Planning the Mission and Composition of the U.S. Merchant Marine Fleet

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As we have indicated in Chapter 3, it is quite easy to perform *sensitivity analyses* for linear-programming models. This is one of the most important features of linear programming, and has contributed significantly to its usefulness as a tool to support managerial decisions. The project described in this chapter provides a practical application where sensitivity analysis plays a major role in understanding the implications of a linear-programming model. The project aims to identify the mission and the optimum composition of the U.S. Merchant Marine Fleet. The fleet should be designed to carry fifteen percent of the U.S. foreign trade in the major dry and liquid bulk commodities—oil, coal, grains, phosphate rock, and ores of iron, aluminum, manganese, and chromium. The study was conducted to design a fleet intended to be operational by 1982. A linear-programming model was used to obtain preliminary guidance with regard to the best ship designs, the sizes, and the mission of the resulting fleet. Subsequently, extensive sensitivity analysis was employed to evaluate the changes resulting in the fleet composition when trade forecasts and port conditions were varied.

For a long time, ships flying the American flag have faced construction and operating costs higher than those of most of their foreign competitors. The gap has widened and, in recent years, shipbuilding in the U.S.A. has cost about twice, and wages for American crews four times, the figures for representative foreign equivalents. This situation has been recognized in legislation. The Merchant Marine Act of 1936 instituted cost-equalizing subsidies in order to maintain U.S.-flag general-cargo liner service. As a result, a substantial share of our foreign general-cargo liner trade is carried by ships built, registered, operated, and crewed by Americans. No similar assistance was available to bulkers and tankers, and so U.S.-flag ships have almost disappeared from such service, apart from certain protected trades. In addition, American shipyards have not had the market or the incentives to share in the modernization of facilities and the mass production of large ships that have been offered in Europe and Japan.

A program intended to cure this situation was announced in 1969. Some of the characteristics of the program were:

1. Subsidies to be extended to construction and operation of tankers and bulkers;
2. Design studies were commissioned for ships that could be mass-produced and that would be economical to build and operate; and
3. Funds were to be appropriated on a large enough scale to enable shipyards to pay off the large capital investment required for modernization.

This effort entailed building 300 ships over the ten years between 1972 and 1982, and in the latter years carrying at least 15 percent of the foreign trade of the U.S.A.

7.1 STRUCTURE OF THE PROBLEM

There are four elements that characterize the structure of this problem: the commodities to be hauled; the types of ships to be included in the overall fleet design; the missions assigned to the ships; and the physical constraints imposed by the loading and unloading capabilities of the ports. We begin by reviewing the impact that these elements have on the problem formulation.

Commodity Movements

Commodity movements are the basic element of the problem's structure. They are tonnages of the commodities in question to be moved in 1982 from a loading port to a discharge port, and they define the mission of the fleet to be optimized. It obviously was impossible to include in our analysis all the details of origins and destinations. Instead, representative (although specific) loading and discharging ports were used.

A trade forecast provided estimates of the origins and destinations of the commodities and their expected volumes of flow. For the purposes of this study, the target for the 1982 U.S. bulk fleet was set by the Maritime Administration at 15 percent of the total foreign trade of the U.S.A. This figure was not applied rigidly for all commodities, but was used as a guide to informed judgment. For example, the goals for individual commodities also were affected by projections of national and industrial behavior, which make U.S. penetration of certain trades quite unlikely. A typical mission for 1982, consisting of tonnages of seven major bulk commodities to be moved along 23 trade routes, is shown in Table 7.1.

Voyages

Voyages essentially consist of round trips from a port of origin with *at most two* destination ports of call, for example, Canada to Baltimore then back to Canada, or Guinea to New Orleans, New Orleans to Japan, and Japan back to Guinea. The primary leg is always loaded, while the return trip may be an empty ("ballast") leg. Backhauls, which are shipments to be obtained from a destination port and brought back to the port of origin, are of major economic importance in bulk shipping. As a result, our structure included voyages with up to two loaded legs and either a backhaul or ballast leg. After at most two loaded legs, a voyage was arbitrarily closed by a return to the port of origin, although this may or may not be the case in practice.

Table 7.1 A Typical Mission (Mission No. 4)

Commodity	*Origin*	*Destination*	*Million tons per annum*
Iron ore	Canada	Baltimore	0.85
	Canada	Philadelphia	0.85
	Peru	Baltimore & Philadelphia	1.1
	Venezuela	Baltimore & Philadelphia	1.6
	Brazil	Baltimore	0.5
	Liberia	Baltimore & Philadelphia	0.8
Bauxite	Surinam	New Orleans	1.9
	Guinea	New Orleans	1.0
Manganese/chrome ore	South Africa	Baltimore	0.8
Grain	New Orleans	East Coast India	0.6
	New Orleans	West Coast India	0.6
	New Orleans	Japan	1.3
	New Orleans	Brazil	1.2
	New Orleans	Rotterdam	2.8
	Portland	Japan	1.3
	Portland	Southeast Asia	1.3
Coal	Hampton Roads	Rotterdam	3.1
	Hampton Roads	Japan	1.1
Phosphate rock	Tampa	Rotterdam	1.6
Oil	Persian Gulf	Philadelphia	5.6
	Libya	Philadelphia	5.6
	Venezuela	Philadelphia	11.3
	Venezuela	New Orleans	3.4

Each commodity movement along a trade route generates at least one voyage; there may be two if alternative routings exist, e.g., New Orleans to Japan via the Panama Canal or via the Cape of Good Hope. Also, there may be no appropriate backhaul for some geographical region, or there may be one or several voyages combining a given commodity movement, with another as a backhaul. Hence the list ("menu") of voyages is much longer than the list of a mission's commodity movements.

The menu of voyages is put together from the mission of the fleet with a table of distances between ports. It is reasonably inclusive, rejecting only such unattractive backhauls as those with less than 50 percent of loaded miles per voyage.

Menu of Ships

The third structural element is the *menu of ships* from which fleets can be chosen to execute the mission. We consider three ship types: *tankers*, with pumps and small hatches, which can carry liquids and also (with some cost penalty) grains that can be handled pneumatically; *bulkers*, with large hatches, suitable for dry bulks (grains, ores, coal, phosphate rock); and *OBO*'s* with both pumps and large hatches, which can

* OBO stands for Oil–Bulk–Ore, a ship that can handle these three types of cargos.

lift any of the major bulk commodities, liquid or dry. Within these types, ships are defined by physical characteristics—cargo capacity, speed, dimensions (especially draft)—and have cost characteristics such as: *construction cost* as a function of number built, *fuel per day* at sea and in port, and *other operating costs.*

Port Constraints

Voyages also suggest the fourth structural element, *port constraints.* There are two kinds: loading and discharging rates, which control the port times, and their associated costs; and dimensions, especially depth of water, which limits the load that a ship can carry. Canals also form a type of port constraint; the Panama Canal, for instance, imposes a toll and a time delay on a ship passing through, and also limits all three dimensions (length, beam, and draft) of a large vessel. These constraints were enumerated from standard sources such as *Ports of the World,* from the Corps of Engineers, and from industry information. Projection of this information to 1982 was very uncertain and was the subject of sensitivity testing.

As an objective function in the optimization, it would have been most appropriate to use the *return on investment* of the fleet of the given mission. In the present study, however, there were several difficulties that prevented its use, most notably the need for a forecast of revenue rates in 1982. This would have been as large a task as our whole project. Therefore, it was decided to take as the criterion the *discounted present value* of the life-cycle costs of the fleet.

Each of the alternatives considered, then, had the following structure. We selected a fleet mission, a set of constraints, and menus of ships and of voyages that could fulfill the mission. The menus, of course, included more types of ships and voyages than ultimately were chosen. The optimum choice (types and numbers) of ships and voyages then was determined. Because of the target date (1982), there were many uncertainties in the trade forecasts, definition of missions, constraints, and details of ship-allocation practices. Therefore it was necessary to make a number of studies—sensitivity tests, in effect—with various missions and menus and constraints. Thus, we could explore the significance of the uncertainties. Nonlinearities relating ship-construction cost to number ordered also called for multiple studies.

There is a significant difference between ship optimization and fleet optimization. Both have been practiced for some time, manually or by computer. *Ship optimization* is usually done by the naval architect, who varies the characteristics of a fairly well-defined ship design so as to minimize cost or maximize profit in one or a few well-defined trade routes. *Fleet optimization* is more likely to be done by a ship operator, who optimizes the allocation of a number of vessels of various types of designs (in existence or to be built) to various trade routes or missions or contracts of affreightment. The result may be a plan of allocation, an evaluation of a mission or contract, or a choice among design for ships to be built. Our project was of the second type. It differs from ship optimization in that a range of ship designs and trades is studied as a whole, and it differs from the fleet optimization usually performed (say, by an oil company) in that the target date is well into the future and none of the fleet currently exists.

7.2 THE LINEAR-PROGRAMMING MODEL

A linear-programming model was developed to obtain the optimum composition and mission of the fleet. The basic characteristics of the model were as follows.

1. The mission was satisfied by allowing ships to make the required number of voyages per year.
2. These voyages may include one load-carrying leg and a return leg in ballast, or two load-carrying legs plus one or two in ballast.
3. The number of ships required depended on the number of voyages and their duration; the linear-programming solution normally involved fractional numbers of ships. This was not considered a source of difficulty. The missions were arbitrary, to a certain extent, and an adjustment to the number of ships, bringing them to integral values, could have been made by adjusting the size of the demands. The aim was to produce an informative set of values rather than a precise set of numbers that would perform a required mission exactly.
4. For each possible voyage, various ships may be employed; the role of the linear program was to select that combination of voyages and ships that executes the assigned mission at minimum life-cycle cost. Several computations were required in order to define data for the linear-programming model.
5. For each leg of a voyage, a calculation was needed to determine the maximum cargo that an eligible ship may carry. This was a function of the *ship*'s characteristics, including physical constraints (especially draft restrictions) and *cargo* characteristics.
6. For each voyage, a calculation was required to ascertain the time taken by any eligible ship. The time *at sea* depended on the ship's speed; the time *in port* depended on the quantity of cargo and the rate of loading and discharging. The latter rates were considered to depend primarily on the port and the cargo in question, and differential loading or discharging rates between different ships were not considered.
7. As implied in the foregoing, the cost of the voyage by a candidate ship was required. This consisted primarily of the fuel cost while at sea, and the port costs, which were based on daily rates and hence depended on loading rates.
8. The capital costs of the ships and their annual fixed costs were included. The linear-programming model that was used assumes constant costs per ship, independent of the number of ships. In order to allow a varying cost structure, in which costs per ship decrease with both the number built and the modularity of design, an iterative procedure was followed. The iterative approach consisted of solving the problem under one set of cost assumptions and then re-doing the problem with adjusted costs if the resulting solution was not consistent with the initial cost estimates. As it was the aim of the study to investigate the effectiveness of different combinations of ships in a variety of situations rather than to produce an exact optimum, this approach proved entirely satisfactory. More formal procedures, employing integer programming, could have been used to address this issue.

7.3 MATHEMATICAL DESCRIPTION OF THE MODEL

Decision Variables

The decision variables adopted were those that defined the composition and employment of the optimum fleet and were denoted, respectively, by n_s and x_{sr}, where

n_s = Number of ships of type s;

x_{sr} = Number of voyages per annum assigned to ship s along route r.

The selection of these variables implied not only the specification of a variety of ship types considered appropriate for inclusion in the fleet, but also the determination of adequate voyages to comprehensively describe the mission to be accomplished by the fleet.

Time Horizon and Number of Time Periods

As stated before, the basic problem was to determine the optimum fleet composition for foreign trade in 1982. Thus, it was necessary to deal only with fairly aggregated information, without regard to detailed information relevant only to decisions affecting the operating schedule of the fleet. Consequently, in the model we considered only one time period, corresponding to the year 1982. No attempt was made to subdivide this year into shorter time intervals, since no great advantage would have been derived from such an approach. Neither did we attempt to examine explicitly the intervening years prior to 1982. That, again, could have been accomplished by using a model similar to that adopted, but incorporating each of the intervening years, in order to explore the *evolution* of the optimum fleet from the present until 1982. However, the development of a construction schedule for the fleet was not the objective of the study.

Constraints

There were two basic constraints imposed upon the fleet. The first one referred to the *mission of the fleet* and can be represented by the following set of equations:

$$\sum_s \sum_r V_{srk} x_{sr} = d_k,$$

for all commodity movements k, where:

V_{srk} = Maximum amount of commodity k that can be carried by ship type s along route r;

d_k = Total annual tonnage (forecast for 1982) of commodity k specified in the mission for the pertinent pair of ports (one for loading, one for discharging).

The summation on r is carried over all routes that connect a particular pair of ports. This constraint, therefore, merely states that the amount carried by all ships, following every possible route, should satisfy the demand in the mission for each commodity and each pair of loading and discharging ports, such as those shown in Table 7.1. The maximum tonnage of a given commodity that can be carried by a ship type was computed outside the model, and was a function of the cargo weight and volume capacities of the ship, the density of the cargo, the maximum ship draft allowed on each leg of each voyage, and further canal or port constraints.

The second set of constraints affecting the fleet referred to the *total time consumed* by the fleet in performing its mission. It simply indicated that the total time used by every ship type could not exceed the number of ship-days available during the year. Assuming that all ships were available 345 days per year, the constraints can be expressed as follows:

$$\sum_{r} t_{sr}x_{sr} - 345n_s \leqq 0,$$

for all ship types s, where

$$t_{sr} = \text{Voyage time for ship type s along route r.}$$

These voyage times also were evaluated outside the model, as the sum of times at sea and times in port. Times at sea were calculated from the ship speed and distance. A safety factor of 10 percent was included to allow for weather, mechanical, and other contingencies. The time in port was considered to be dependent on the type and quantity of cargo and the ports concerned. (Additional constraints could have been incorporated to introduce lower or upper bounds on the *number* of ships of any type.)

Objective Function

As indicated before, the objective function selected for our model was the minimization of the life-cycle cost of the fleet. One element of the life-cycle cost was the operating cost for a given ship type, which can be expressed by the following relationship:

$$C_s = \sum_{r} C_{sr}x_{sr},$$

for all ship types s, where

$$C_{sr} = \text{Variable operating cost incurred by ship type s along route r;}$$
$$C_s = \text{Total variable cost of ship type s.}$$

Now, if we let

$$a_s = \text{Annual fixed operating cost of ship type s,}$$

then the total annual operating cost for all ships is given by:

$$\sum_{s} (C_s + n_s a_s).$$

Allowing for an inflation rate of 4 percent and considering a discount rate α, a 25-year life for each ship, and a capital cost I_s for ship type s, the total life-cycle cost of the ship can be expressed as follows:

$$\begin{aligned}\text{Life-cycle cost} &= \sum_{s} n_s I_s + \sum_{s} (C_s + n_s a_s) \sum_{t=1}^{25} \left(\frac{1.04}{1+\alpha}\right)^t \\ &= \sum_{s} [\beta C_s + n_s(I_s + \beta a_s)],\end{aligned}$$

where

$$\beta = \sum_{t=1}^{25} \frac{1.04^t}{(1+\alpha)^t}.$$

In the standard cases the discount rate α was set at 10 percent, giving a value of $\beta = 13.0682$.

The model was solved under a variety of assumptions on the data. The aim of these investigations was to produce a combination of ships and voyages that was optimum, not merely in the sense that it minimized the life-cycle cost of the fleet for given values for the problem data, but also that it produced a minimum or near-minimum cost over as wide a range of probable values for the data as possible. Because of the long time horizon involved in the study, uncertainties in the data cannot be ignored, and must be addressed in a meaningful way. In particular, we would like to consider uncertainties inherent in the trade forecasts, the operating costs, and the physical constraints. Other problem parameters were subject to policy decisions, e.g., major port developments. By performing many sets of optimization computations, it was possible to investigate how stable the solution was with respect to uncertainties in the numerical data.

7.4 BASIC FINDINGS

Ship Designs

The primary objective of this project was to provide guidance as to the optimum ship sizes and types. The relevant experiments and their output are discussed below.

Size and Standardization

A modular set consists of ships having the same bow, stern, machinery, and superstructure, but with options (tanker, bulker, OBO) for the cargo-containing midbody. The modular sets offer large economies for multiple production.

Table 7.2 summarizes studies of both ship size and standardization. The three sections of the table compare the optimum fleet and its total cost for a representative mission for three different ship menus:

1. a menu containing a wide range of ships, considered to be designed and built in small lots;
2. a menu consisting solely of a PanMax (maximum ship able to transit the Panama Canal) modular set "P" and a modular set "O" at about 110,000 dwt (dwt stands for the deadweight of the ship); and

Table 7.2 Standardization Economies

Ship	*dwt* (thousands of tons)	*Draft* (feet)	*Number used*	
Menu 1—Without modular construction				
FP (B)*	45	35	1.6	
FI (B)	66	39	4.7	
FO (B)	105	45	4.5	
TP (T)*	73	44	14.4	
YO (T)	111	45	18.9	
MO (O)*	108	45	6.2	
Cost: $2293 million				
Menu 2—With modular construction (1)				
BP (B)	67	43	1.4	(a)†
TP (T)	73	44	14.4	
FO (B)	105	45	8.2	
YO (T)	111	45	18.9	(b)†
MO (O)	108	45	6.2	
Cost: $2267 million (saving: $26 million)				
Menu 3—With modular construction (2)				
BP (B)	67	43	1.4	(a)
TP (T)	73	44	15.3	
BQ (B)	128	51	8.5	
TQ (T)	120	49	20.1	(c)†
OQ (O)	130	52	5.0	
Cost: $2356 million (extra cost: $63 million)				

* (B) = Bulker; (T) = Tanker; (O) = OBO.
† (a) Modular set "P"; (b) Modular set "O"; (c) Modular set "Q".

3. a menu of the PanMax modular set "P" and a larger modular set "Q" at 120,000–130,000 dwt.

When a number of ships are going to be constructed, it is possible to take advantage of a modular design, primarily with regard to large ship sizes.

Each ship type is represented by a code of two alphabetic characters. Its deadweight (in thousands of long tons) and design draft (feet) are given. The final column of each section of the table shows the number of the various types chosen in the optimum fleet, and the bottom of each section indicates the cost of the mission. The fractions of ships were not rounded off, since the purpose was guidance and analysis, rather than an exact fleet-construction program.

Comparing the first and second parts of the table shows that the voyages optimally assigned to nonmodular ships FP and FI in the first menu are shifted to larger and more costly modular ships in the second. The added cost of this change is more than offset by the savings in multiple modular construction, and the total cost drops by $26 million. If we insist on the larger modular set "Q", however, the third part of the table shows that the third menu produces costs $89 million higher than the second menu, so the smaller set "O" is unequivocally preferred. The difference between "O" and "Q" can also be looked at another way. Draft restrictions force the use of more ships (33.6 versus 32.8) of the larger "Q" sets than of the smaller "O" set. A higher total cost is therefore inescapable.

OBO's

The analysis that we have performed underestimates the attractiveness of the OBO design. We allow a payoff in return for the extra cost and flexibility of the OBO only within the deterministic confines of single backhaul voyages. That is, only if oil and a dry commodity are attractive for backhauling in a single voyage will the OBO even be considered, since an OBO costs more than a tanker or dry-bulker of similar size and speed. The flexibility of the OBO, however, permits the ship operator to move from any trade to any other in response to demand and good rates. The need for this flexibility might arise on successive voyages, or over a period of a year or more.

A fair evaluation of the OBO design could not be made straightforwardly, so instead we investigated the reverse question: What would be the extra cost if a certain number of OBO's (say, 15) were forced into the fleet, and then employed as near optimally as possible? Table 7.3 gives the result for two possible missions. This major shift in fleet composition cuts back only slightly on the tankers; dry-bulkers almost disappear; but the cost of the fleet rises by only about $20 million, or one percent. Such a cost could well be offset by only a slightly higher utilization during the life of the ships.

Table 7.3 Effect of Requiring at Least 15 OBO's (modular P, O ships)

			Mission 3.3		*Mission 4.3*	
Ship	*dwt* (thousands of tons)	*Draft* (feet)	*No restriction on* OBO's	15 OBO's	*No restriction on* OBO's	15 OBO's
Bulkers:						
BP	67	43	2.3	2.3	1.4	
FO	105	45	5.3	2.3	8.2	1.5
Tankers:						
TP	73	44			14.4	14.4
YO	111	45	29.3	29.3	18.9	18.2
OBO's:						
OP	67	43				1.4
MO	108	45	12.0	15.0	6.2	13.6
Life-cycle cost ($ millions)			2340	2362	2267	2284

7.5 SENSITIVITY ANALYSIS

Variations of Mission

A major change of mission, of course, will produce some change in fleet composition because of different requirements. It also will lead to a change of total cost because of new mission size. As an example, we generated a pair of basic missions, of which one, identified as "Mission No. 4," included a number of cargo types that were omitted from "Mission No. 3." The more inclusive mission called for a different number of ton-miles and had many combinations of a commodity with a particular pair of loading and discharge ports. Further, it introduced some special requirements, and also gave many new backhaul opportunities.

Despite this major change, only one new design was accepted by the linear program, although the *number* of ships was, of course, considerably changed. The two fleets are compared in Table 7.4. It can be seen that, of the ship menu of 28 designs, the less inclusive mission called for six designs, and the more inclusive one used the same six plus one other. The total cost was affected only slightly (less than 4 percent), and the change had the same sign as the change of ton-miles.

Table 7.4 Comparison of Two Basic Missions

	Mission identification number	
	No. 3	*No. 4*
Description of mission:		
Total tonnage, dry bulk (millions)	24.3	24.3
liquid bulk (millions)	25.9	25.9
Total ton-miles (billions)	290	260
Total combinations of commodities, loading ports, and discharging ports	15	23
Description of optimum fleet:		
Bulkers: FP (45,000 dwt)	2.7	1.6
FI (66,000 dwt)	3.2	4.7
FO (105,000 dwt)	1.5	3.7
BQ (128,000 dwt)	0.8	0.6
Tankers: TP (73,000 dwt)		14.4
YO (111,000 dwt)	29.3	18.9
OBO's: MO (108,000 dwt)	12.2	6.2
Total number of ships	49.7	50.1
Unused designs in ship menu	22	21
Approximate total cost* ($ millions)	2373	2293

* Adjusted for serial production and quantity discounts; not adjusted for modularity.

The foregoing major variation of missions tests the fleet's sensitivity to uncertainty as to the trades in which it will be engaged. We also made experiments with a larger number of smaller variations, which would correspond to uncertainties in the trade forecast of U.S.-flag share of trade. Each of the two basic missions was transformed into a set of five variant missions, by increasing or decreasing each tonnage in the basic mission by a random amount bounded by "high" and "low" trade forecasts. The optimum fleets for the variant missions then were determined. In the case of the variants of Mission No. 4, the *same seven designs* appear, plus (in two variants) a small fraction of a ship of an eighth design. Furthermore, the *number* of ships does not change greatly. On this basis, we conclude that the fleet is not very sensitive to uncertainties in the mission. Extended experiments on Mission No. 3 show even less sensitivity, since the same six designs were used throughout the basic mission and its variants.

The fleet's lack of sensitivity to variations of mission is a fact of profound importance. If the opposite had been found, the linear-programming model as formulated could not have been used as a basis for planning 1982's ships. The uncertainties in the employment of the fleet would have had to be included explicitly in any model in order to perform such advance-design work. Since the optimum ship types are not sensitive to the uncertainties of trade forecasting and market capture, we can have confidence that the design work suggested by the model is appropriate, although, as time proceeds, we may have to adjust the numbers to be built of the various types.

Oil Demand

At one point in marketing research, it was felt that the oil companies generally might have little interest in a U.S.-flag fleet. We therefore studied the effect of this possibility on the optimum fleet by making computations for a basic mission and for missions in which the oil demand was cut in half and finally reduced to zero. The fleet composition changed in a predictable manner. Tankers decreased, and OBO's disappeared, of course, since their pumps and piping no longer provided any advantages.

Backhauls

Several runs indicated the major importance of backhauls to the fleet. One pair is summarized in Table 7.5. If backhauls are used to the optimum extent, fleet life-cycle cost is cut by 15 percent, from \$2.7 to \$2.3 billion. The comparison is against a run in which no backhauls are permitted, but the mission and ship menu and the other data were otherwise identical. The number of ships also is cut by 20 percent. Naturally, the OBO design disappears in the no-backhaul case, as there is no payoff for its flexibility.

The conclusion is that good utilization is very important to the economic success of a bulk fleet. Backhauls must be found, and for the situations where they are elusive because of markets or geography, *crosshauls* of foreign-to-foreign cargoes will be needed.

Table 7.5 Effect of Utilizing Backhaul Opportunities (Mission No. 4)

Ships	*dwt* (thousands of tons)	*Draft* (feet)	*Number of ships* *Without backhaul*	*With backhaul*
Bulkers:				
FP*	45	35	6.1	1.6
BP*	67	43		
FG	50	35		
FI	66	39	1.9	4.7
HI	38	39		
GN	103	48		
FO	105	45	8.7	3.7
BQ	136	53	4.7	0.6
FQ	129	51		
GQ	132	52		
FT	152	55		
Tankers:				
UD*	35	37		
UG*	50	37		
YP*	69	42		
TP*	73	44		14.4
YG	50	35		
JI	65	38		
YI	65	38		
YO	103	44	38.1	18.9
TQ	120	49		
YT	142	49		
YU	150	52		
TY	300	80		
OBO's:				
NI*	62	41		
MP*	63	41		
OP*	67	43		
MG	51	36		
MI	69	40		
MO	110	46		6.2
OQ	139	54		
MQ	133	52		
NQ	136	53		
MT	157	57		
QT	170	63		
Total cost ($ millions)			2721	2293
Utilization			50%	67%

* Able to transit Panama Canal.

Grain Stevedoring

The costs of loading and discharging grain were subject to considerable uncertainty. We therefore made some sensitivity tests on these costs.

Carriage of grain in tankers imposes substantial extra stevedoring costs, compared with dry-bulk or OBO designs with large hatches. We received estimates of this cost ranging from 40¢/per long ton to $1.20 or $1.50, depending on the ports concerned and the particular experience of the estimator. Most of the runs reported here were made with the minimum penalty cost of 40¢/long ton, which had little effect against the low construction cost of tankers and the backhaul utilization by oil. We also tried calculations with 80¢ and $1.20 penalties, as well as a flat prohibition (which corresponds to an infinite penalty).

The estimated range of this penalty or extra cost was just about sufficient to drive most grain shipments out of tankers and into dry-bulkers or OBO's. In view of the scale of the penalty, it is clear that variations of the relative charter-market rates for tankers and dry-bulkers or OBO's will strongly affect the fraction of grain shipped in tankers. This aspect of tanker utilization, therefore, was extremely difficult to predict for 1982.

Port Constraints

It was very difficult to predict harbor depths for 1982; therefore, several experiments were made to explore the sensitivity of the fleet to these constraints. It turns out that this is an area of great sensitivity.

In discussion of our first round of results, the question was put to us: What would happen if all the ports in the study were deepened by 10 percent? At that time, the ship menu contained very few designs larger than those already used in the optimum solution. The linear program seemed unlikely to be able to take advantage of the greater draft limits, since the port constraints reflecting draft limits were not binding. We then looked at the effect of *decreasing* all depths by 10 percent. (The Panama Canal was held constant in the process.) Table 7.6 gives the result. The largest dry-bulker (BQ) and OBO (OQ) were forced out of the optimum fleet entirely, and the number of each remaining design was increased, because shallower drafts cut the payloads. The total number of ships in the fleet and the total cost both increased by over 15 percent, a substantial change.

Another study focused on oil imports. For the major portion of this tonnage, Philadelphia had been taken as a representative port with a depth of 50 ft in 1982 (38-ft draft limit). Much oil goes into the North Jersey area also, with a similar limitation. The large tonnage suggests the question: What if the Delaware were deepened? Two cases are reported in Table 7.7. The first column is the basic optimum fleet; the second shows the change if the Delaware were dredged to equal the Chesapeake (48.5-ft draft); and the third removes the limitation entirely by assumption of an *offshore discharge terminal*. The trend toward larger tankers and OBO's is obvious. More dry-bulkers are used in the offshore-terminal case because the very large

Table 7.6 Effect of Decreasing All Port Draft Limitations by 10 Percent

			Number of ships			
			Variant of Mission No. 4		*Variant of Mission No. 3*	
Ships	*dwt* (thousands of tons)	*Draft* (feet)	*Standard drafts*	*Decreased drafts*	*Standard drafts*	*Decreased drafts*
Bulkers:						
FP*	45	35	1.6	1.8	2.7	2.9
FI	66	39	2.0	2.3	0.1	
FO	105	45	2.5	8.2	1.0	6.3
BQ1	136	53	4.5		4.5	
Tankers:						
YP*	69	42	15.2	18.0		
YO1	103	44	21.5	24.9	32.6	38.0
OBO's:						
MO	110	46	1.4	2.1	7.7	8.5
OQ1	139	54	0.6			
Total ships in fleet			49.3	57.6	48.6	55.7
Total cost ($ millions)			2203	2550	2287	2643

* Able to transit Panama Canal.

tankers are unsuitable for any backhaul service. As the draft constraint is relaxed, the corresponding decreases in fleet cost are quite large, and they are even larger in a similar experiment using the other basic mission. These reductions should be compared with the costs of dredging, or of building the offshore terminal and attendant storage and pipelines. In that comparison, the savings should be multiplied by perhaps 5 or 6, since only about 15 percent of the U.S. trade is included in the mission, whereas the improvement would cut costs for all of the cargo shipments.

Note of Design and Operating Drafts

Draft limitations play a central role in this study of large dry- and liquid-bulk carriers, since the shipment sizes that are available are almost unconstrained. We therefore requested that ship costs and characteristics be supplied for conceptual designs optimized for a given draft, rather than for a given deadweight as is the usual custom. This objective function caused the ships to be just as long and as wide for their draft as is reasonable, and so they differ from the ordinary vessels designed without this purpose.

Another peculiarity also was observed in our fleet optimization: ships often are not fully loaded. This may arise from two causes. First, even on a voyage without backhaul, it is not novel to find that a fully loaded smaller ship is less economical

Table 7.7 Effect of East Coast Oil Draft Changes

			Number of ships					
			Mission No. 4			*Mission No. 3*		
Ships	*dwt* (thousands of tons)	*Draft* (feet)	*Standard draft*	*48.5-ft draft*	*No limit for oil*	*Standard draft*	*48.5-ft draft*	*No limit for oil*
Bulkers:								
FP*	45	35	1.6	1.6	6.0	2.7	2.7	2.5
BP*	67	42						0.4
FG	50	35						
FI	66	39	4.7	3.4	1.9	3.2	3.9	1.1
HI	69	39						
GN	102	47						
FO	105	45	3.7	5.0	6.5	1.5	2.0	6.9
BQ	128	51	0.6	0.8	2.5	0.8	1.2	0.3
GQ	132	52						
FT	150	55						
Tankers:								
UD*	35	35						
UG*	50	37						
TP*	73	44	14.4	7.0				
YG	50	35						
JI	65	38						
YI	65	38						
YO	111	45	18.9	5.4	5.4	29.3	1.5	8.5
TQ	120	49		6.5			12.8	
YT	140	52		6.4	2.3			5.4
TY	302	80			7.1			1.8
OBO's:								
OP*	67	43						
MG	52	36						
MI	69	40						
MO	108	45	6.2			12.2		
OQ	130	52		2.8			4.9	
NQ	136	53		2.8			3.9	
MT	153	56						
QT	168	62			3.3			9.2
Life-cycle cost			2293	2003	1872	2373	1986	1884

* Able to transit Panama Canal.

than a part-empty larger ship. The latter has a greater area (equivalent to tons per inch immersion), so it carries a greater payload at a given draft. Also, vessel construction costs, and especially operating costs, increase very gradually with size. This is especially true for U.S.-flag operation, where crew wages are expensive. The cost data supplied to us assumed no increase of crew with size. These two effects, in general, produce an optimum (lowest cost per ton-mile) ship size so large that operating partly empty was economically feasible. Of course, if this is carried to an extreme, light ship-weight and similar counterbalancing variables finally produce rising costs. One wonders whether shipowners often take this view into consideration in planning new construction.

Second, partial loading of ships is enhanced because of the availability of backhauls. It may well be that the backhaul ports are shallower than those of the primary haul, but the limited load of backhaul cargo is still feasible and attractive economically.

SUMMARY AND CONCLUSIONS

The work described hereinabove produced results as summarized below.

Guidance as to Ship Designs

1. A modular set of ships (tanker, bulker, OBO) of about 110,000 dwt is distinctly preferred over a similar but somewhat larger set (120,000–130,000). Hence, the technique is able to indicate optimum ship designs fairly precisely.
2. The savings of multiple modular construction more than offset the extra costs of ship standardization.
3. Forcing 15 OBO's into the fleet causes only a very small increase in total cost, which most likely is more than offset by the advantages of the OBO's flexibility.

Sensitivities

1. The composition of the optimum fleet was insensitive to small changes in the mission to be performed, and even fairly large changes had no serious effect. This result is essential for using deterministic linear programming for planning the optimal fleet in 1982.
2. Deletion of half or all the oil from a mission has the expected effect. OBO's disappear, and tankers are reduced in importance.
3. The fleet cost and composition are very sensitive to the opportunities for backhauls. If the latter are excluded arbitrarily, the fleet cost rises by 20 percent.
4. Port constraints have a major influence on optimum ship designs and fleet life-cycle costs. In the Delaware–North Jersey area, an extra 10 ft in the channel, or an oil discharge terminal of unlimited depth, would cause a major decrease in overall fleet life-cycle costs.

Techniques Used

The linear-programming approach used in this study has many important advantages. For one thing, it provides a systematic framework in which a very large number of details can be accommodated. For example, the calculations of the effect of port constraints on shiploads were handled easily within the linear program as part of its input calculations. The system also keeps track of all the various voyages and port calls that are involved. Even if it were only a bookkeeping device, the program would be very useful.

The important thing, however, is that it permits the analyst to view the problem from a systems standpoint. Thus, ships were optimized, not with respect to a few specific voyages or ports, but rather as part of the overall system of ships, ports, voyages, and commodity flows. Ships interact with each other because one can partly, but not completely, substitute for another (as to backhauls, payloads, and so on), and also because of serial production economies. It is important to take these interactions into account.

Finally, the approach provides a ready means for performing sensitivity analysis. The importance of being able to explore variations in the data was demonstrated by our analysis of the future uncertainties in the mission.

In this study we have not dealt with the complete shipping system by any means. However, the approach could be extended easily to include more elements in this system. For example, if we were concerned about new materials-handling methods, a slight extension would include these activities in the linear program and thereby optimize both the ship type and the loading and discharging facilities at the ports. As indicated by our studies of port depths, we could extend it still further to perform a simultaneous optimization of terminals and harbors as well as of the ships themselves.

EXERCISES

1. *Problem Definition*

   Discuss the characteristics of the problem presented by the design of the U.S. Merchant Marine Fleet. What are the basic elements of the problem? What assumptions are being made in order to develop a mathematical model? Do these assumptions reduce the realism and, therefore, the usefulness of the model significantly? What is the primary role of the model? How do you envision that the model will be used in supporting decisions regarding the planning of the fleet? What important considerations are omitted from the model formulation?

2. *Time Horizon and Number of Time Periods*

   The model considers only one time period, corresponding to the year 1982. Why not use a multiperiod planning model? How can one study the dynamic issues associated with developing the proposed fleet for 1982? What would be a reasonable way of exploring the evolutionary development of one fleet from 1970 to 1982?

3. *Decision Variables and Constraints*

   Discuss the selection of the decision variables. Are there alternative formulations of the model based upon other decision variables? Should the variables be constrained to be integers? What are the implications of these additional constraints? Is there any useful information that can be obtained from the shadow prices of the constraints? Can you provide an estimate of the number of variables and the number of constraints involved in a typical fleet-composition problem?

4. *Objective Function*

Do you agree with the objective function used in the model? What assumptions are implicit in the computations of the life-cycle cost? Is it reasonable to use life-cycle cost in a one-period model? What alternatives might you consider? How would you determine the value of the discount rate α to use? What about the inflation rate?

5. *Basic Findings*

Analyze the results provided in Table 7.2. What conclusions can be drawn from these results? Discuss the interpretation of the results given in Table 7.3. Would you favor the introduction of OBO's into the fleet?

6. *Sensitivity Analysis*

List the kinds of sensitivity analyses you would propose to run for this problem. How would you program the runs to make the computational time required to process them as short as possible? Interpret the results given in Tables 7.5, 7.6, and 7.7.

7. *Multiple origins*

In practice, some voyages will not be closed by a return to the port of origin after at most two loaded legs, as assumed in the model. Rather, a ship might embark on a new voyage from another origin or might make several loaded legs prior to a return to the origin. How would these modifications be incorporated into the model? Is this omission serious?

8. *Detailed Scheduling*

The planning model analyzed in this chapter has as a viewpoint the overall optimization of the Merchant Marine Fleet. Contrast this viewpoint with the attitude of the owner of a small subset of this fleet who is interested in optimizing the performance of *his* available ships. Indicate what should be the characteristics of an appropriate model to support his decisions. Particular emphasis should be given to the degree of detail required in this new model, and the timing implications. Suggest a hierarchical procedure that links the planning and the detailed scheduling models.

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