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A MODEL FOR MARITIME TRANSPORTATION SYSTEMS

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ABSTRACT

For nations that are substantially involved in world trade or have worldwide responsibilities, the existence and control of a strong merchant fleet is almost essential. Ideally, this merchant fleet should have some minimum level of capability and should also be self-supporting (no subsidy needed). For some nations, such as the United States and Japan, this ideal condition does not seem to be even roughly satisfied. Moreover, even with a large amonut of subsidy, a reasonable level of capability may not be attained. This raises the question of identifying ways in which a nation can improve its maritime operations. The mathematical model described in this paper is concerned with this problem. Procedures are outlined for quantifying and interrelating the many factors that are involved in a worldwide maritime operation over a given period

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of time. In broad terms an operations analysis is conducted through the use of a computerized simulation model. The simulation model consists of the inputs to the over-all maritime system, a method of determining the operation of the system on the basis of these inputs, and the outputs that result from this operation. Some of the inputs and system interrelations are controlled by the nation whose maritime operation is being considered for improvement. An evaluation criterion is used for representing the over-all desirability of the system outputs from the viewpoint of this nation. Then, on a parametric analysis basis, a study can be made with respect to the choice of inputs and interrelations (of those controlled) that are most desirable for this nation. Methods are outlined for deciding on inputs that are not controlled and for efficiently performing the simulation.

INTRODUCTION

The maritime problem considered in this paper is of a very extensive and complicated nature. No attempt is made to present a complete solution to this problem. The material that occurs is limited to a specification of the situation considered and to the establishment of a framework for dealing with situations of this type. That is, the problem is defined, its ingredients are identified, and a method of solution is outlined. However, very little technical detail is given.

The general goal is to identify ways in which a nation can improve its maritime operations, where this nation is involved in a worldwide maritime effort. The approach for attaining this goal is to develop an acceptably realistic mathematical model for representing the aspects of the world maritime operations that are important to this nation. This operations analysis model is of a simulation nature and would be applied by use of a high-speed computer.

Since the nation considered is involved in worldwide trade, and competes with other nations for this trade, consideration of the over-all system in which its maritime operations are imbedded seems necessary.

Improved operation of the merchant fleet of this nation is of primary interest. However, improvement of the operation of fleets that cooperate with this nation can also be of interest, etc.

In the scheduling and operation of fleets, random occurrences such as ship breakdown can be important. In general, random damage and other types of random events can have an important influence on the system operations. Consequently, a Monte Carlo type of simulation model seems to be needed.

A number of things can be investigated by use of a satisfactory simulation model. These include determination of the preferable composition for the fleet, establishment of suitable rate schedules for cargo transportation, examination of the ability of a given fleet to handle specified tasks, etc. Although simulation results are only indicative of what would occur, they furnish a reasonable basis for reaching decisions of many kinds.

Development of a simulation model that is both feasible and realistic is not easy. A huge amount of flexibility is required to quantitatively allow for the many kinds of inputs and relationships that should be included in the model. In addition to the usual economic and operational aspects of maritime efforts, political effects involving nations and coalitions of nations may need to be considered. The developmental complications are greatly increased by the time-dependent and random nature of the situation. To obtain a feasible model, a substantial amount of aggregation of effects must be accomplished without too much loss of realism.

The simulation model will undoubtedly be massive, since limitations on loss of realism place bounds on the amount of aggregation that can be used. Thus, a simulation run will be both expensive and time-consuming. This places practical restrictions on the number of simulation runs that can be made. Special statistical methods, such as the linearized nonlinear regression method of Reference (1), should be helpful in making effective use of simulation outputs and, hence, in reducing the required number of simulation runs.

A measure of effectiveness is needed for representing the relative desirability of an over-all maritime operation from the viewpoint of the nation being considered. To avoid application difficulties, this evaluation criterion should be expressible as a one-dimensional number, with, say, increasing values representing increasing desirability to this nation. Actually, although several viewpoints may occur with respect to what is to be accomplished, development of a suitable one-dimensional measure of effectiveness should be possible for each viewpoint. Then a weighted average of these measures of effectiveness furnishes a consensus evaluation criterion. Ordinarily, an evaluation criterion is primarily concerned with the economic aspects of the maritime operation.

Given an evaluation criterion that is suitable for the viewpoint being considered, the relative desirability of many of the possible courses of action can be examined. Also, subject to budgetary and other limitations, an approximately optimum course of action for the nation considered can usually be determined.

The next three sections contain a general discussion of the problem, an outline of the simulation approach, and a description of the method used to handle uncertainties regarding future situations. Following these are three sections that are devoted to a specification of the types of national fleets that occur, an outline of the model for the over-all system, and a discussion of the trade competition problem. The final three sections contain discussions of the general characteristics of the simulation model, for form and nature of an evaluation criterion, and the developmental steps followed in realistically obtaining an adequate level of aggregation in the model.

GENERAL DISCUSSION OF THE PROBLEM

From the ports of origin to the ports of final destination, the flow of cargo in maritime commerce is influenced by many factors. Also, the amounts and types of cargo available for shipment by a given nation are influenced by supply and demand, political relationships, ship availability, cargo rates, tariffs, subsidies, international exchange, cargo-handling capability, timing limitations, etc. Moreover, the composition of a nation's merchant fleet ordinarily covers a wide spectrum of types of carriers, types of business, etc. Thus, operation of the worldwide maritime transportation system is exceedingly complicated, even when considered from the viewpoint of a given nation.

The existence of a strong merchant fleet is important to nations that are substantially involved in world trade. The general economic level of a nation can be very dependent on the financial success of its maritime transportation operation. Also, for nations with worldwide responsibilities, the availability and control of a substantial number of ships is important with respect to the ability to meet potential overseas emergencies. Here, some of the ships controlled by a nation might not be registered with that nation.

The United States is one of the nations that has been experiencing difficulties in maintaining a strong merchant marine. In spite of a substantial subsidy program, there has been an appreciable decline in the merchant fleet that is United States registered. Japan is another nation that is experiencing financial difficulties with its merchant marine.

Building faster and more efficient ships, that will operate at lower costs, represents a possible solution to these maritime problems for the Unites States and Japan. However, converting this general guideline into a detailed course of action for a nation involves many considerations, including many types of complicated interactions.

The simulation approach described in this paper furnishes a quantitative method for investigating the implications of various possible courses of action. In particular, the development of organized methods for determining approximately optimum courses of action (perhaps by iteration) seems to be possible.

GENERAL SIMULATION CONSIDERATIONS

As used here, a simulation model is a method for representing the important aspects (from a given viewpoint) of the operation of a real-life system over a given time period. In general terms, a model consists of the inputs to the system, determination of the system operation, and outputs from this operation.

With respect to type, the ingredients of a simulation model can be classified as inputs or relationships. The initial conditions, and quantities introduced from external sources during the simulation run, are the inputs. The various interactions and interrelations occurring in the model represent the relationships. Every part of the model is an input and/or a relationship in some context.

Some of the inputs and relationships are subject to deliberate change. In a sense, this is the case for all parts of the model. However, the possibility of change is considered only for those parts that are controllable and which seem to have important influences on the system operation. In a game theory way, the parts that can be changed represent strategies. Some of these strategies are at least partially controlled by the nation whose maritime operation is being considered for improvement. However, many of the strategies are also at least partially controlled by other nations. One of the fundamental difficulties in obtaining a satisfactory simulation model is the development of an acceptable solution to this problem of conflicting interests. Trade competition theory, which deals with this problem, is discussed later.

Another fundamental difficulty lies in developing suitable procedures for quantifying and interrelating the huge number of factors that are involved. The method for accomplishing this, which consists of a stepwise aggregation of effects, is described later.

Many of the inputs and relations depend substantially on the world situation that will exist during the time interval in which the maritime operation is being simulated. It is, of course, not possible to accurately anticipate this situation except for short time intervals in the immediate future. However, for many of the types of information that are to be obtained from simulations, there are reasonable ways of representing future world situations. Some methods for accomplishing this are considered next.

REPRESENTATION OF FUTURE SITUATIONS

No attempt is made to predict the world situation that will actually exist during the time period of the simulation. Instead, the reasonably possible world maritime situations, in terms of their influence on the inputs and relationships of the model, are divided into a number of classes. Here, each class consists of possible situations of a somewhat similar nature. For each class, a specific world situation is chosen as being representative of that class. That is, the possible world situations are represented by a finite number of detailed and completely specified situations with respect to the inputs and relationships of the model. This procedure of using a single situation to represent a class of situations is similar to that encountered in statistical decision theory.

The representative world maritime situations furnish the various directions in which the unpredictable factors influencing world trade might be reasonably expected to proceed. If a given course of action is at least moderately desirable for all of these representative situations, it should be desirable for any type of world situation that might reasonably be expected to occur for the future time period being considered. Unfortunately, courses of action that are simultaneously desirably over such a diverse set of situations would seem to be very rare. Thus, some type of compromise approach is needed for deciding on the consensus desirability of a contemplated course of action over the spectrum of world situations that might reasonably occur.

One meaningful approach to compromise solutions is in terms of the relative probabilities for the classes of situations that are considered. It should nearly always be possible to at least roughly estimate these relative probabilities. Then, assuming that the representative situations for these classes are the only possible situations, estimates are available for the probabilities of each direction in which the world maritime situation might reasonably proceed. The expected value of the evaluation criterion, over the representative future situations, can be estimated through use of these probabilities. That is, for a given course of action, let the value of the evaluation criterion be determined for each representative situation. The weighted sum of these values, using the probabilities for the representative situations as weights, furnishes this estimate.

TYPES OF NATIONAL FLEETS

From the viewpoint of the nation being considered, the maritime fleets of nations engaged in worldwide operations can be classified into five types. The first type consists of ships that are registered with this country. The second type consists of ships that are not registered with this nation but are controlled by it (owned by citizens of this country, etc.). For the third type of fleet, the ships act cooperatively with this nation but are not controlled by it. For the fourth type, there is no control and the ships are neutral with respect to cooperation with this nation. Finally, for the fifth type, the ships are deliberately uncooperative with this nation in regard to world trade efforts.

Any financial assistance from the nation considered is ordinarily limited to aiding the fleet that is registered with this nation and to aiding the shipbuilding industry that is located in this nation. However, a healthy economic status for the nonregistered fleet that is controlled can be highly desirable. Also, the well-being of fleets that are cooperative with this nation, but not controlled by it, can be of interest. Depending on the world political situation, the competition with the noncooperative fleets may be such that some lowering of the economic status of the registered fleet, etc. might be desirable if this leads to a sufficient lowering of the economic status of the noncooperative fleets.

Also, an improvement in the economic status of the neutral fleets is usually favored over such an improvement for the noncooperative fleets.

For reference convenience, these types of fleets are identified by Roman numerals, listed according to the numbering used in their description. As an example, Fleet I is that registered with the nation whose maritime operations are being considered. As another example, Fleet V is that which is outright uncooperative with this nation.

OUTLINE OF SYSTEM MODEL

The ingredients of the model for the worldwide transportation system, with the given nation receiving special consideration, can be identified in a gross sense. Also, the manner in which the various parts of the model are related can be at least roughly outlined. This material, stated in the form of a diagram is given in Figure 1. Here, the economic situation is considered to be the outcome of predominant interest. The rate schedule and the support policy for Fleet I receive special consideration because these are under the direct control of the nation whose maritime operations are being investigated. In many cases, only the financial outcome for Fleets I and II would be of much interest, with the outcome for Fleet I usually being of primary importance.

The inputs that are not controlled by the nation considered must be predicted, at least in some representative sense. Nearly all of these inputs are closely related to the maritime situation for the future time period considered. The method used for representing future maritime situations has already been discussed. It should perhaps be emphasized that a representative situation covers the inputs for the entire maritime system. Thus, the prediction of world trade offerings is coordinated with the prediction of the composition and characteristics of port facilities, of the composition and characteristics of Fleet V, for the constraints and requirements imposed on maritime operations (for example, by law), etc.

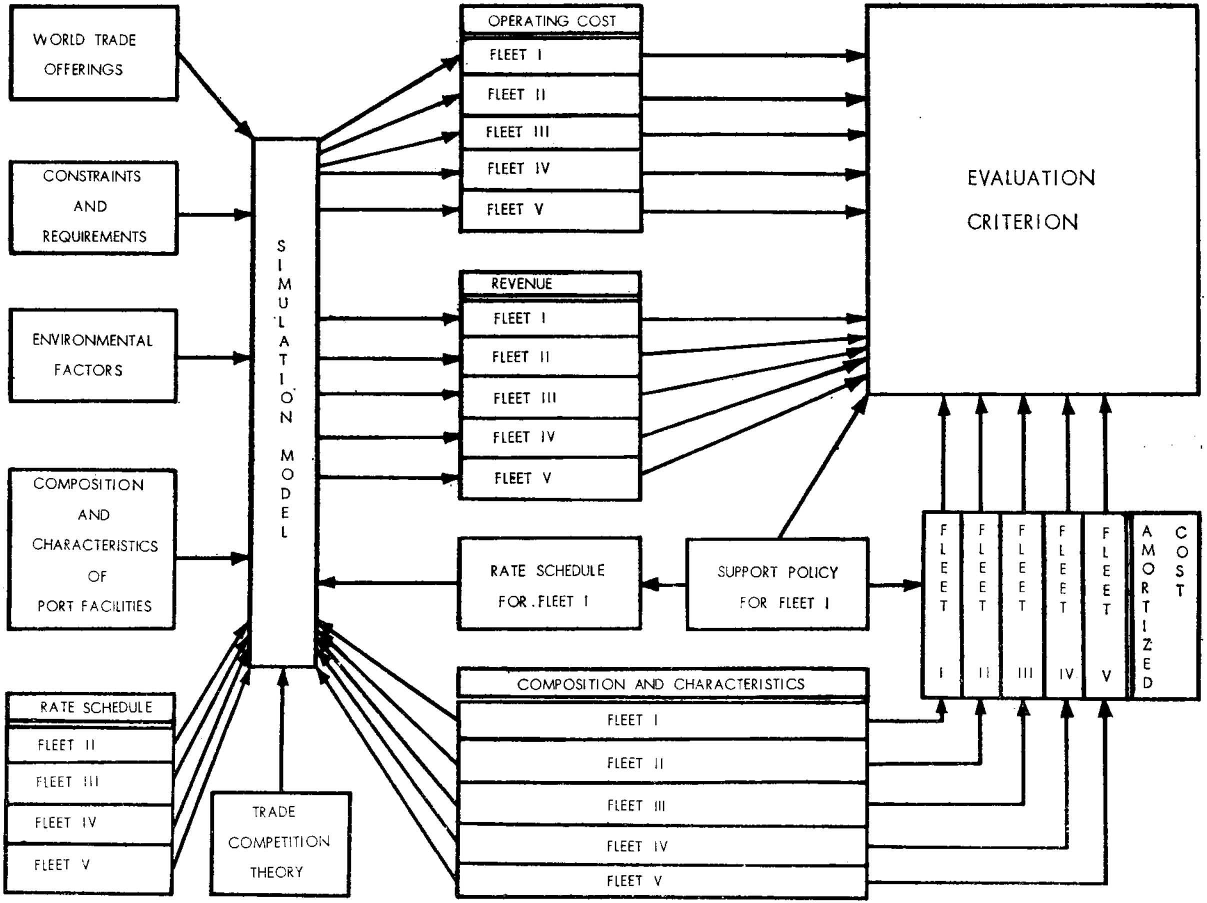

FIG. 1 DIAGRAM OF MARITIME TRANSPORTATION SYSTEM MODEL

TRADE COMPETITION THEORY

Deciding how the world trade offerings will be divided among the various fleets that compete for this business is exceedingly difficult. In fact, the development of a set of rules whereby the exact division can be determined from the existing situation seems to be impossible.

A usable approach world be to consider that the given nation plus the nations with which it closely cooperates constitute one fraction and that all the other nations make up a second fraction whose interests directly oppose those of the first fraction. Then a solution could be obtained by use of two-person fixed-sum game theory. However, this viewpoint tends to oversimplify the situation. Also, the resulting solution would tend to be conservative. That is, it would emphasize protection of the interests of the given nation against all the eventualities that are considered to be allowable. This conservative attitude can be undesirable.

A more promising approach can be developed along the lines of the method stated for handling the prediction of future maritime situations. This can be combined with exploratory use of the simulation model to evaluate the short range implications of the various representative solutions that are considered for division of trade offerings.

More specifically, the decisions concerning assignment of world trade offerings can be divided into a series of consecutive steps, where each step constitutes a separate decision problem. For each of these steps, depending on the situation that exists at that time, the class of different trade assignments that seem reasonable is identified. Then a finite number (not too large) of specific assignments are chosen to represent this class. Here, each specific assignment is representative of some given part of this class of allowable partition of the available trade.

For each representative assignment at a give step, the simulation model can be used to investigate the short range implications of the use of this assignment. Here "short range" might be interpreted as the time period between this assignment and the time that the assignment is to be made for the next step. Sometimes, the assignments over a moderately long time interval are strongly related in their effects. Then, the totality of these assignments should probably be considered to constitute a single assignment that is associated with a single step.

This information from exploratory simulations, combined with other considerations (political, etc.), would seem to furnish at least a rough basis for estimation the relative probabilities for the representative assignments at a step. Under the assumption that only these assignments are possible for the given step, estimates are obtained for the assignment probabilities. Then, at each step, the trade competition method consists in randomly selected one of the representative assignments according to the estimates of their true but unknown probabilities.

METHOD OF SIMULATION

The model for simulating the over-all system operation can be patterned after the model given in Reference (2) for logistics operation in a randomly damaged system. In fact, transportation represents a special type of logistics damaged operation. Although the modifications outlined in the remainder of this section have not been made in technical detail, the following discussion is phrased in the present tense.

The basic model of (2) is modified and extended in several ways. First, much less emphasis is placed on the details of damage, repair, and maintenance. Second, the transportation system is not under a single unified control. That is, it consists of a number of parts, with each part controlled by a different nation. Moreover, competition exists among at least some of these parts. Third, virtually no induced attrition occurs (a peacetime situation). Fourth, the available goods for the various maritime fleets depend on the trade competition method that is used. Thus, uncertainty is involved with respect to trade available to a given fleet, and this uncertainty is of a somewhat different nature from that considered in (2). Also, there are other modifications and extensions.

To obtain the simulation model, the over-all maritime system is divided into subsystems. The choice of the subsystems depends on the use and location of the important transportation items (ships, ports, etc.), the other types of inputs to the over-all system, and the other types of relationships in this system. The time scale is converted to a discrete form by subdivision into intervals. Each discrete time represents a given time interval and the effects associated with a specified time are the effects that occurred during the corresponding time interval.

The subsystems can interact in many ways, depending on what is needed to adequately represent the over-all maritime system in terms of the subsystems. Time is used as the basis for coordination among subsystems. Beginning with the initial posture of the complete system, the simulation is performed over all subsystems for the first time interval. These results, combined with any inputs from outside the system, furnish the conditions for the beginning of the second time interval. This procedure is continued until the end of the time period being considered is reached, and furnishes a simulation run.

The same mathematical form is used for representing the operation of each subsystem. However, the variables in this functional form have values that depend on the subsystem and the time considered. This use of a "fundamental mathematical unit" has desirable features from a computing viewpoint. About all that needs to be programmed on a high-speed computer is the mathematical model for a subsystem and its relations with other subsystems (all of which are represented by this same mathematical form).

As already mentioned, no technical detail concerning the simulation model is given here. However, the model of Reference (2) is stated in technical form and furnishes a prototype for developmnnt of the model for maritime operations.

EVALUATION CRITERIA

To a large extent, the purpose of the simulation is to investigate the economic implications of various courses of action by the nation whose maritime operations are being considered for improvement. The over-all desirability of a given course of action is measured by the use of a one-dimensional evaluation criterion. The value of this criterion is based on a number of considereations (see Figure 1). Most of the quantities involved in determining this value are outputs of the simulation over the given time period.

The form used for the evaluation criterion depends on which part of the economic picture is being emphasized. From the viewpoint of the nation being considered, optimizing the economic situation for Fleet I should be desirable in some respects. However, the resulting economic status of the other fleets, the resulting conditions of all the fleets, etc. should not be overlooked. There are a number of meaningful forms for the evaluation criterion.

A simulation run yields a random outcome for an evaluation criterion. That is, with respect to a given simulation situation (fixed inputs and relationships), the value of an evaluation criterion is a quantity with a probability distribution. This probability distribution furnishes the most thorough representation of the properties of the evaluation criterion with respect to the given situation. However, a very large number of random repetitions of a simulation situation would be needed to reasonably estimate the distribution of the evaluation criterion for that situation.

Instead of representing an evaluation criterion by its distribution, some "average" value of the distribution could be used (for example, its mean or its median). That is, the "true value" of the evaluation criterion is considered to be some specified type of average for its probability distribution. Ordinarily, any reasonable type of average value can be rather accurately estimated from a moderate number of random repetitions of the simulation situation considered.

In some cases, random situation runs for a number of different situations can be combined to obtain estimates of the average values for these situations and for a continuum of intermediate situations. The linearized nonlinear regression method of Reference (1) can be used for this purpose.

DEVELOPMENT CONSIDERATION

As mentioned, an important consideration in the construction of the simulation model is the development of a fundamental mathematical unit that is of an exceedingly flexible nature. The general nature of this mathematical unit is especially important with respect to the stepwise procedure that is advocated for developing the final aggregated form of the model. Namely, this unit should be able to represent the systems that occur at the various levels of aggregation that are considered in obtaining the final form of the simulation model.

From a developmental viewpoint, the simulation model can be considered to have progressed through several levels. The final (highest) level consists of the aggregated model that is used for simulating the over-all maritime operation. Except for the highest level, the purpose of the results for a given level is to furnish information for use in developing the results for the next higher level. The models for these lower levels furnish representations for parts of the over-all system. The lowest level contains models for a large number of relatively small parts.

Hence, the problem of obtaining a sufficient amount of aggregation without too much loss of realism is treated in a stepwise fashion. The flexibility conditions imposed on the fundamental unit are emphasized by the requirement that this unit should be able to represent systems ranging from small detailed parts of the maritime operation to the entire operation. Construction of such a unit involves great care and appreciable ingenuity. However, obtaining a mathematical unit with these properties seems to be definitely possible.

For simulations using advanced high speed computers, development of a satisfactory mathematical unit can often be accomplished by combining a number of functional forms of a rather general nature. Here, each functional form depends on one or more variables and, usually, on one or more parameters. Of course, the choice of a functional form that is suitable for representing an entire class of relationships requires considerable insight and experience. In addition to its ability to handle broad classes of situations, this approach has the advantage that programming reasonable kinds of functional forms on high speed computers is usually not very difficult.

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