det Norske Veritas, and the internal ones from considerations of geometry.

6.2 TANKER STRUCTURAL OPTIMISATION

Moe [1969] reports on a 12-parameter optimisation of the structure in the cargo section of a typical large tanker, noting the fact that the applicable cost criterion has over 150 components arising from material and labor considerations. The twelve parameters are indicated in Figure 3, which is taken from Moe [1969], and are listed in that figure.

FIGURE 3

Twelve-Variable Optimisation of Moe(1969)



Transverse Section

X(1) spacing between longitudinals in bottom and deck
X(2) thickness of bottom plating
X(3) thickness of deck plating
X(4) section moduli for the bottom longitudinals
X(5) section moduli for the deck longitudinals
X(6) stiffener spacing on longitudinal bulkhead and in ship side
X(7) position of the longitudinal bulkhead from centre line
X(8) the lowest stringer position above base line
X(9) distance between stringer 1 and 2
X(10) distance between stringer 2 and 3
X(11) distance between stringer 3 and 4
X(12) thickness of plating in ship side

The solution was subject to 19 external and 10 internal constraints. Considering that several of the constraints are of the integer type, it is unfortunate that discussion of the presence of local minima was not given.

The program developed for that 12-parameter optimisation includes the ability to incorporate high-strength steels at appropriate points, and to reduce the number of stringers from four to three

6.3 CORRUGATED BULKHEAD

Gisvold [1970] reports on the structural weight minimisation of a vertically corrugated bulkhead for a tanker with a variable number of horizontal stringers. The approach to the problem is to specify the number of stringers, N_{STR}, then optimise the appropriate variables, all of which except one are non-integer. The integer variable is the number of corrugations.

The number of variables is $(2N_{STR} + 4)$, and the number of constraints is $(6N_{STR} + 9)$. Of those constraints, there are $(5(N_{STR} + 1))$ external and the remainder are internal. The external ones arise from minimum thicknesses, section moduli and moments of inertia prescribed by the classification society. The internal constraints arise from considerations of geometry. Gisvold reports only the case for $N_{STR} = 3$; giving rise to 10 variables, 20 external constraints, and 7 internal ones. When the number of corrugations is allowed to be non-integer, the 10-variable optimisation required over 2000 evaluations. When that variable was sufficiently penalised if non-integer, over 3000 evaluations were required to find an optimum with an integer number of corrugations.

6.4 PRINCIPAL CHARACTERISTICS OF A TANKER

The report by Nowacki [1970] is representative of optimisation studies dealing with the principal characteristics of a vessel; and in which the applicable criterion incorporates capital and operational cost factors. That optimisation involves five free variables, nine internal constraints and four external ones. The sixth variable, subject to parametric study, is the draught.

Some of the direct constraints on the free variables (e.g. $0.50 < C_B < 0.86$) arise from lack of mathematical modelling ability beyond that range, in which case they are considered to be internal constraints. The external constraints arise from consideration of stability, freeboard, etc.

Several of the discussers of the paper point out that the optimum design, for each value of the draught, appears to be limited by several of the constraints arising from lack of extrapolability. That situation is not unusual for comparable studies, and indicates quite clearly that either (1) the mathematical model is slightly in error; or (2) that current practice is not near-optimum, and further basic research is required in order to extend the mathematical model (and practice) to greater ranges of parameter-values.

6.5 TANKER SUBDIVISION

Lorentz [1970] studied the optimum positioning of transverse bulkheads in a large tanker, under the premises that the vessel have two longitudinal bulkheads, a double bottom, and that the transverse bulkheads in the wing tanks be at the same longitudinal position as those in the centre-line tanks. Thus the number of wing tanks (including clean ballast) is identical to the number of centre tanks, and each transverse set has the same length. The object of optimisation is to maximise the cargo capacity of vessel having specified principal dimensions.

The variables are the longitudinal positions of the transverse bulkheads separating the tanks. Thus for, say, 6 sets of tanks, there are 5 variables. The depth of double bottom is fixed during the optimisation, as is transverse position of the longitudinal bulkheads. The number of bulkheads, N_{BHD}, (i.e., the number of variables) was also fixed for each optimisation.

There are N_{BHD} internal constraints arising from the geometry; and (N_{BHD} + 9) external constraints arising from maximum tank lengths, draughts and trims in ballast and loaded conditions, maximum allowable bending moment in loaded and ballast conditions, and maximum allowable shear in both conditions. An additional constraint, number ($2N_{BHD}$ + 10) is that the longitudinal positions of the bulkheads must coincide with the deep-web frame spacing.

The maximum number of variables used by Lorentz [1970] was 8, with 25 or 26 constraints. The matter of imposing that last constraint is discussed by Gisvold [1970]. He notes the significant difference between the optima for the discrete (integer) and continuous (non-integer) solutions, and comments, "the fallacy of stating that a discrete optimum design usually may be found in the vicinity of the continuous optimum is clearly demonstrated".

This author would add a further note of caution to that by pointing out that the above-described solution was obtained with a fixed deep-web frame spacing. Obviously, it is possible to alter that spacing somewhat, in which case it is believed that the "discrete" and "continuous" optima would be considerably closer than those observed by Gisvold [1970]. Further discussion regarding the rigidity of that constraint is given in Section 5, Flexibility of Restrictions.

7. STRUCTURAL ANALYSIS

It is not the intention of this section to present an exposition on ship structural analysis, but rather to discuss its recent development in regard to the ability to incorporate such analysis into a design optimisation study. The possible number of references for this discussion is quite lengthy. Rather than include them all, mention is made only of the ones not discussed elsewhere in this paper which offer sufficiently different contributions as well as being generally available in good technical libraries.

Without doubt, one of the first papers that should be studied is that by Abrahamsen [1969], which is an excellent general backgrounder, comparable to a specialised text book. It is especially commended inasmuch as Mr. Abrahamsen is associated with one of the classification societies.

The report by Yuille [1960] clearly demonstrates the interaction between a more rigorous approach to a component of the design problem (namely, transverse structure) and the availability of computers, as discussed in the Introduction. The paper does not make decisions, in that optimisation of parameters is not discussed. But the paper does demonstrate the computation of several stresses and deflection in a transverse ship's structure.

When an optimisation procedure prescribes the associated design parameters (including structure), the possible violation of a stress and/or deflection constraint can thereby be examined. Thus it effectively acts as one of numerous sub-components necessary in the total optimisation mechanism necessary for a 'correct' design solution. A more general discussion regarding optimisation of ship structures, along with several clearly explained examples, is given by Akita [1970].

The long-term use of such an analysis as part of an overall design program is recognised by Kendrick [1970], who has presented finite-element techniques for tanker structural design. In that paper the point is made that such 'highly refined' techniques can quite easily be incorporated into the preliminary design procedure, if the designer recognises the desirability (and benefits) of doing so.

Kendrick's [1970] optimism regarding the marriage of theoretical approaches to final-design characteristics of structure is not matched by the pessisism expressed by HSC* [1971]:

> Ship structural design is rapidly acquiring a more theoretical basis because of advances in the knowledge of structural analysis, and in the knowledge of material behaviour. Even with these advances, it is still not possible to design the structure of a ship entirely from theoretical bases with the same confidence and economy of structure that can be achieved by designing to the rules of a classification society.

Certainly Lund's [1971] work, among others, in tanker frame design would not give substance to the Hull Structure Committee's evaluation of the state-of-the-art.

The relative timing of the introduction of 'economy' into the design, as mentioned in the quotation above, is given a fresh approach by Mitchell [1971] who presents a review of the state-of-the-art of the

* Hull Structure Committee.

application of finite element techniques to ship structures. In doing so he points out that "there is an increasing requirement for speeding up the process of finite element analysis due to the demand for incorporation of the method into standard design techniques." One of the primary reasons for so doing, he states, is that "modifications to the initial design as a result of [subsequently] computed stress levels can be very expensive indeed unless implemented at an early stage."

Nielsen's [1971] work is dedicated to that "speeding up" of structural analysis, recognising that it will ultimately be incorporated into a larger over-all design program.

The attitude expressed by Mitchell [1971], indicated above, was echoed in W.J. Dorman's discussion of the paper by Nielsen [1971]:

> To realise the full benefit that can be derived from the use of finite-element methods of structural analysis, these techniques must be integrated into the design process at an early stage....Early identification of highly stressed regions....is extremely important in the overall design concept.

While most structural analysis of ships has been centred on the midship and cargo carrying sections, the paper by Nagamoto [1970] extends the analysis, by a different method, to the fore and aft ends of the vessel as well. It is not proposed at this time, however, that analysis of the fore and aft structures be incorporated into the "total optimisation" discussed in Section 12.

8. ANTI-POLLUTION MEASURES IN TANKER DESIGN

As noted below (Section 10), a significant set of external constraints on the tanker design arises from considerations of sea pollution arising from accidental collision on stranding of the vessels. Although the matter of subdivision arrangement usually comes to mind when the subject is discussed, there are other areas of possible innovation. Excellent general discussions on the matter appear in the paper by Price [1971], and more importantly, that by Porricelli [1971].

The paper by Dillon [1971] deals with specific designs for several vessel types, incorporating anti-pollution concepts. A major part of Dillon's paper is oriented toward the elmination of dirty ballast water, by increasing the clean ballast capacity to over 40% of the vessel's displacement. As he points out, however, the capital cost of tankers will use as the percentage of clean ballast capacity increases, while some of the operating costs will decrease.

In October 1971 the Intergovernmental Maritime Consultative Organization adopted the requirements and limitations summarised in Appendix II, which is adopted from IMCO [1971].

As indicated above, Dillon [1971] recognised the economic penalty aspect of decreasing the pollution potential. Prior to that, Fisher [1970] projected the foundational concept of this part of the present paper in comparable terms:

> In the event...that "damage-from-accident" criteria be applied to large vessels, it will be necessary to include in cost-optimisation procedures the effects of insuring minimal damage from possible accidents. The consequent size of the vessel might well be substantially smaller than it would be without such criteria.

The subdivision optimisation study reported here is carried out from the owner's point of view. The optimisation is done with regard to the minimum legal requirements as given by the IMCO regulations, since they will be the least expensive in capital, though perhaps not in operating costs. The numerous suggestions regarding segregated ballast as given by Dillon [1971] and Porricelli [1971] are acknowledged, but not incorporated into this study due to lack of economic motivation.

That point of view may be construed as not inconsistent with the discussion of Porricelli's [1971] paper by the Chairman of the U.S. Maritime Administration, H.D. Bentley:

> The problem of a relatively pollution-free tanker operation is not beyond the technological abilities..., but the costs of achieving such a situation must be kept firmly in mind.

9. THE OBJECT FUNCTION

It is necessary to discuss the object function of this particular study, due to its over-simplification. First, the preferred non-simplified function is discussed; followed by the reasons for choosing the simplified one at this time.

As stated in Section 2, an economic criterion is expected. Moe [1969] indicates that such a criterion will consist of over 150-200 cost functions, which arise from considerations of the diverse elements of the ships structure, among other things. If, for this discussion, the weight of the structure is taken to be indicative of cost, then all of the following in the cargo section alone need be accounted for:

(1) trans. frames.
(2) trans. stiffeners.
(3) trans. bhds.
(4) long'l girders.
(5) long'l stiffeners.
(6) long'l bhds.
(7) side plating.
(8) deck plating.
(9) bottom plating.

It is apparent that the spacings of the frames and girders will directly affect the total weight. For maintenance of stress levels, Lund [1971] shows that the spacing of the long'l bulkheads will also significantly affect the weight of the frames. Thus, perhaps over 10 weight groups should be included in the object function of this study.

It is recognised, however, that this study introduces a new class of external constraints (arising from the IMCO regulations) to the subdivision optimisation problem. In light of that, the decision was made to first establish the feasibility of realistically satisfying all those constraints simultaneously, in which the "realistic" refers to an arrangement of tanks that would be acceptable to a ship owner from an operational point of view.

Thus, the object function of this study includes only the effect of:

i) The total number of transverse wing bulkheads, and the weight of each.

ii) The total number of transverse centre bulkheads, and the weight of each.

iii) The average cargo tank capacity.

Considering the vessel to have fixed beam and depth, and a nominal cargo section length, then the only way to increase the average tank capacity is to (a) decrease the number of bulkheads, (b) decrease the clean ballast volume, and (c) decrease the slop tank capacity.

But since for other operational reasons the nominal slop tank capacity is fixed, the object function then becomes the total weight of the transverse bulkheads multiplied by the fraction of volume devoted to clean ballast, and divided by the total number of cargo tanks.

10. PROBLEM DEFINITION

The assumed general configuration of the tanker is that of two longitudinal bulkheads without a double bottom. For a given set of principal dimensions and a specified nominal total length of cargo tank section (L_{TOT}), the object is to find the subdivisionconfiguration that produces minimum total weight of transverse subdivision bulkheads. In accord with Figure 4, the independent variables are:

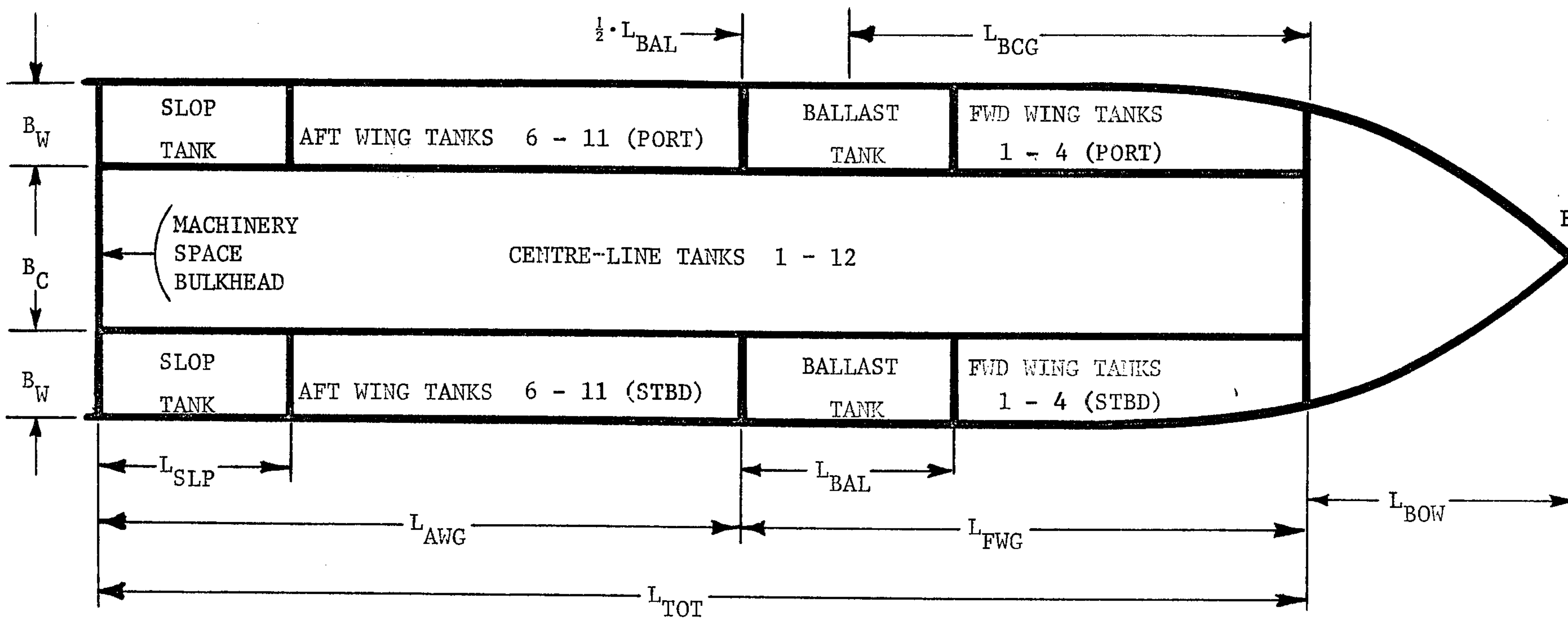
1 - 11: The lengths of centre tanks 2-12. (The length of no.1 is obtained by subtraction from L_{TOT}).

12 - 14: The lengths of forward wing tanks 2-4. (The length of no.1 is obtained by subtraction; and the length of the clean ballast tank, no.5, is derived from the 23rd variable.)

15 - 19: The lengths of aft wing tanks 7-11. (The length of no.6 is obtained by subtraction; and the length of the slop tank, no.12, is derived from its nominal volume requirement.)

FIGURE 4

General Lay-Out of Tanker
with Two Longitudinal Bulkheads



20: The beam of the centre tanks. (The beam of the wing tanks is obtained by subtraction.)

21: The longitudinal position of the centre of the clean ballast tank.

22: The deep web frame spacing.

23: The volume of the clean ballast tanks, as a percentage of the total volume $L_{TOT} \cdot B \cdot D$.

Regarding Figure 4 the nominal volumes of the ballast and slop tanks are specified, thus indirectly specifying their lengths.

The optimisation is subject to the following 12 external constraints:

1: The volume of all centre tanks must be $\leq V_{C-MAX}$.

2: The volume of all wing cargo tanks* must be $\leq V_{W-MAX}$.

3: The lengths of all centre tanks must be $\leq L_{C-MAX}$.

4: The lengths of all wing cargo tanks* must be

5: The greatest possible oil outflow due to collision must be $\leq V_{MAX}$.

6: The greatest possible oil outflow due to stranding must also be $\leq V_{MAX}$.

7 & 8: The deep web frame spacing must be $\leq$ 6.5m and $\geq$ 3.5m.

9: The deep web frame spacing must be an integer multiple of 5cm.

10: The beam of the centre tanks, B_C, must be an integer multiple of 5cm.

---

* Including the slop tanks, which may be used to carry cargo.

11: The total length of the cargo tank section, L_{TOT}, must be within 2.0m of the nominal value.

12: The volume of the slop tanks must be 2.5 $\pm$ 0.5 percent of the volume $L_{TOT} \cdot B \cdot D$.

The following four internal constraints are applicable:

13: The total length of the cargo tanks, L_{TOT}, must be an integer multiple of the deep web frame spacing.

14: The length of each tank must be an integer multiple of the deep web frame spacing.

15: The beam of the centre tanks must be $\leq$ the vessel's beam.

16: All tank lengths must be non-negative.

The weight of a transverse wing bulkhead is given by -

$$W_W = C_o \, B_W^{1.33} \, D^{1.37}$$

For a transverse centre bulkhead, B_C is substituted for B_W. The above formulation is taken from Buxton [1966] for a corrugated O.T. bulkhead incorporating horizontal girders. Other criteria could be substituted in place of that one if required, but the point to be remembered is that this aspect of the problem later becomes part of the overall economic optimisation of the entire vessel design.

For this study, the optimisation technique employed is that known as Nelder and Mead's, the same one used by Fisher [1972a]. It has proven to be a sound all-purpose technique, and in this study has efficiently produced optima for up to 23 variables. A slight modification to its application has been employed, however, in the introduction of integer-type constraints, as described below.

Prior to indicating that change, however, it is noted that in the two years since the Fisher [1972a] study was completed, this author has studied the application of integer constraints to general optimisation procedures. The result of many hours of computing experience has been to show that greatest efficiency in optimisation is achieved by the creation of two parallel 'vectors'. The first one is the unconstrained set of values handled by the general optimisation technique. The second is a rounded-off constrained set of values.

For example, in the present problem, the 22nd variable is the deep-web frame spacing, which must be an integer multiple of 5cm. In a typical optimisation, the 22nd component of the first vector is unconstrained [e.g. 5.0668m] while the same component of the second vector is the "rounded-off" value [e.g. 5.05m]. At the same time, another typical component (a centre tank length) has values of 33.6310m and 35.35m in the first and second vectors, respectively.

A glance at the list of 23 variables at the beginning of this section indicates that the first 22 are obviously subject to the indicated type of rounding-off. But, in fact, the last one (percentage clean ballast) is also subject to a rounding-off, inasmuch as it has to be an integer multiple of the volume contained between two adjacent web frames in a wing tank. Typical values for that 23rd component of the two vectors are 0.0787 and 0.0814.

Although by use of the technique noted above the total number of trials for each optimisation was not great, each trial did take a considerable amount of time due to the need to "determine by trial at all conceivable locations the worst combination of compartments that would be breached" in collision or stranding [IMCO, 1971].

Recognising the nature of this as a feasibility study vis-a-vis the IMCO requirements, the internal subdivision optimisation has been performed for only one set of principal characteristics:

LBP	=	375.0m
B	=	63.5m
D	=	31.7m
T	=	22.7m
C_B	=	0.86
DWT	=	400 ktons (approx.)

In accord with Figure 4 , the value of L_{BOW} is 28.0m, and that of L_{TOT} is 305.0 $\pm$ 2.0m.

As mentioned in the last paragraph of Section 4, the number of centre and wing tanks were systematically altered. The optimisation procedure in each situation was begun with the nominal length L_{TOT} divided into equal lengths corresponding to the number of centre tanks. (That is consistent with the operational preference of having equal volume tanks.) The initial length of the clean ballast tank was calculated from the initial estimate of the percentage ballast [8%]. The initial lengths of the remaining wing tanks were obtained by dividing (L_{TOT} - L_{BAL}) into the corresponding number of equal segments (see Figure 4). The initial estimate of the centre tank beam was 55% of the vessel's beam.

The optimisation procedure was abandoned if more than $5n^2$ trials were unsuccessful in convergence and satisfaction of all constraints, where "n" is the number of active variables. Due to the difficulty of finding a feasible solution, in all instances the initialising procedure described above meant that infeasible starting points were used (see the last paragraph of Section 3).

11. OPTIMISED SUBDIVISION CONFIGURATIONS

11.1 GENERAL DEVELOPMENT

A number of preliminary optimisations with the developed procedure indicated a slight inadequacy in the previously defined object function. Specifically, the solutions did not have an instinctively acceptable appearance, in that the sizes of the tanks* for optimised designs varied considerably. As indicated in the Introduction, the "acceptability" required mathematical definition, which has been subsequently incorporated into the object function as indicated below.

The origin of this problem of considerable variation of tank sizes, while satisfying the IMCO requirements, lies with the fact that although the optimisation is begun with equal tank sizes, there was no motivation in the programs to maintain approximate equality of tank sizes. Yet the demand for equality of tank sizes would be an additional (if loose) constraint, adding to the more rigid constraints already operable.

A succession of trials led to the realisation that it is first necessary to obtain a feasible solution, prior to one having an acceptable appearance. Once the feasible solution is achieved, the uniformity of tank sizes is promoted in the re-started optimisation by multiplying the object function by the sums of non-dimensional variances from the most common (not average) tank size.

Although a large number of optimum solutions for the manually varied number of wing and centre tanks have been obtained, only two are

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* The wing tanks and centre tanks are considered separately.

reported herein, inasmuch as one of them represents what is believed to be the global minimum, according to the applicable criterion; and the other is very close to the global minimum, but has a very interesting feature to it.

It will be observed below that the minimum number of separate cargo tanks yielding an acceptable configuration for the stated dimensions is 25 (17 variables). Optimisations were conducted for as many as 35 cargo tanks (23 variables). The rapidity with which feasible solutions are obtained decreases as the number of tanks is decreased. For 37 tanks, approximately 200 trials are necessary; and for 25 tanks, almost 1800 trials* are required. In all instances, about 200 additional trials are used to establish a more acceptable variation of tanks sizes.

Finally, prior to discussion of the specific results, it may prove relevant to indicate that, at the time of writing, this author has not seen published any proposed VLCC designs that will satisfy the IMCO requirements, without an unusually large clean ballst capacity.

11.2 THE GLOBAL OPTIMUM

The global optimum subdivision is shown in Figure 5. A number of features merit discussion; and the two graphs in that figure require explanation.

In accord with the IMCO criteria and prescribed limits of damage from either collision or stranding, it is possible, for a given configuration, to calculate the oil outflow if the centre of damage is at any specified point along the vessel's length. The two graphs in Figure 5 indicate the maximum relative oil outflow at all points along the length if that point is within the damaged length.

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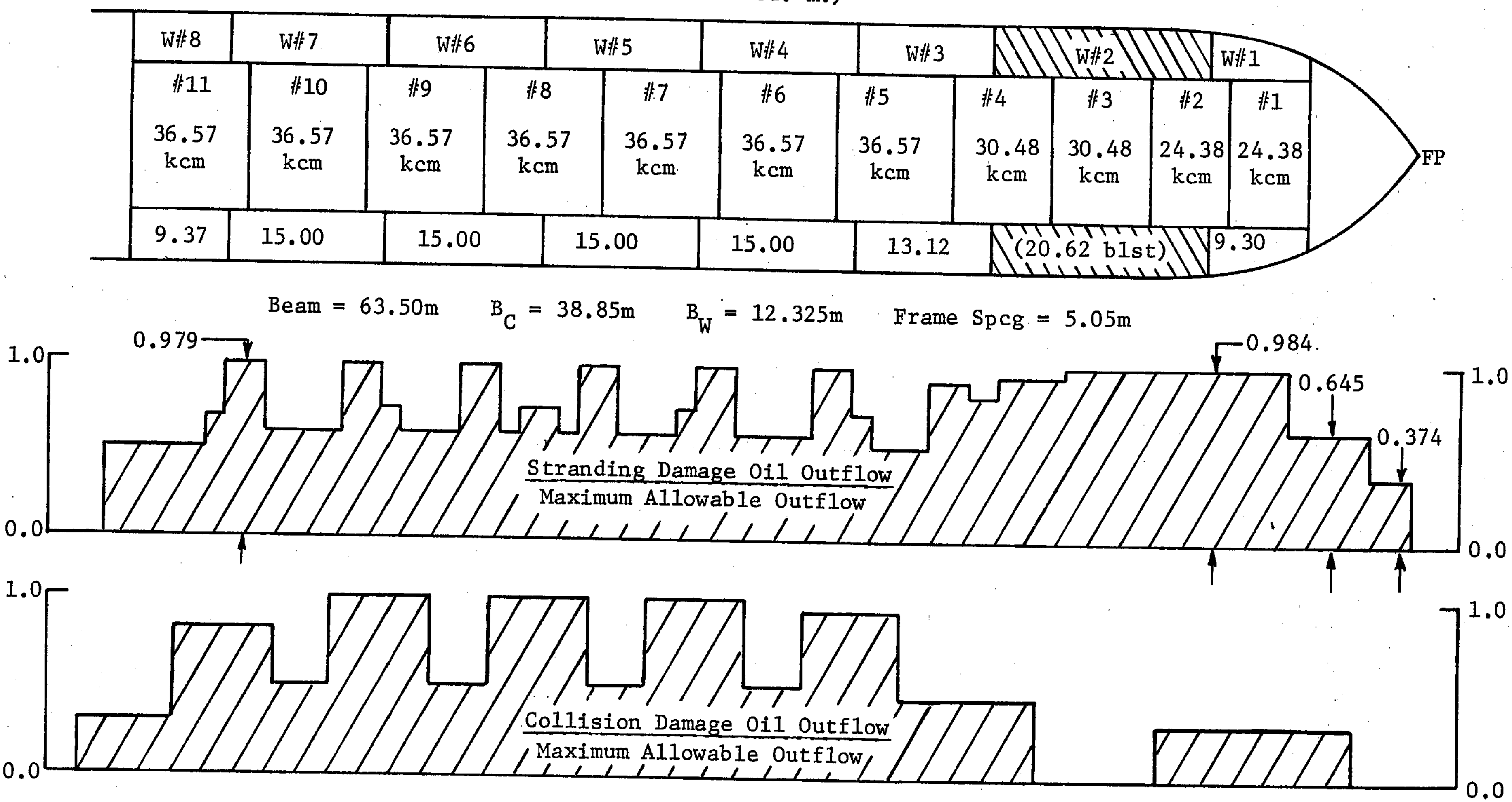
* The usual limitation of $5n^2$ trials was over-ridden after examination of progress to that point (see last paragraph of Section 10).

FIGURE 5

OPTIMUM TANKER SUBDIVISION

Total Cargo Capacity = 549.3 kcm (including slop tanks)

(1.0 kcm = 1000 cu. m.)



As an example, if the FP is included in the stranding damage of length 'l_s', that damage could extend from the FP to 37.5m aft, which means that C#1 and W#1 (one side only) are opened to the sea. Thus the outflow is (24.38 + 9.30)/3.0 or 11.23 kcm*, which is 37.4% of the maximum allowable outflow of 30.0 kcm. If the centre tank beam is less than the transverse extent of damage (t_s = 10.0m), the volumes of oil in the wing tanks on both sides would be included.

At a point 10.70m aft of the FP, the damage could extend into C#2, thus adding 24.38/3.0 = 8.13 kcm to the outflow, for a total of 19.36 kcm or 64.5% of the maximum allowable.

Noting that the clean ballast tank does not contribute to the calculated outflow, and that l_s and t_s both decrease past 0.3LBP, the similar calculation at each point is performed and plotted on that graph.

For the collision damage, the factor 1/3 is not applicable. Also, inasmuch as the wing tanks have a beam greater than the transverse extent of the collision damage 't_c', the centre tank volumes are not included in the calculation of collision damage oil outflow.

The optimised frame spacing is found to be 5.05m. The apparent reason for that lies in the realisation that the length of stranding damage aft of 0.3LBP is stated by IMCO to be 5.00m. Thus, for example, if C#10 and C#11 are both involved in stranding damage, then W#7 is also involved but W#8 is not. If, however, the frame spacing is 5.00m, then W#8 would be included in the oil outflow calculation, resulting in a 108.3% relative outflow, instead of the indicated 97.9%.

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* See Appendix II.2 for expanation of the factor 1/3. Note 1.0 kcm = 1000 cu.m.

The length and position of the clean ballast tank in this design (Figure 5) is dictated by the fact that the stranding damage length forward of 0.3LBP is 37.5m. If W#1 is one frame spacing longer, adding 1.87 kcm, then when C#1, C#2, C#3 and W#1 are simultaneously involved in stranding damage*, the relative outflow is 100.5% instead of the indicated 98.4%.

The position of the bulkhead at the aft end of the clean ballast tank is chosen by consideration that when C#2, C#3 and C#4 are simultaneously involved*, W#3 is not involved in the stranding damage, but would be if the clean ballast tank W#2 was one frame space shorter.

Further discussion of that configuration is given in Sub-section 11.4, Comparative Features.

11.3 ALTERNATE OPTIMUM

As indicated previously, one of the optimised subdivision configurations shows and interesting feature. Inasmuch as it is an optimum, though not global, it is henceforth referred to as the 'alternate optimum.' It's configuration is shown in Figure 6. The third centre tank is the notable feature, being only one frame space (5.05m) in length. The incorporation of it arises from the use of the exception regarding the multiplier 1/3 in calculating the outflow due to stranding. It's use is illustrated by two calculations.

Consider the aft end of the stranding damage to be in C#3 of Figure 6; in which case C#1, C#2, W#1 and W#2 are also involved, resulting in an acceptable outflow of 89.26/3.0 = 29.75 kcm. But if the aft end of the stranding damage is immediately aft of the bulkhead between C#3 and C#4, then the

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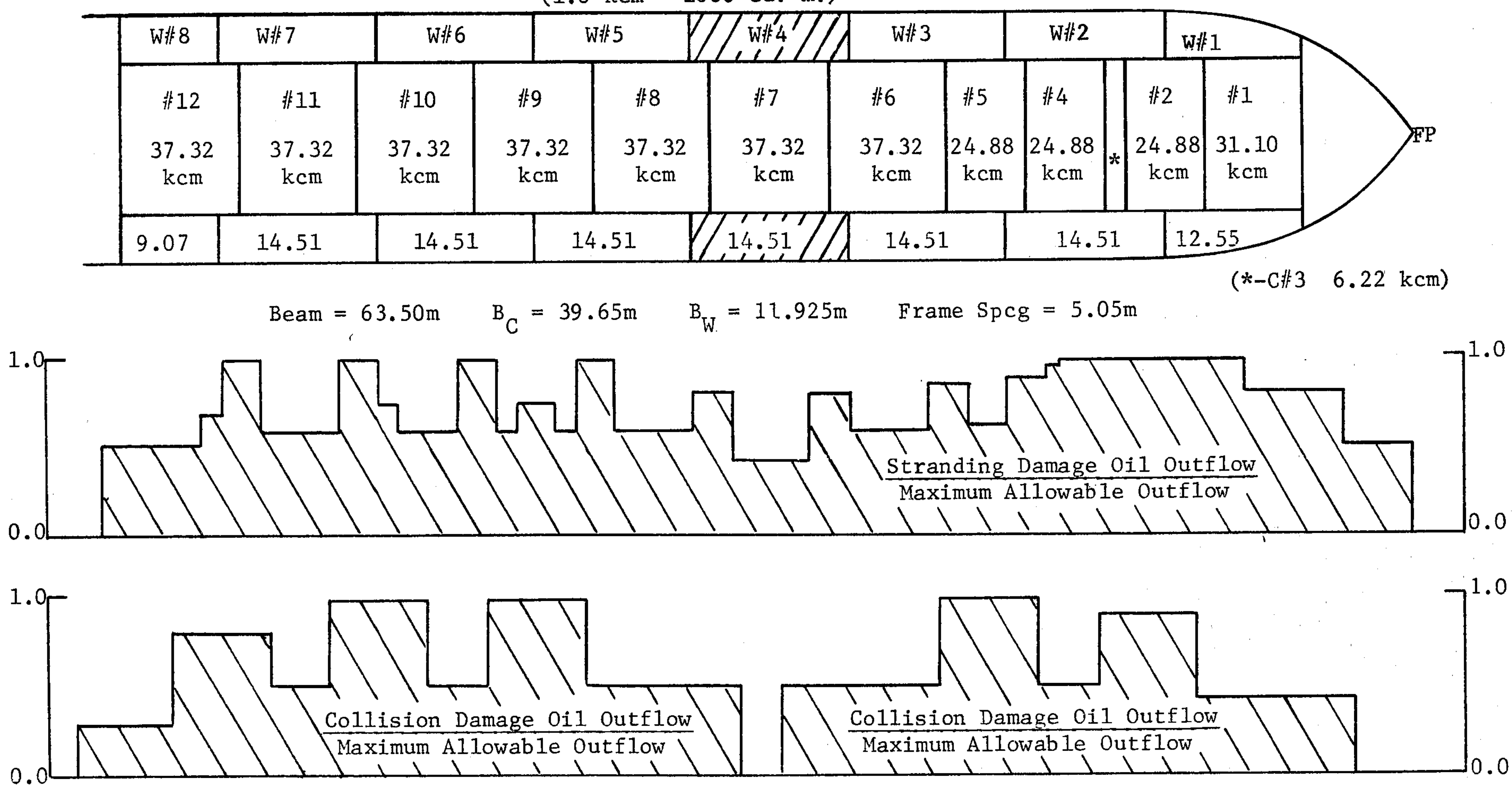
* In Figure 5, the length of C#2 is 20.20m, and that of C#3 is 25.25m.

FIGURE 6

ALTERNATE OPTIMUM TANKER SUBDIVISION

Total Cargo Capacity = 561.5 kcm (including slop tanks)

(1.0 kcm = 1000 cu. m.)



volume of C#4 is also included. Thus an apparently unacceptable outflow of (89.26 + 24.88)/3.0 = 38.05 kcm is expected.

But as noted in Appendix II.4(a), since four centre tanks are involved in that stranding damage, a factor of 1/4 instead of 1/3 may be used, in which case the calculated outflow volume is actually (89.26 + 24.88)/4.0 = 28.54 kcm. Other calculations can be done as well, in which case it would be observed that the combined lengths of (C#2 + C#3) or (C#3 + C#4) being less than the stranding damage length means that the factor 1/4 can be used at other appropriate times too.

Two other points pertinent to that configuration should be noted. Firstly, if W#1 is eight instead of seven frame spaces long, adding 1.81 kcm to its volume, the outflow involving damage to C#1, C#2, C#3, W#1 and W#2 would be an unacceptable (89.26 + 1.81)/3.0 = 30.36 kcm.

Secondly, the 5.05m frame spacing, being only 5cm longer than the stranding damage length aft of 0.3LBP, also makes use of the precisely defined IMCO regulations.

The purpose of bringing these facts to the reader's attention is to emphasize the fact that once the constraints are clearly defined, optimisation schemes can quite easily be implemented.

11.4 COMPARATIVE FEATURES

The acceptability of the small centre tank of the alternate optimum (Figure 6) from an operational point of view is doubtful. It may be desirable, however, to reserve that C#3 for clean ballast use, in which case the total cargo capacity is reduced from 561.5 kcm to 555.3 kcm. But the operational characteristics of the design might thereby be enhanced.

It is noted that the global and alternate optima have the same number of wing tanks, but the alternate has an additional centre tank. Is the cost of that extra bulkhead over-come by the increased cargo capacity? Table 3 indicates the comparison between those two designs, with the alternate's C#3 being used either for cargo or clean ballast. The last line of that table indicates that if only the weight of transverse bulkheads is considered, the extra bulkhead of the alternate optimum is undesirable.

That criterion does not reflect the fact that the ballast tanks of the global optimum are larger as well as further forward than those of the alternate; thus potentially subjecting the vessel to greater bending moments when ballasted, or necessitating an undesirable (and more lengthy) ballasting and de-ballasting sequence.

Another interesting result, not illustrated herein, is obtained when the wing ballast tanks are allowed to extend to the forward end of the cargo section of the vessel. In that case, a configuration is obtained that is identical to the global optimum (Figure 5) except that W#1 is not present. Thus only 23 cargo tanks are needed (avg. cap'y = 23.07 kcm). There is almost no detectable change of the criterion in the last line of Table 3, being 1.0006, since 3.33% of the weight is lost* while the cargo volume is reduced by 3.39%.

While capital costs are thereby reduced, the configuration is considered undesirable inasmuch as the wing ballast tank is then over 80m in length. The operational acceptability of such a configuration is also suspect, but is consistent with the IMCO regulations, which restrict only the lengths of the cargo tanks to, for this design, L_{W-MAX} = 75.0m.

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* considering only the weight of the transverse bulkheads.

TABLE 3

Characteristic Features

of Optimised Subdivisions

(capacities in 1000's of cu. m.)

	Global Optimum	Alternate Optimum with 2 Blst Tnks	Alternate Optimum with 3 Blst Tnks
No. of Cargo Tanks	25	26	25
No. of Centre Tanks*	11	12	11
No. of Wing Tanks*	14	14	14
No. of Blst Tanks	2	2	3
Total Cargo Cap'y	549.3	561.5	555.3
Avg. Tank Cap'y*	21.97	21.60	22.21
Avg. Centre Cap'y*	33.24	31.10	33.36
Avg. Wing Cap'y*	13.11	13.45	13.45
Total Blst Cap'y	41.24	29.02	35.24
Avg. Blst Cap'y	20.62	14.51	11.75
Blst Cap'y/Cargo Cap'y	0.075	0.052	0.063
Relative Total Weight of Transverse Bhds	1.000	1.090	1.090
Relative Weight per Unit Cargo Cap'y	1.000	1.066	1.078

* - does not include ballast tanks, but does include slop tanks.

12. TOTAL OPTIMISATION

As indicated in the Introduction, there are a large number of "bits and pieces" of computer applications in ship design. Discussions and examples of them have been given in previous sections and in Appendix I. It is now proposed that, where appropriate, several groups of the previously optimised structural, subdivision and configuration parameters can be simultaneously optimised, with benefits accruing through the recognition (discussed in Section 5, Flexibility of Constraints) that the optimum of the whole will be less than the sum of the optima of the parts.

Rather than merely list all the parameters that have been optimised, consideration must first be given to the necessity of including each parameter. As noted in Section 6.1, Kavlie [1966] found it unnecessary to include the structural parameters of the intermediate decks in the optimisation of the longitudinal strength decks and double bottom of the car carrier. The resulting five optimisations were one of 10 variables, and four of three variables each. The computational costs of those 5 optimisations is less than one-third the cost of one 22 variable optimisation, since computing time varies approximately as the square of the number of parameters.

That separation of parameters, for optimisation purposes, could be effected because there was only a very weak mutual effect between each group.

But caution need be exercised in the direction of parameter independence, as illustrated by the comments of Moe [1969] in discussing a fore-runner of that work, Moe [1968]:

> A program for the optimisation of only longitudinal strength members in a typical tanker [Moe, 1968] has been used with success in several practical design applications.

> That program disregarded the coupling which exists between the design of the longitudinal members and the three dimensional grillage system consisting of transverse and longitudinal frames. It was therefore recently found desirable to develop a more complete design model which incorporates all the above mentioned structures as well as the transverse bulkheads.

Consequently, the number of free variables rose from six to 12. (see Table 2).

It is, therefore, encumbent on the designer to ascertain the necessity of including certain parameters in an optimisation through investigation of the "strength" of the coupling between them. As indicated above, however, the "easy way out" of including all the parameters will be a very costly one.

At the other extreme, however, if a coupling is very rigid, then it's presence can be used to reduce the number of free variables. Lund [1971], for example, demonstrates that only one variable is required to effectively designate each section of a transverse web frame, instead of four detail dimensions. Similarly, Moe [1968] reports that, rather than use four dimensions for different types of longitudinals, the section modulus alone suffices.

With those cautions in mind, the coupling is considered. Firstly, the grouping of the principal characteristics is seen to be valid by the works of Mandel [1968], Nowacki [1970], Fisher [1972 a] and Erichsen[1972].

Secondly, while for some classes of vessels the link between subdivision configuration and principal characteristics may be sufficiently weak to be disregarded, the IMCO requirements invalidate that point of view for tanker design. If the individual tank sizes were approximately proportional to the deadweight, that link would be weak. But inasmuch as the IMCO regulations prescribe <u>absolute</u>, not relative, limits, the relative subdivision configuration is severely affected by the magnitude of the principal characteristics. Consequently, the average cargo tank capacity will remain approximately constant (20-30,000 cu.m.), thus inhibiting the "economy of size".

The link between those two groups (principal characteristics and subdivision dimensions) is thereby established, thus indicating that future tanker preliminary design studies must include both.

The third and fourth groups are the transverse and longitudinal structures, respectively. The need to consider them together is established by the quotation, above, from Moe [1969].

It is observed that in considering transverse bulkhead weights only, as in the subdivision optimisation reported previously, the optimised beam of the centre tanks was consistently over 60% of the beam of the specified vessel. Extrapolation of Lund's[1971] work shows that the 10% increase from 50% of the beam (usual practice) may result in a transverse web frame weight increase of about 20% - which is a very severe penalty to pay for satisfying the IMCO requirements with as few tanks as possible.

The question now arises: is it more costly to have increased web frame weights, or a finer degree of subdivision with more transverse bulkheads? It is noted that not only is the structural weight and cost affected by finer subdivision, but the outfit is also altered by corresponding increases in piping and pump systems. Clearly, then, the link between subdivision (to satisfy IMCO requirements) and transverse structure (to satisfy strength requirements) is firmly established. Hence the four groups of parameters are linked as shown in Figure 7.

For convenience, the variables may be re-grouped for planning the suggested total optimisation, as in Table 4, which lists the 51 variables that require simultaneous optimisation.

FIGURE 7

LINKAGE OF PARAMETER GROUPS

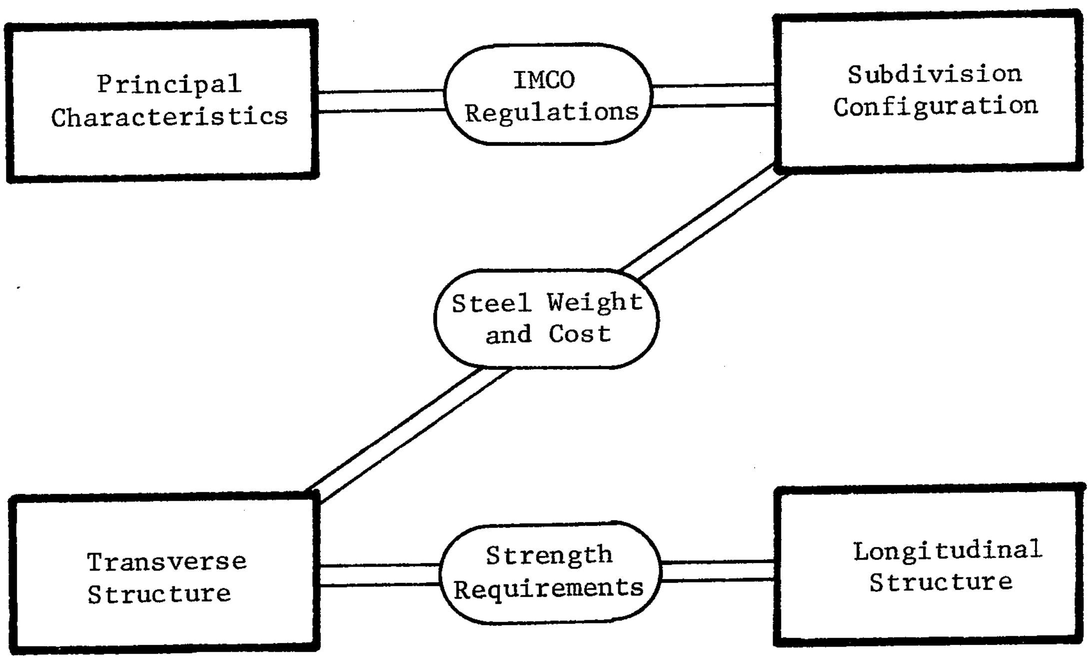


TABLE 4

FREE VARIABLES IN TOTAL OPTIMISATION [a]

Principal Characteristics (6)

X_1 - length b.p.

X_2 - beam

X_3 - depth

X_4 - block coeff.

X_5 - deadweight

X_6 - service speed

Subdivision Configuration (20)

X_7 - centre tank beam

X_8 - cargo section length

X_9 to X_{19} - centre tank lengths [b]

X_{20} to X_{25} - wing tank lengths [c]

X_{26} - clean ballast cap'y

Spacings (5)

S_1 - web frame

S_2 - bot. & deck long'ls

S_3 - bhd. & side long'ls

S_4 - lower cross-tie

S_5 - upper cross-tie

Long'l Pltg. Thicknesses (8)

t_1 - bottom

t_2 - deck

t_3 - side (upper)

t_4 - side (mid.)

t_5 - side (lower)

t_6 - bulkhead (upper)

t_7 - bulkhead (mid.)

t_8 - bulkhead (lower)

Web Frame Pltg. Depths (8)

W_1 - under deck (centre)

W_2 - under deck (wing)

W_3 - on bottom (centre)

W_4 - on bottom (wing)

W_5 - at side

W_6 - at long'l bhd.

W_7 - lower cross-tie

W_8 - upper cross-tie

Section Moduli (4)

Z_1 - bottom long'ls

Z_2 - deck long'ls

Z_3 - side long'ls

Z_4 - bhd. long'ls

Notes: (a) total number of variables is 51.
(b) total number of centre tanks is 12.
(c) 8 wing cargo tanks, 2 fwd of ballast, 6 aft, plus one slop tank on each side.

That listing makes use of the rigid coupling of several possible parameters, as discussed previously. For the purposes of discussion, the variable defining longitudinal stiffeners is taken as the section modulus; and the parameter designating the sections of the web frame is the depth of the web at each point. The variables are illustrated in Figure 8 .

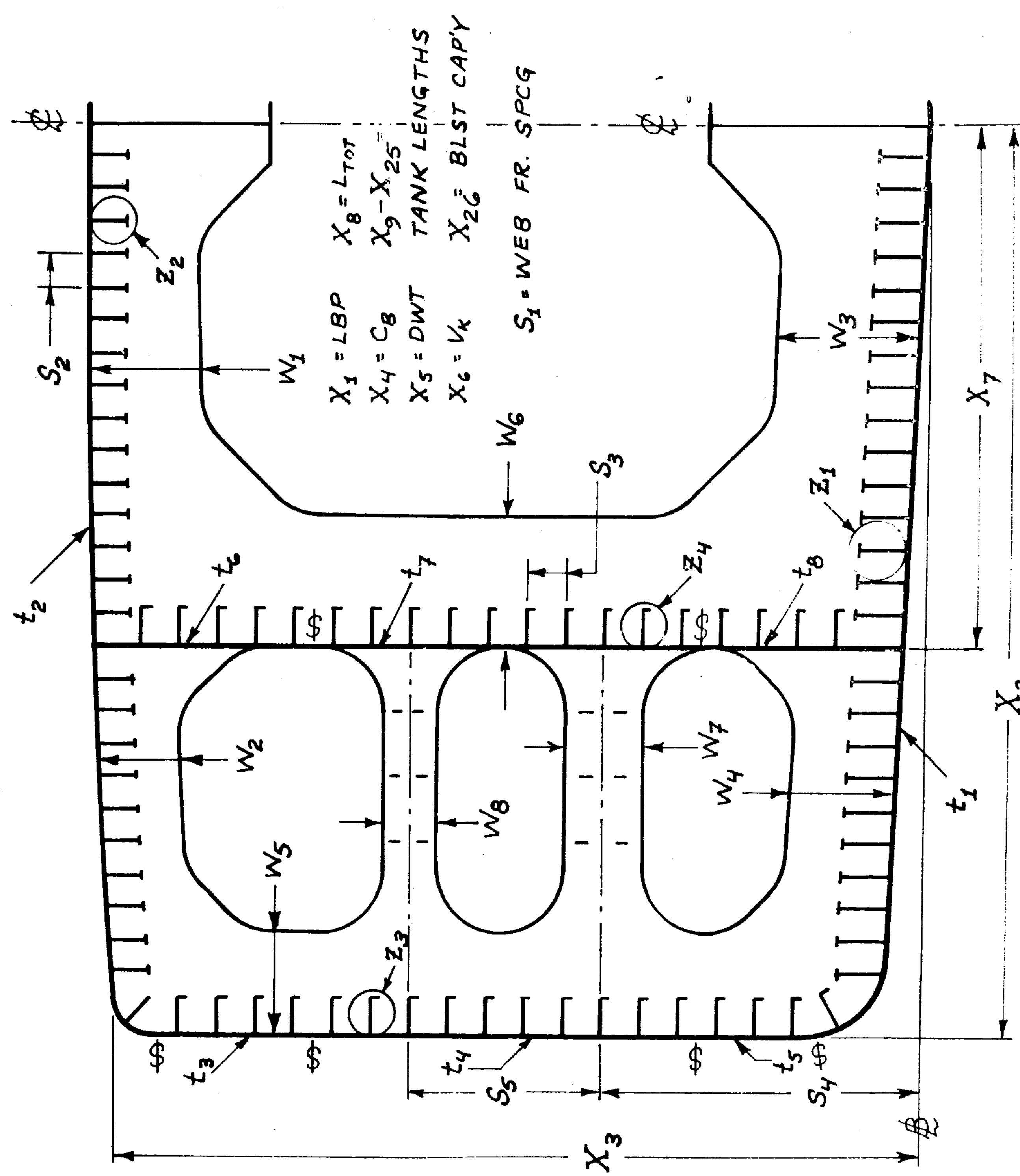
It may be noted in that figure that side girders have not been included. It is pointed out by Mori [1967] that they do not make any effective contribution to strength of the transverse structures. They do contribute to the longitudinal bending strength, however. That paper concludes, then, that inasmuch as the required longitudinal section modulus can be attained by means other than the installation of side girders, it is therefore better not to install any.

Obviously not all of those 51 variables are present in every design. The use of one cross-tie in the wing tank will omit the two parameters, S_5 and W_8. The criterion may be established in such a manner as to omit one or two of the principal characteristics. The thickness of the longitudinal bulkhead (t_6, t_7, t_8) may be fixed to the section modulus of the bulkhead stiffeners (Z_4). But also, for very large vessels, the number of centre and wing cargo tanks may be greater than the 28 allowed for by that listing. Only future attempts to use the entire group will indicate which variables are redundant, and which others have been ommitted.

The dimensions included, explicitly and implicitly, in the suggested list of free variables for the design optimisation (Table 4) are sufficient in scope to enable a structural stress analysis, as disscussed in Section 7, to be incorporated into the optimisation process. The purpose is to insure the early identification of potentially over-stressed regions of the structure.

FIGURE 8

FREE VARIABLES FOR OPTIMISATION



It is not intended that a complete stress analysis be included in every trial design of the optimisation scheme. Rather, a sequential process like that of Moe [1969] is envisioned, in which general relationships arising from the rules of classification societies are first used. But inasmuch as the imposition of the new IMCO constraints is expected to yield optimum configurations significantly different from former practice, the stress analysis becomes mandatory.

13. VARIATIONS ON A THEME

Although the suggested list of variables in the total optimisation proposed in the previous section appears to be all-encompassing, a substantial number of assumptions have been made, but should not be considered as final decisions. Whilst it is possible to carry out an optimisation with all of those variables, using all of the implicit assumptions, the relative "cost" of each decision (listed below) should be ascertained by use of a new optimisation scheme in which a different decision is utilised.

Regarding the structural configuration, 10 decisions are necessary prior to commencing such an optimisation procedure. Eight of the ten offer two possibilities only, and two of the decisions offer three possibilities. Altogether, then, the total number of possible combinations of decisions is $2^8 \cdot 3^2 = 2304$. In some instances, the number of variables in the optimisation is affected by the decision. Nevertheless, it is not proposed that over 2300 variations be optimised, each of which involve approximately 50 parameters. It is suggested, however, that careful consideration be given to the decisions; and that their likely consequences be ascertained in some manner, to the satisfaction of the designer.

The first two decisions arise from considerations of subdivision configuration.

(a) A double bottom may or may not be present. If present, then the depth of it is an additional variable to be optimised, as well as the thickness of the plating and the section modulus of the stiffeners along it.

(b) The number of longitudinal bulkheads is variable. Normally two in number a centre-line bulkhead may or may not be included with or without the wing bulkheads. Thus one, two or three may be used. If only one is used (on the centre-line), one less variable is required.

The next two decisions involve the web frames:

(c) The vertical girder of the web frame is either inboard or outboard of the longitudinal wing bulkhead. In Figure 8 it is inboard, and in Figure 3 it is outboard.

(d) The number of cross-ties in the wing tank may be either zero, one or two. If none are present, two less variables are needed; and if one is used, one less parameter need be optimised.

The fifth and sixth decisions involve the structural configuration of the bulkheads. The number of variables need not be affected, although Gisvold's [1970] study is an 11-parameter optimisation of the design of a corrugated bulkhead. Some, but not all, of those 11 parameters have already been included, however.

The two bulkhead-related decisions are:

(e) The bulkheads may be either plane or corrugated.

(f) The bulkheads may be stiffened with either horizontal girders or vertical webs.

Buxton [1966] offers evidence that the relative influences of breadth and depth on weight and cost vary considerably with each choice.

The last four decisions in structural matters involve the usage of mild or high strength steels. For each of the following four areas, a decision regarding steel type is required:

(g) Bottom and deck plating and stiffeners.

(h) Side plating and stiffeners.

(i) Longitudinal bulkhead plating and stiffeners.

(j) Transverse structures.

Regrettably, the number of significant decisions necessary for total optimisation are not limited to the 10 noted above. When the principal characteristics as well as structural configuration are subject to optimisation according to a criterion that includes capital as well as operational costs, then the type of prime mover becomes a matter of objective decision as well. Thus the eleventh decision, offering four possibilities, is:

(k) The main engines may be slow-speed diesel, medium-speed diesel, steam turbine or gas turbine.

That fourth possibility may not appear realistic for larger tankers in 1973, but may become so within the next several years, subject to changes in the relative capital and operational costs of each type of prime mover.

A twelfth decision related to the principal characteristics and the main engines is that of the propellers:

(1) The vessel may be either single or twin screw.

Further decisions regarding secondary machinery characteristics for large tankers (prime movers for pumps and alternators) do not appear to be significant in the optimisation of a design, and are therefore not included in the present list of actively required decisions.

A clear distinction must be made between (a) the multitude of optimisations called for by considering the possible effects of these decisions, and (b) the numerous optimisations sought in connection with the probabalistic variations mentioned in Section 2 and by Fisher [1971]. The use of probabalistic studies, using semi-random techniques, is linked with uncertainty in the design. But there can be no uncertainty in the decisions called for above.

"Most probable values" of costs are a fact of everyday life, in that future values could be any reasonable percentage different. It does not make sense, however, to talk about the presence of a double bottom varying by several percent from its most probable value. It is a go/no-go situation, unlike costs, etc.

Often the decisions required as listed above are made for non-tangible or non-economic reasons. There is nothing wrong with such a decision-making process. But through the use of the total optimisation schemes suggested in Section 12, and with the benefit of the variations on that theme offered in this section, the tangible or cost penalty or benefit of making such a decision can be ascertained.

14. CONCLUSION

As indicated in the Introduction, ten years ago Professor Benford identified the movement toward the totally integrated decision process in preliminary ship design. The question unanswered at that time, and phrased more recently by Mr. Nachtsheim, is essentially: by what mechanism will that decision process be achieved?

This paper has set forth some of the concepts that require recognition and consideration prior to embarking on that process, which itself may be considered as a six-stage process, centered on a large-scale optimisation.

Firstly, acceptance of an appropriate criterion is necessary. The criterion will most likely (but not always) be an economic one. It will have to give due consideration to the fact that the ship is but part of a larger system. Highly subjective pre-optimisation decisions are initially required, fundamental to the overall purpose of the design of a transportation system, including giving regard to socio-economic as well as pure economic consequences.

Secondly, toward a more technical basis, the extent of the system parameters that can be 'played-off' against one another must be established. A thorough study of the proposed system must be made for the purpose of determining which design variables can be included in the optimisation. Simultaneously, direct and indirect constraints on those parameters must be phrased with mathematical-type rigor.

Thirdly, the relative rigidity and flexibility of the constraints must be established. At the same time, the elements of 'good judgement' must be given mathematical expression (e.g., equality of tank sizes, as in Section 11).

Fourthly, the complex of physical, economic and operational relationships, linking all of the independent design variables, must be put into mathematical formulation. This step in the design process is the one requiring the greatest effort, and is also the one having the least degree of confidence associated with it.

Fifthly, the preliminary choice of values of the design variables is made through the use of an optimisation scheme. This stage of the process incorporates the study of the effect of decisions of the type listed in Section 13, Variations on a Theme.

Lastly, the effect of guesses, assumptions and approximations in the relationships established in the fourth step are examined through the use of further optimisations based on probabalistic variations of coefficients, etc. These may be applied systematically to all possible combinations of modifications to the mathematically expressed relationships; but it is more likely that a semi-random process is preferred.

Those are the six major steps required in the integrated or simultaneous decision process necessary for ship design. It has been suggested in this paper that, due to the unusual linking of parameters for certain classes of vessels, the design variables involved in the process may require far greater detailing at an earlier stage than is usually associated with the concept of preliminary design. But, as an example, even the necessity of an early stress analysis has been shown to be desirable in certain instances.

Because it is one of the least complicated vessel types, the application of this design process to tankers is expected to be manifested first. The various elements necessary for that usage, involving over 50 independent design variables, have all been formulated and applied in smaller parameter groups. The ability to cope with all forms of constraints, including the recent IMCO regulations governing anti-pollution aspects of subdivision configuration, has also been demonstrated in this and previous papers. In principle, there is no reason to prohibit the simultaneous optimisation of all those parameters. Difficulty will be encountered in finding an appropriately 'strong' optimisation procedure, however.

There will undoubtedly be a large number of local optima, due to the presence of several integer restrictions. Further, it is expected that the problem will involve over 40 external and 50 internal constraints, some of which may impede the rapid optimisation of the over 50 parameters. Since the number of trials necessary for optimisation varies approximately as the square of the number of variables, it is realised that a considerable amount of computer time will be required for this 'total optimisation.' Further, the economic justification for such a study may not be readily apparent.

But as the 'cost' of errors in judgement increases, as it is rapidly doing in a number of trades and operations involving fleets of over 10-12 vessels, the relative cost of such studies will more willingly be borne.

NOMENCLATURE

B	beam of vessel.
B_C	beam of centre tanks.
B_W	beam of wing tanks.
C#3	centre tank no. 3.
D	depth of vessel.
kcm	1000 cubic meters.
L_{AWG}	total length of after wing tanks, including slop tank (Figure 4).
LBP	length between perpendiculars.
L_{BAL}	length of wing clean ballast tank (Figure 4).
L_{BCG}	distance from forward end of L_{TOT} to centre of gravity of wing ballast tank (Figure 4).
L_{BOW}	distance from the forward perpendicular to the forward end of L_{TOT} (Figure 4).
L_{C-MAX}	maximum allowable length of a centre tank.
L_{FWG}	total length of forward wing tanks, including ballast tank (Fig. 4).
L_{TOT}	total length of cargo tank section of vessel.
L_{W-MAX}	maximum allowable length of a wing cargo tank.
l_c	longitudinal extent of assumed collision damage.
l_s	longitudinal extent of assumed stranding damage.
l_{s-aft}	value of l_s aft of 0.3LBP behind the forward perpendicular.
l_{s-fwd}	value of l_s forward of 0.3LBP behind the forward perpendicular.
$S_1 - S_5$	variables for optimisation (Figure 8).
T	draught of vessel.
$t_1 - t_8$	longitudinal plating thicknesses (Figure 8).

t_c	transverse extent of assumed collision damage.
t_s	transverse extent of assumed stranding damage.
t_{s-aft}	value of t_s aft of 0.3LBP behind the forward perpendicular.
t_{s-fwd}	value of t_s forward of 0.3LBP behind the forward perpendicular.
V_{COL}	volume of oil outflow due to collision.
V_{C-MAX}	maximum allowable volume of a centre tank.
V_{MAX}	maximum allowable oil outflow due to either stranding or collision.
V_{STR}	volume of oil outflow due to stranding.
V_{W-MAX}	maximum allowable volume of a wing cargo tank.
$W_1 - W_8$	web frame plating depths (Figure 8).
W#2	wing tank no. 2.
$X_1 - X_{26}$	variables for optimisation (Figure 8).
$Z_1 - Z_4$	section moduli of longitudinals (Figure 8).

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NECIES - North-East Coast Institution of Engineers and Shipbuilders.

RINA - Royal Institution of Naval Architects.

SNAME - Society of Naval Architects and Marine Engineers.

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APPENDIX I

Example of Constraint Interaction.

1. Introduction

The inclusion of this Appendix in the present paper is to demonstrate the previously unreported interaction between an object function and the simultaneous presence of boundary and integer-type constraints in a multi-dimensional optimisation. A minimum number of details are given below, in order to keep the essential aspects of the illustration clear. Most of the basic information used is contained in the reference Fisher [1972a], unless stated otherwise. The problem involves the construction of a bulk/ore carrier in a specified shipyard.

2. Problem Statement

The principal characteristics of a 15-knot ore carrier are to be found according to a minimum required freight rate (RFR), for 15-year operation on a 6,400 mile round trip route, for which the vessel is in ballast in one direction. Examination of the associated capital cost per DWT is also desired. The design is subject to the following constraints, arising from owner and shipyard requirements.

(i) The maximum LBP acceptable to the shipyard is 760 ft.

(ii) The maximum beam acceptable to the shipyard is 106 ft.

(iii) The engine is to be one of the following:

(A) 10,000-12,000 BHP, 6 cyl. @ 76 cm. bore.
(B) 12,000-14,000 BHP, 7 cyl. @ 76 cm. bore.
(C) 14,000-16,000 BHP, 8 cyl. @ 76 cm. bore.
(D) 16,000-17,400 BHP, 6 cyl. @ 90 cm. bore.
(E) 17,400-20,300 BHP, 7 cyl. @ 90 cm. bore.
(F) 20,300-23,200 BHP, 8 cyl. @ 90 cm. bore.

(iv) The service speed is to be 15.0 ± 0.02 knots.

3. Background

In the Author's Reply of Fisher [1972a], it is stated that local minima were found to be in valleys created by the numerous step functions arising from the use of a discrete set of machinery configurations. The additional length and beam restrictions applicable to this further study are shown to create new and/or different minima as well.

The exceptions to the use of information contained in the reference Fisher [1972a] are as follows:

(i) Capital costs for one vessel only (no facilities) are used, and are taken at 1.7 times the previously stated levels.

(ii) The steel weight estimate is made according to Fisher [1972b].

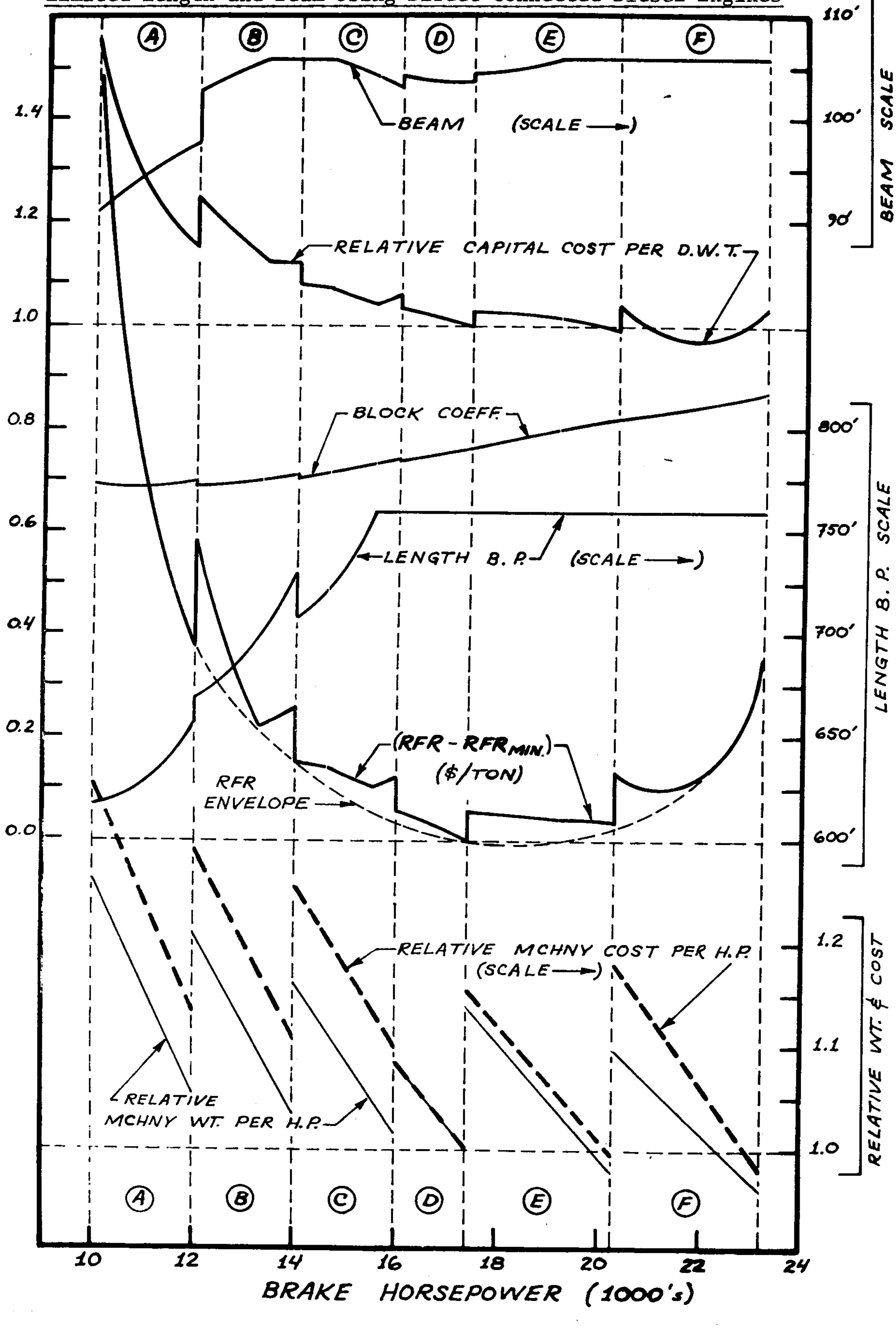
(iii) The residual resistance is determined according to parabolic interpolation of the regression coefficients of Sabit [1971].

4. Results

The RFR-optimised principal characteristics have been determined for all BHP's between 10,000 and 23,200. The object function and several of the optimised characteristics are displayed in Figure A1. Seven local minima have been identified, the lowest among them being the global minimum, which is associated with engine "D" being utilised at 100% maximum continuous rating.

FIGURE A1

Optimised Characteristics of a 15-Knot Bulk Carrier with Limited Length and Beam Using Direct-Connected Diesel Engines



Other local minima are not always found at the 100% engine-ultisation points.

In that figure, the absolute values of LBP, B and C_B are shown (English units). Also shown, at the bottom, are the weights per BHP and capital costs per BHP for each of the discrete power plants, divided by thos associated with the global minimum. The capital costs per DWT are also divided by those of the global minimum-RFR design. The RFR curve shown is not a relative one, but rather shows the difference (in $/ton) between each optimum RFR and the global minimum.

Numerous aspects of that study merit further discussion, but for the purposes of this paper they are limited to the following remarks.

(i) The application of an integer-type constraint (going from one power plant to another) produces a step in the object function.

(ii) The application of a boundary constraint (length or beam) produces a discontinuity in the slope of the object function.

(iii) Three of the seven local minima occur at the points of application of the integer-type constraint (A,D and E).

(iv) Three of the seven local minima occur at the onset of activity of a boundary constraint (mid-B, mid-C and mid-E).

(v) One of the local minima occurs elsewhere (mid-F).

5. Comments

It is emphasized that the results shown are RFR-optima for the specified BHP. Over 40 optimisations were performed to establish Figure A1, averaging 221 trials for each of the 5-parameter optimisations.

Interestingly, from about 19,200 BHP onward, the configuration was chosen more to dissipate the available horsepower, than to use it efficiently for 15 knots service speed.

It is also noted that in the vicinity of 22,000 BHP, the capital cost per DWT arising from the RFR optimisation is lower than that of the global minimum-RFR, under-scoring the fact that the choice of criterion is significant in decision-making.

If the capital cost per DWT is optimised, rather than the RFR, the optimum principal characteristics are found to be slightly different from those shown in Figure A1, but are not included here for the purpose of maintaining brevity.

APPENDIX II

Description of 'IMCO' Limitations.

The requirements of the Inter-Governmental Maritime Consultative Organization (IMCO) relating to tank arrangements and the limitation of tank size as used in this study are summarised in the following sections.

1. Damage.

The assumed extent of damage arising from collision or stranding are stated. In general, the longitudinal, transverse and vertical extents of damage may be considered to define a parallelepiped. In the collision situation, the size of the three dimensions are fixed, and it is measured inboard from the maximum beam and upward from the base-line.

For the case of stranding damage, the longitudinal and transverse extents of the damage (l_s, t_s) are larger forward of 0.3 LBP from the FP of the vessel than they are aft of that point. If the transverse extent (t_s) is greater than the beam of the centre-line tanks (B_C), then it must be assumed that wing tanks on both sides, as well as the centre tanks, will be breached in stranding.

Likewise, if the transverse extent of collision damage (t_c) is greater than the beam of the wing tanks (B_W), then centre-line tanks as well as wing tanks will be breached in collision.

This author's interpretation of the use of the two different longitudinal and transverse extents of stranding damage, forward and aft of the 0.3 LBP point, is shown in Figure A2.

According to the regulations:

> These values represent the maximum assumed damage in such accidents, and are to be used to determine by trial at all conceivable locations the worst combination of compartments which would be breached by such an accident.

2. Oil Outflow

The volume of oil outflow due to collision (V_{COL}) is a function of the total volume of the breached cargo tanks and the relative beam of the wing tanks, with the exception noted below (section 4). The volume of a ballast tank is not included.

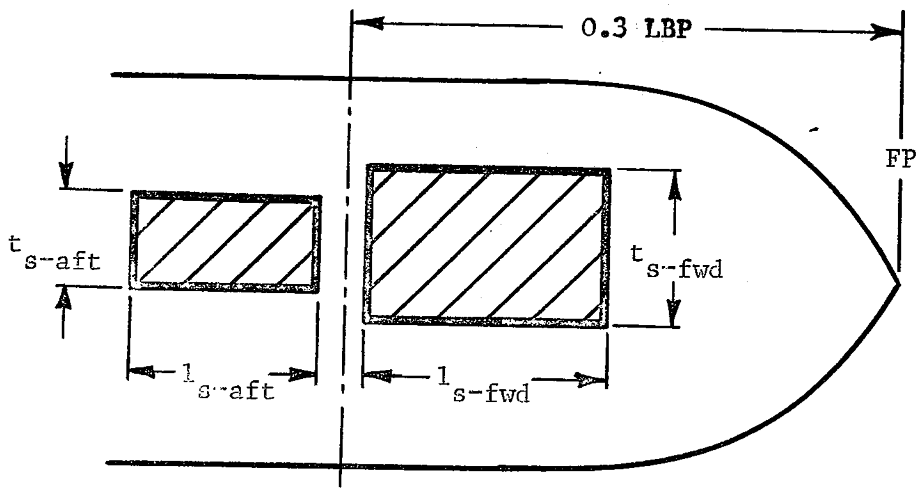
For tankers without double bottoms, the oil outflow due to stranding (V_{STR}) is to be calculated as one-third the total volume of the breached cargo tanks, with the exception also noted in Section 4.

3. Limitations on Tank Sizes

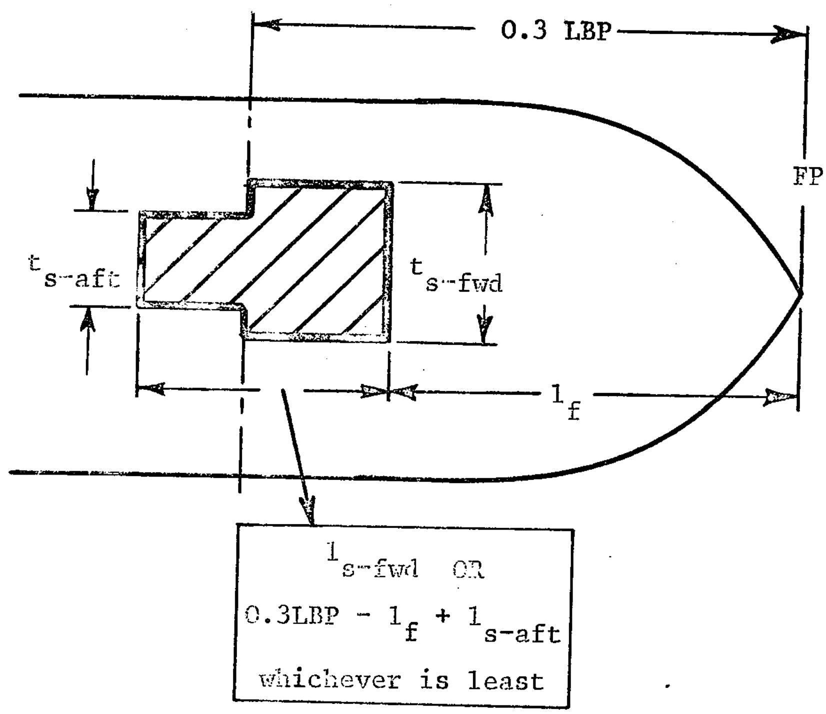
The maximum outflow of oil (V_{MAX}) is (a) 30,000 cubic meters for vessels having a deadweight less than approximately 420,000 metric tons; (b) 40,000 cubic meters for vessels of over 1 million DWT; (c) and $400\sqrt[3]{DWT}$ for vessels between those sizes.

FIGURE A2

Interpretation of Extents of Stranding Damage



(a) Damage entirely forward or aft of 0.3 LBP.



(b) Damage forward and aft of 0.3 LBP.

Limitations on the maximum volume and maximum lengths of wing and centre tanks are also specified. They are denoted V_{W-MAX}, V_{C-MAX}, L_{W-MAX}, and L_{C-MAX}.

4. Exceptions

The exceptions to the above regulations for which allowance has been made in this study are these two: (a) If stranding damage simultaneously involves four centre tanks,a coefficient of one-fourth (rather than one-third) may be used in the calculation of V_{STR}. (b) In calculating V_{COL}, the apparent volume of a wing tank adjacent to a clean ballast tank may be reduced from the actual volume if the length of the ballast tank (L_{BAL}) is less than l_c, the collision damage length.