THE ROYAL INSTITUTION OF NAVAL ARCHITECTS

AUSTRALIAN DIVISION

SELECTION OF FUELS FOR SHIPS

BY

C.G.J. STAFFERTON B.E.

PRESENTED AT SYDNEY

ON

WEDNESDAY, 8TH JULY, 1981.

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S E L E C T I O N   O F   F U E L S   F O R   S H I P S

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ABSTRACT

Beginning with the problem of selecting fuels for ships, a decision analysis model is developed. The overall model presented in this paper enables a decision maker to begin with a broad, ill defined problem and to finish with solutions as accurate as the information which is available for use in the study. In the first part the decision maker identifies alternative solutions and selects attributes against which to evaluate the alternatives. On the basis of available information and with the aid of the subjective decision making model, the decision maker can refine the list of alternatives originally identified, to a short list of superior alternatives. In the second part the decision maker formulates simple linear relationships between the alternatives. The relationships reflect policy goals and the alternatives are decision variables. By proposing different scenarios in which the decisionmaker expects to be operating, then solving the goal programming problem for each scenario, the decision maker can generate information on which to act, or on which to develop policy for the future.

Both the forced subjective decision making method and the goal programming method are powerful decision making tools. Their advantages are that both methods facilitate the subdivision of complex problems into simple components which are more easily analysed. The subjective decision making method is simple enough to be used manually, although the SUBDEC package (14) is recommended, because it saves both time and effort, particularly in checking for degeneracy of logic in the decision making process. The goal programming method can be solved graphically for problems, which have two decision variables. Where more than two decision variables exist the modified simplex algorithm is needed (15). Although this can be used manually it is recommended that code be written so that the algorithm and post optimality analysis can be done on a computer.

Both methods, however, have a distinct disadvantage. Neither model will produce accurate, perfect and absolute solutions unless accurate, complete and perfect information is used in them.

THE PROBLEM

The general problem considered in this paper is the concern of shipowners and operators over the rapidly increasing fuel prices and long-term forecasts of shortfalls in commercially available conventional marine fuels. The reasons for the problem are now history. In the northern winter of 1973-74 a radical increase in oil prices began successive rounds of price rises. Those rises had a marked effect on the prices of marine diesel oil and marine fuel oil. In addition, and partly as a result of increased prices, oil refining techniques have been improved so that more of the higher grade distillates and less lower grade and residual fuels are produced.

TOWARDS A SOLUTION USING DECISION ANALYSIS MODELS

Various solutions to the problems of increasing prices and diminishing supply of conventional fuel have been suggested in the literature. As an aid to the shipowner or operator a decision analysis model has been developed to facilitate analysis of the alternative solutions with regard to selected attributes. Using this model a shipowner may determine, on the basis of information available to him, which of the alternatives is superior and what the composition of a new fleet should be. The decision analysis model is divided into two (2) distinct sections. The first,facilitates selection of superior alternatives. The second enables the shipowner to determine the optimal mix of a fleet which is composed of the superior alternatives.

For the purposes of this study a Panamax type bulk carrier with a speed of 15 knots has been selected to run a coal trade between Australia and Japan. This is in response to the growing world demand for coal and the predicted increase in demand for bulk tonnage (1). A quantity of 10 million tonnes is to be transported to Japan annually. This represents about 20% of the total predicted coal exports from Australia to Japan (2).

TABLE 1 Principal Particulars of the Basis Ship

Type	Panamax Bulk Carrier
Length	213.00 m
Breadth	32.24 m
Depth	18.00 m
Summer draught	12.60 m
Total displacement	73, 130 tonne
Cargo deadweight	56, 896 tonne
Service speed	15 knots

ALTERNATIVE SOLUTIONS TO BE ASSESSED

Twelve (12) alternative solutions to the problem of fuelling ships in the future were found from a literature survey (3). Those twelve (12) alternatives described in general terms are:

1. Diesel - conventional fuels
   - marine fuel oil (bunker C) and marine diesel oil.

2. Diesel - poor residual fuels

   - conventional fuels of inferior quality e.g. high density; sulphur, water and heavy metals in high concentration (4)

3. Diesel - water emulsified fuels
   - conventional fuels with up to 15% emulsified water content.

4. Diesel - synthetic fuels
   - liquid fuels produced from coal, oil shale or tar sands.

5. Diesel - coal-oil slurries.
   - conventional fuels with concentrations of 10% to 15% of coal particles of less than 20 microns particle size.

6. Coal - spreader-stoker boilers
   - coal firing of a water wall boiler where coal is distributed, according to size, across a travelling grate (5).

7. Coal - fluidized bed combustor;
   coal of up to 2.5 cm size combusted in a bed of 98% or 99% inert material (ash or stone) which is fluidized by forced draught. Main boiler tubes are immersed in the bed.

8. Gas Turbines
   - includes both aero-drived and heavy duty marine gas turbines.

9. Nuclear Propulsion
   - small shipboard nuclear reactors similar to those on N.S.SAVANNAH, N.S. OTTO HAHN or N.S. MUTSU (6).

10. Wind - said assisted motor;
    - conventioanl type of motor vessel assisted by a simple sail configuration, such as the SHIN AITOKU MARU (7).

11. Wind - motor assisted sail
    - a fully rigged ship with some form of auxiliary engines for manoeuvring in post, in confined seaways and for emergencies.

12. Wind - wind turbines
    - vessel using vertical axis wind turbines and either mechanical, hydraulic or electrical transmission of power to the propeller.

ATTRIBUTES TO CONSIDER

The alternatives are compared and evaluated against a group of selected attributes. Those attributes reflect the areas which the ship-owner is concerned with, will significantly effect or be effected by the final solution. The attributes selected for this model are:

1. Current state of technology - this reflects on the technology available to the shipowner.

2. Technological outlook for the near future - an assessment with regard to research and development projects.

3. Government Policy

   - this allows a particular national or political preference to be accounted for in decision making (Government Policies can seriously effect the viability of a project (8)).

4. Industry's Attitude

   - Unproven technology may attract undue prejudice, because of the historical background of an industry.

5. Environmental impact - shipboard

   - The effect of an alternative on the immediate shipboard environment - the living and working environment of the crew. (This is included in response to constant demands for better living and working conditions.

6. Environmental impact - shoreside

   - The more distant effects of a shipboard system, from pollution in the vicinity of the vessel to the effects of industrial development in the hinterland to support changing fuel demands. (Assessment with regard to this attribute should recognize the complexity of the inter-relationships of industrial systems).

7. Technological Sophistication -highly developed technology requires highly skilled operation and service personnel; both are expensive commodities, whereas simpler, more robust technology can be operated and maintained by men of lesser training.

Assessment of a Shipowner's Utility for Alternative Solutions Using Forced Subjective Decision Making.

Having determined the alternatives and the attributes against which they are to be assessed, the shipowner is in a position to begin analysing his subjective preference for each alternative fuel system. First the attributes should be ordered according to the influence, which the shipowner perceives they will have on current practice. This is done by comparing each attribute with all the others; a value of 1 is assigned to the attribute, which is considered more influential and 0 is assigned to the less influential. (All decisions should be recorded with reasons for each decision. If new information becomes available adequate records will facilitate re-evaluating of the decision analysis).

The decisions for weighting of the attributes are set out in Table 2.

TABLE 2 Weighting of Attributes

ATTRIBUTE	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21
1. Current state of technology.	0	0	0	1	1	1															
2. Technological outlook	1						0	½	1	1	1										
3. Government policy		1					1					1	1	1	1						
4. Industry's Attitude			1					½				0				1	1	1			
5. Environmental impact-shipboard.				0					0				0			0			0	1	
6. Environmental impact-shoreside.					0					0				0			0		1		1
7. Technological sophistication.						0					0				0			0		0	0

As perfect information is not always available, inadequate or insufficient information makes the assessment of utility of one attribute over another difficult. Therefore it is possible to assign equal values, ie ½ to each item, as in decision 8 of Table 2. Because this effectively makes two items equal for this set of decisions, all other decisions made with respect to those items must be consistent; i.e. if $A = C$ and $A > B$ then $C > B$ (9).

The same procedure is followed in assigning preferences to the alternatives for all attributes until a series of tables are assembled. These tables summarize the shipowners subjective decisions for each alternative solution with respect to the selected attributes. As an example, the decisions with respect to attribute 1, the "Current state of technology" are give in Table 3.

To evaluate the utility attached to each attribute (Pj) or alternative (rij), the assignments are summed and normalized (Rij) for each attribute:

$$Rij = \frac{rij - ri\,min}{ri\,max - ri\,min} \qquad \text{Equation 1}$$

where: $ri\,min$ = minimum value of r for that attribute.
$ri\,max$ = maximum value of r for that attribute.

Normalized values fall between 0 and 1. This technique is particularly useful when qualitative information is introduced to the analysis; for example a comparison of fuels could be made with "cost per kilojoule as an attribute.

To determine the merit junction (the compounded utility values) the value attached to each alternative is multiplied by the value attached to each attribute. For each alternative the products are summed:

$$\sum_{j=1}^{n} Rij\ Pj = Mj \qquad \text{Equation 2}$$

where: Rij = normalized utility ratings
Pj = utility of attributes
Mj = merit function for alternatives.
n = number of alternatives

Alternative		Decision No (1 … 66)	Total	r_j
Diesel – Conventional	1	1 1 1 1 1 1 1 1 1 1 1	11	0.167
– Residual	2	0 1 1 1 1 1 1 1 1 1 1	10	0.152
– Water Emulsify	3	0 0 0 1 0 1 1 1 0 1 1	6	0.091
– Synthetic	4	0 0 1 1 0 1 1 1 0 1 1	7	0.106
– Coal Oil Slurry	5	0 0 0 0 0 1 0 0 0 1 1	3	0.045
Coal – Spreader Stoker	6	0 0 1 1 1 1 1 1 0 1 1	8	0.121
– Fluidized Bed	7	0 0 0 0 0 0 0 0 0 1 1	2	0.030
Gas Turbine	8	0 0 0 0 1 0 1 1 0 1 1	5	0.076
Nuclear Propulsion	9	0 0 0 0 1 0 1 0 0 1 1	4	0.061
Wind – Sail Assisted Power	10	0 0 1 1 1 1 1 1 1 1 1	9	0.136
– Power Assisted Sail	11	0 0 0 0 0 0 0 0 0 0 1	1	0.015
– Wind Turbine	12	0 0 0 0 0 0 0 0 0 0 0	0	0.000

TABLE 3 ASSESMENT OF ALTERNATIVES WITH RESPECT TO ATTRIBUTE 1 (CURRENT STATE OF TECHNOLOGY)

ATTRIBUTE NO.	1	2	3	4	5	6	7	M_j	RANK	% DIFFERENCE FROM RANK 1
ALTERNATIVE NO. / P_j	(0.143)	(0.214)	(0.286)	(0.214)	(0.048)	(0.095)	(0.000)			
1	1.000	0.365	0.599	0.814	0.500	1.000	0.683	0.686	4	18.3
2	0.922	0.814	0.796	0.910	0.500	1.000	0.545	0.840	1	0.0
3	0.545	0.545	0.599	0.545	0.500	1.000	0.455	0.602	5	28.3
4	0.635	1.000	1.000	0.725	0.500	0.645	0.683	0.831	2	1.1
5	0.269	0.090	0.599	0.365	0.500	0.645	0.365	0.392	8	53.3
6	0.725	0.814	0.895	1.000	0.053	0.151	0.910	0.765	3	8.9
7	0.180	0.635	0.697	0.635	0.053	0.151	0.814	0.514	6	38.8
8	0.455	0.269	0.099	0.455	0.197	0.796	0.269	0.333	10	60.4
9	0.365	0.180	0.000	0.000	0.796	0.000	0.000	0.129	12	84.6
10	0.814	0.725	0.296	0.180	1.000	0.401	0.180	0.481	7	42.7
11	0.090	0.545	0.296	0.180	1.000	0.401	1.000	0.339	9	59.6
12	0.000	0.000	0.296	0.180	1.000	0.401	0.090	0.209	11	75.1

TABLE 4. NORMALIZED RATINGS FOR ALL ALTERNATIVES, WEIGHTING OF ATTRIBUTES, MERIT FUNCTION (M_j) AND RANK.

Table 4 shows the normalized utility ratings (Rij) the utility of attributes (Pj) and the merit junction for alternatives (Mj) with the rank each alternative, according of the magnitude of Mj. The shipowner now has a rational ordering of his preference for each alternative fuel system. The relative utility of one alternative over another can be seen clearly when alternatives are arranged according to their relative preference in the merit function. Figure 1 indicates the distribution of utility or the relative preference for alternatives. Clearly the two variants on conventional diesel engines are most preferred, followed by a coalfired boiler.

HOW RELIABLE IS THE ASSESSMENT?

By definition this analysis is subjective and is based upon imperfect information. Therefore, no absolute solutions can be generated. The superior alternatives, as determined by the shipowner, are those within some arbitary band width of the highest ranking alternative. In this case a band width of 20% is used. The sensitivity of the merit function to changes in utility for each of the superior alternatives is calculated to determine the effect of changed utility values on the relative utility of the superior alternatives.

Each utility rating (Rij) is assessed for its influence on the merit function. For a change of 'C' percent in the utility rating, the expression for the new merit function is:

$$M^{*}j = Mj \pm Rij\ Pj\ C \qquad \text{Equation 3}$$

where: C = percentage change in utility rating
$M^{*}j$ = modified merit function.

For example, improved techniques for burning poor residual fuels may warrant a reassessment of utility. A 20% change in utility for alternative 2 (Diesel - poor residual fuels) with respect to attribute 1 (Current State of Technology) would result in a 2.6% change in utility. Tabl 5a indicates the relative influence which each attribute has on the choice of an alternative

TABLE 5A Change in Merit Function for a 20% Change in Utility

ALTERNATIVE	ATTRIBUTE	% CHANGE IN Mj FOR C = 20%
2	1	3.07
	2	4.12
	3	5.38
	4	4.60
	5	0.57
	6	2.25
	7	0.00

Table 5b indicates the relative influence of the attributes on the choice of an alternative when the utility is varied.

TABLE 5B

ALTERNATIVE	ATTRIBUTE	% CHANGE IN Mj FOR C = 20%
2	1	3.07
4		2.18
6		2.71
1		4.17

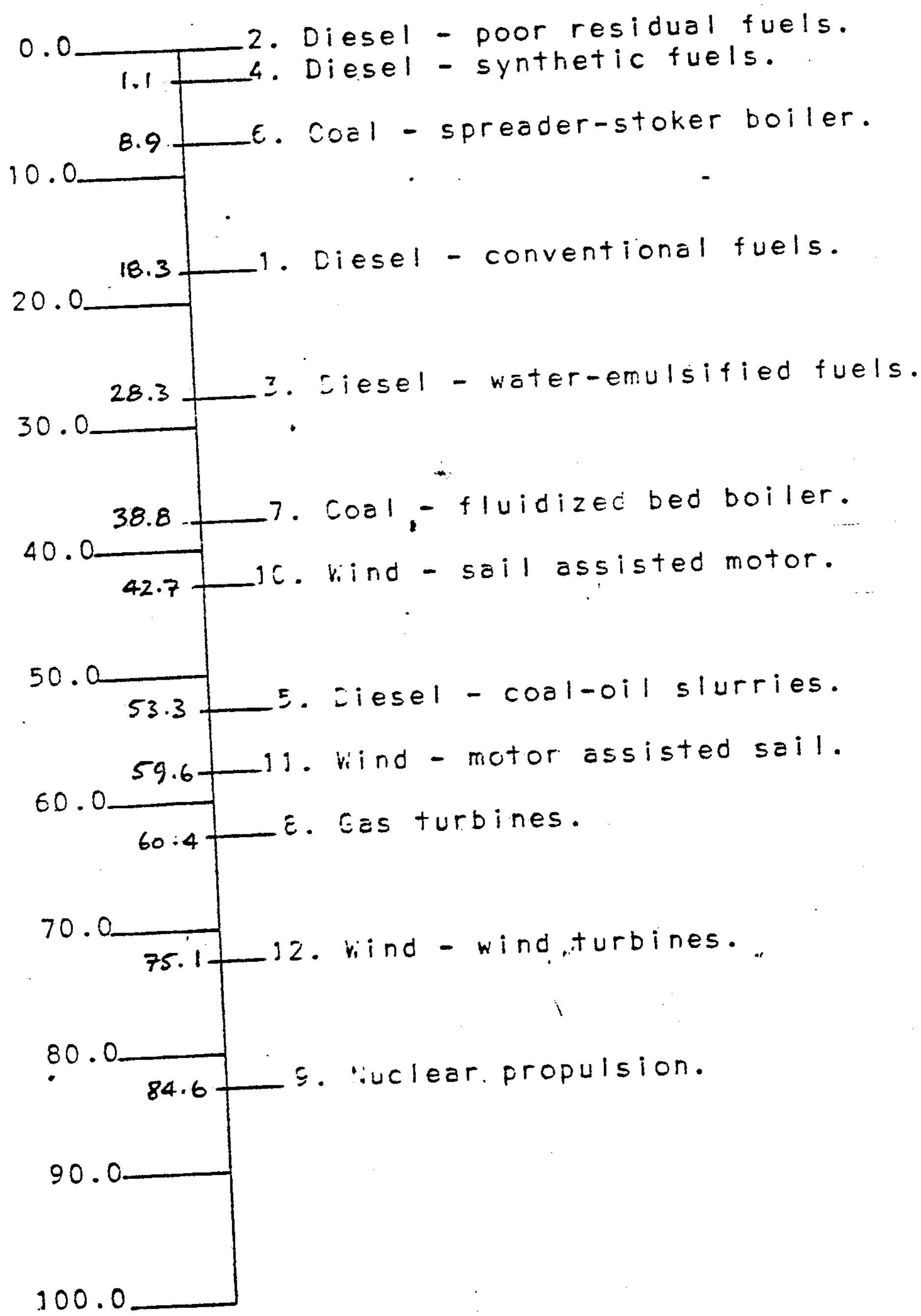


Figure 1 Relative preferences for alternatives.

(Percentage difference from the highest ranking alternative.)

Of the twelve alternative solutions initially defined the shipowner now has a group of four superior alternatives which may be further investigated. The superior alternatives fall into two basic categories - diesel powered ships and coal fired ships.

If a new fleet is not to be composed entirely of conventially powered vessels, or entirely of vessels with some new system a a rational method must be used to determine the composition of a new fleet.

DETERMINING THE COMPOSITION OF A NEW FLEET USING GOAL PROGRAMMING

Having, in the owners estimation, determined the superior fuel systems we move on to find the composition of a new fleet. For simplicity, and as diesel engines are being developed to burn different types of fuel, only two types of fuel, only two types of ship are considered. The coal fired ship is considered as one type and the diesel powered ship as another.

A number of goals are set, each representing a critical component of the annual cash flow in the operation of a commercial vessel (10). The goals (Table 6) are ranked in order of their contribution to revenue, then operating costs. The desired mode of achievement of each goal is also indicated.

TABLE 6 Goals and their Modes of Achievement

G1 :	Quantity of cargo carried	minimize underachievement
G2 :	Capital cost of the fleet	minimize overachievement
G3 :	Fuel cost of the fleet	minimize overachievement
G4 :	Voyage time	minimize overachievement
G5 :	Port time	minimize overachievement
G6 :	Maintenance costs	minimize overachievement

The problem can be formulated in the following manner:

Find $\bar{x} = (x_1, x_2)$
where = number of diesel powered motor ships.
= number of coal fired steam ships.
so as to minimize

$$\bar{a} = \{P_1(n_1 + p_2), P_2(p_3 + p_4), P_3(p_5 + p_6)\}$$ Equation 4

where $P_1\ (n_1 + p_2)$ is a good set which aims to minimize underachievement of the quantity of cargo (n_1) and minimize overachievement of the capital cost (p_2) - P_1 indicates that this goal set has highest priority.

$P_2(p_3 + p_4)$ is the goal set which aims to minimize the overachievement of fuel cost and of voyage time.

$P_3\ (p_5 + p_6)$ is the goal set which aims to minimize overachievement of port time (p_5) and maintenance costs (p_6).

The problem formulation, equation 4, is subject to the following goal constraints.

TABLE 7

G1 : Quantity of cargo carried:	691,286.4 x1	+	679,148.6 x2	=	10,000,000.0
G2 : Capital cost of the fleet:	18.5 x1	+	22.2 x2	=	296.8
G3 : Fuel cost of the fleet:	297,350 x1	+	89,740 x2	=	2,811,814
G4 : Voyage time :	24.8 x1	+	24.8 x2	=	328.6
G5 : Port time :	14.2 x1	+	22.5 x2	=	205.5
G6 : Maintenance Costs:	1.00x1	+	-1.15x2	=	0.00

Priorities, P1, P2, P3 are determined by the shipowner. All coefficients and goal values are calculated according to currently available information (11). Data for goal G2 : Capital cost of the fleet is based on information about shipbuilding costs for the first half of 1980 (12), and assumes that a new building price for coal fired vessels is approximately 20% higher than for a diesel powered vessel.

This formulation allows a set of equations, each of different units, to be used to find the optimal number of each type of vessel in the new fleet. The problem can be solved numerically or graphically. A graphical method of solution is shown here. (A numerical approach is shown in reference 13).

Begining with the ordinate and abscissa, each representing a vessel type (Figure 2) constraints are added to the graph (Figures 3 & 4). By observing the desired mode of achievement of each goal it is possible to find a feasible design space. If the desired solution can be expressed in real numbers, the optimal solution will be found at the vertex of this space. This solution satisfies the greatest number of goals, according to the priorities assigned to those goals. A real solution to this problem is $X_1 = 7.25$, $X_2 = 7.35$ (Figure 5). However, in this case an integer solution is required. A set of integer solutions will be found within the feasible design space; the most desireable integer solution is that one closest to the real solution. In this case the solution is x1 = 10 and x2 = 5; that is 10 diesel powered vessels and 5 coal fired vessels (Figure 6).

Given the simplicity of this method it is possible to change ship characteristics, values of input data and priorities of goals to investigate other variants. For example Table 8 gives the solution for a fleet of coal fired ships with a speed of 15 knots and diesel powered ships with a speed of 14 knots. The solution is 2 coal fired ships and 14 diesel powered ships. With changed fuel prices and the priority for fuel cost and capital cost reversed there is a dramatic change in fleet composition. A fleet developed under such constraints consists of 8 coal fired ships and 7 diesel powered ships.

SUMMARY

By using a forced subjective decision making technique it is possible to break a complete problem down into components which can be researched and evaluated. As information available to the decision maker is seldom perfect the results of a subjective decision analysis reflect two important effects in decision making:

1. decisons are always based on some subjective or intuitive conception of what is appropriate in a given circumstance.

2. solutions are dependent upon the subjective influence of the decision maker in analysing the information which is available; such information may not always be adequate to determine the best possible solution.

Where no single solution is required some method of determining the composition of a fleet must be devised. Goal programming allows determination of the fleet mix without resort to exhaustive and expensive economic analyses and comparisons. By setting some basic linear relationships as goal constraints and by determining the goals, mode of achievement and priority of those goals it is possible to find optimal solutions.

Both parts of this decision analysis model allow a complex problem wh[illegible] is influenced by and which influences a wide range of areas to be solved using a systematic approach.

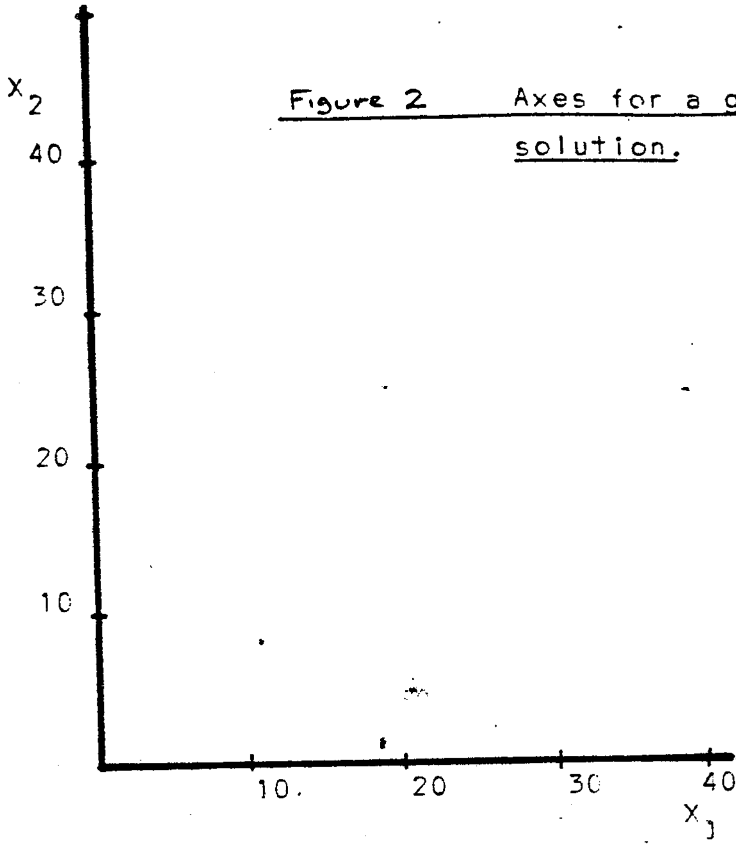


Figure 2 Axes for a graphical solution.

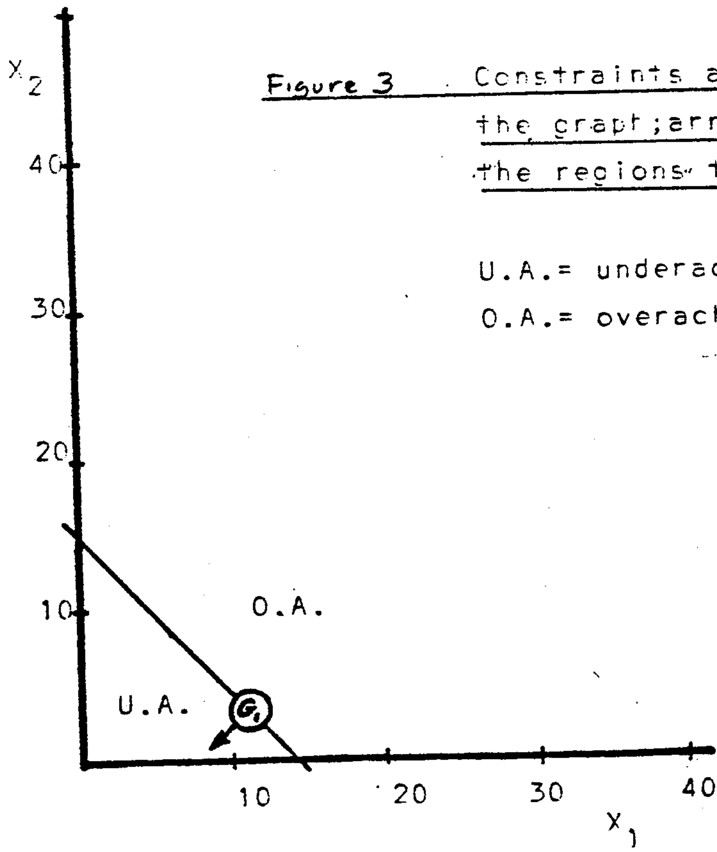
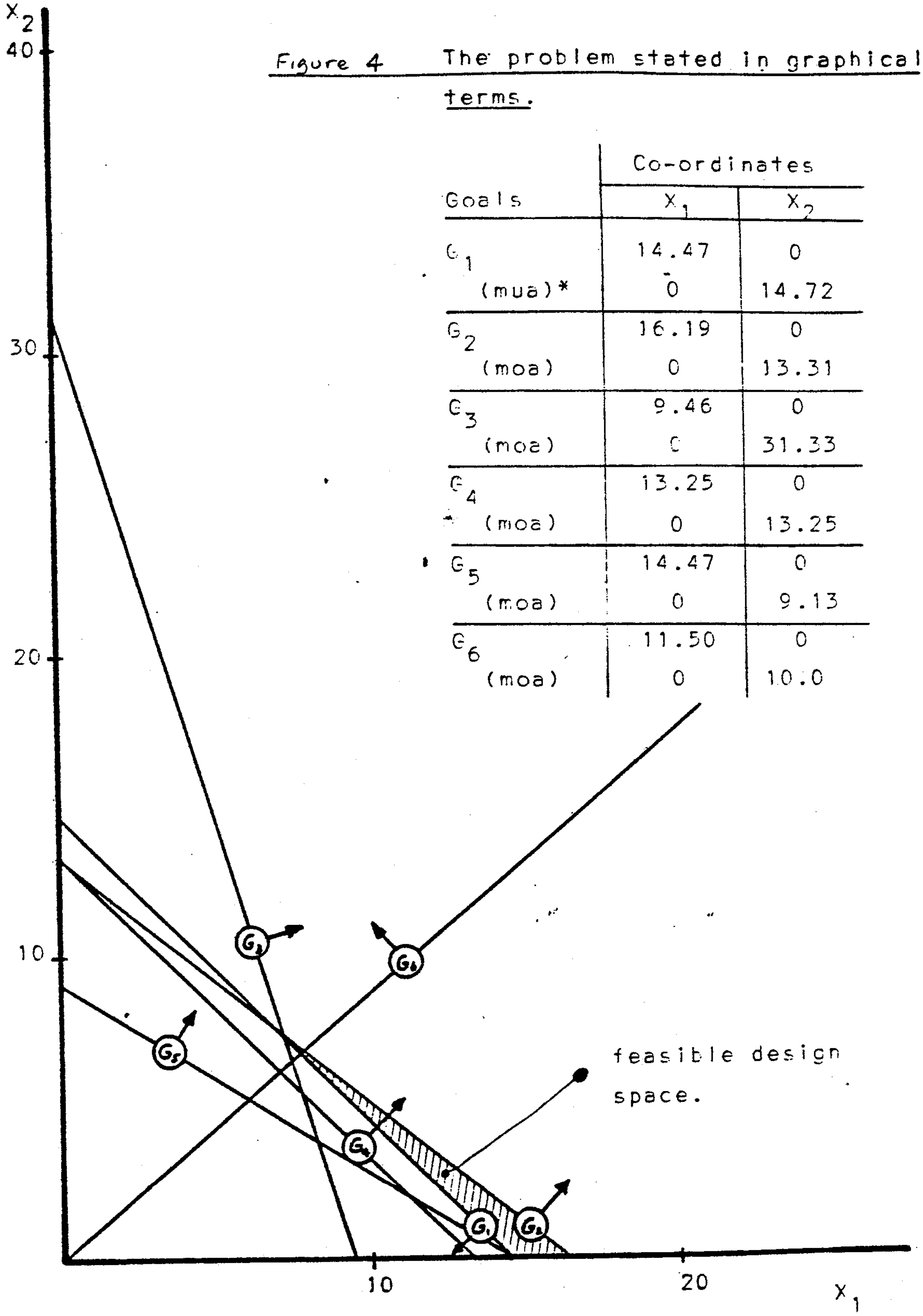


Figure 3 Constraints are added to the graph; arrows indicate the regions to be avoided.

U.A.= underachievement.

O.A.= overachievement.

Figure 4 The problem stated in graphical terms.



Goals	Co-ordinates x_1	x_2
G_1	14.47	0
(mua)*	0	14.72
G_2	16.19	0
(moa)	0	13.31
G_3	9.46	0
(moa)	0	31.33
G_4	13.25	0
(moa)	0	13.25
G_5	14.47	0
(moa)	0	9.13
G_6	11.50	0
(moa)	0	10.0

* (mua) indicates: minimize underachievement of the goal
(moa) indicates: minimize overachievement of the goal

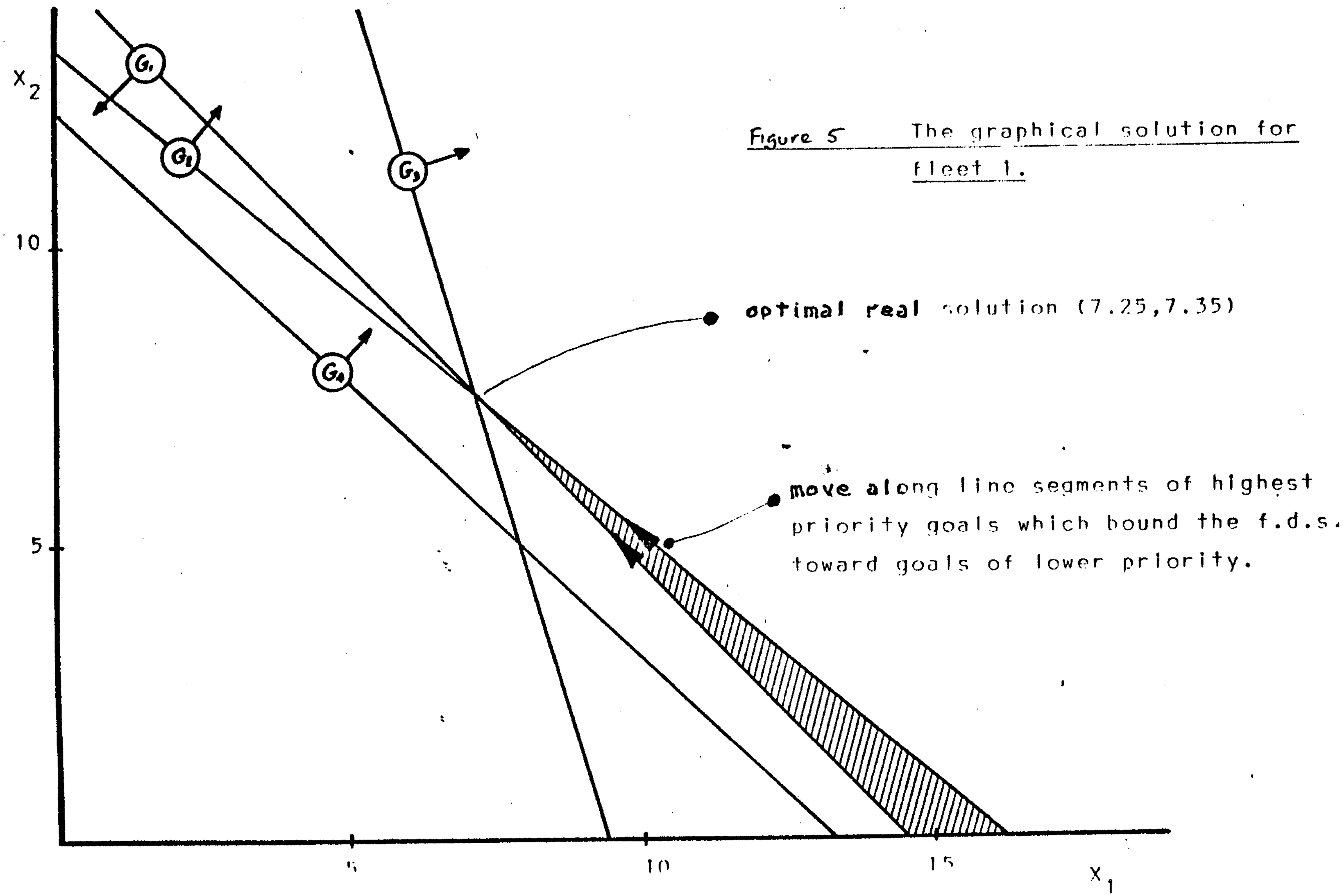


Figure 5 The graphical solution for fleet 1.

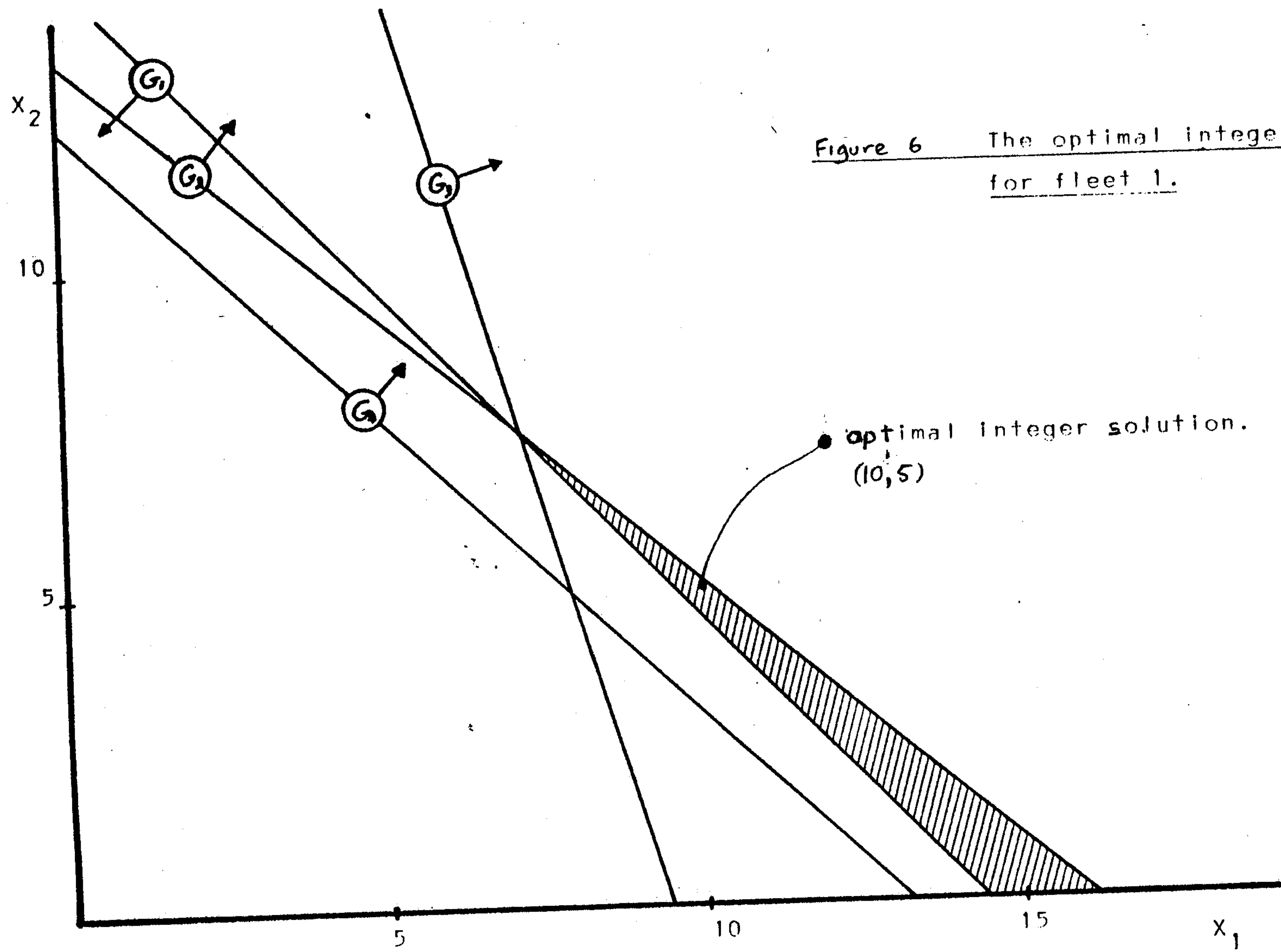


Figure 6 The optimal integer solution for fleet 1.

Table 8

Optimal fleet combinations.

Fleet	Unit components of fleet	No. of vessels	Total number of vessels
1	coal-fired ship at 15 knots diesel motorship at 15 knots	5 10	15
2	coal-fired ship at 15 knots diesel motorship at 14 knots	2 14	16
3	fleet 2 with fuel prices increased coal by 10%, diesel by 50% - and achievement function changed to $a = \{P_1[g_1(n_1 + p_3)], P_2[g_2(p_2 + p_4)], P_3[g_3(p_5 + p_6)]\}$ (i.e. a higher priority for fuel cost than for capital costs.)	8 (coal) 7 (diesel)	15

Whilst being systematic, the method is not inflexible and allows modifications to be made as information and attitudes change.

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