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A Production Function Approach to the Measurement of Short Term Readiness of Navy Units

by

Seymour Kaplan

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13. ABSTRACT

This paper constitutes some initial independent thoughts on an approach to the measurement of short run readiness of Navy units. Readiness is assumed to be expressed in terms of values associated with having the unit in a given state when certain requirements are imposed upon it as the result of the specification of a set of "missions". That is, we associate readiness with the ability to successfully complete a set of tasks rather than with the physical state of any material component or group of components of the system.

The term "short run" is used to distinguish the time periods over which readiness is determined from those where the response ability of the system can change due to obsolescense and deterioration as well as because of changing resource levels and mission requirements. However, the time span is considered sufficiently long to allow the specification of missions over time periods such as weeks or months. Other papers will examine alternate short and long term approaches to the problem.

Resource requirements are determined for each mission by a transformation of the mission statement to a quantitative basis. This in particular requires the specification of a measurable set of "output requirements" for each mission. Once the output or performance requirements are stated, the problem is to determine to what degree resource availabilities enable us to meet these requirements.

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Summary and Recommendations

This paper constitutes some initial independent thoughts on an approach to the measurement of short run readiness of Navy units. Readiness is assumed to be expressed in terms of values associated with having the unit in a given state when certain requirements are imposed upon it as the result of the specification of a set of "missions". That is, we associate readiness with the ability to successfully complete a set of tasks rather than with the physical state of any material component or group of components of the system.

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Resource requirements are determined for each mission by a transformation of the mission statement to a quantitative basis. This in particular requires the specification of a measurable set of "output requirements" for each mission. Once the output or performance requirements are stated, the problem is to determine to what degree resource availabilities enable us to meet these requirements.

We feel that there is great advantage in being able to use a numerically valued function for determining the degree to which requirements can be met for each mission. Our approach is to use a production function concept to express the level of performance available from given amounts of resources and to compare this level with required levels. Important qualitative insights into readiness should be possible once estimates concerning certain characteristics of these functions are obtained. If this approach appears feasible, we propose that a deeper investigation in conjunction with Navy personnel who are involved in the day to day problems of readiness, be undertaken to determine whether (1) mission statements can be quantified and (2) whether mathematical production functions for level of individual mission accomplishment can be approximated.

This paper will discuss some mathematical forms to portray individual mission performance. The general idea is to obtain a set of individual mission readiness values for all missions specified at a particular point in time and then considering (1) the relative probabilities of these missions (2) their relative importance, (3) the relationships between them and (4) their probable time sequencing, to achieve some type of aggregation over the different missions. Much consideration needs to be given to which types of aggregative procedures are appropriate and which are not.

Introduction

Readiness, the condition of being ready, is defined as the condition of being "completely prepared or in fit condition for immediate action or use" [3]. The definition does not state for what actions or uses the entity whose readiness is in question should be prepared, but presumably we can assume that they are those which it is called upon to perform because of self-preservation, preceived military advantage, or command from a higher authority. Also, the definition seems to imply that readiness is a binary valued characteristic - either the entity is completely prepared or it is not.

With regard to the Navy we will assume that the entity in question can represent any operating unit of the Navy. In this respect it may be a single ship, a group of ships, or an entire command such as the Pacific Fleet. We shall also assume that the actions or uses correspond to missions which the unit is ordered to carry out by a higher authority such as the President, Secretary of Defense, fleet commander, etc. In addition, we shall drop the binary assumption of the definition and consider that readiness can exist at intermediate levels between the condition of "not ready" and that of "completely ready". If we now take these two conditions as representing the end points of the real line segment in the interval (0,1) we are leading ourselves into considering readiness as a scalar valued characteristic. For reasons which have to do with the ultimate uses of a readiness measure we wish to pursue the concept of scalar values in this paper. Although we do not wish to restrict ourselves to whether the scale must be cardinal or ordinal, this paper will be primarily concerned with the possibility of developing a cardinal scale. Such a scale, if meaningful, will obviously be more desirable. Whether one can be developed remains to be seen.

Thus, we are considering our definition of the Navy readiness in the sense of the degree or extent to which the system or subsystem is prepared to immediately carry out any subset of an initially specified set of missions which may be assigned to it. Note that the term "immediately" still appears in our definition. We consider that readiness can change as a function of time* but for any time interval T, over which a set of missions is specified the definition refers to the ability to successfully complete them. Since many missions will involve an action or operation over a time interval T , our definition allows the readiness to change during the interval if our ability for successful completion has been altered. We also at this point wish to consider readiness as a deterministic characteristic of the unit rather than stochastic.

We intend to measure the extent to which any subset of the initial set of missions can be carried out by assigning a value to the system associated with having given amounts of various resources available to it. Since any subset of the complete set of missions can possibly occur, ranging from no missions to all of them, we must also decide whether to base our measure of value on the most likely subset. the "worst possible" subset or some other combination of mission occurences. This problem is taken up later.

The first part of this paper is to suggest an approach to determining the response possible with any individual mission. The ability to perform a mission is usually thought of in terms of how available resources compare with required levels. If all required resources are available at levels equal to or greater than that needed then we would

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*It could be considered to vary either continuously or discretely.

ordinarily say that the system is at full readiness for the mission and no problems with measurement occur [*] Difficulties enter when one or more resources are at less than required levels. Then, what is the ability of the system to perfo m the mission? This question must be answered from the point of view of operational usefulness. It is not enough to state only the percentage of resources at less than required level, or the magnitudes of such deficiencies. What is clearly needed is something which tells decision makers whether any response to the mission requirement is possible, and hopefully the degree of such a response. The principal difficulties arise when trying to assess the degree of response possible given certain levels of inadequacy of various resources.

The problem is complicated by the fact that certain resources are required by more than one mission. Thus. the decision maker often has to make allocations which affect readiness, and it becomes difficult to talk about readiness unless one assumes particular allocations of resources to missions. One is tempted to become involved in problems of determining readiness under "optimal" allocation of resources but this is really premature since the very definition of any objective function needed to determine optimality will depend on the measure of readiness which we finally settle on. The assumption of this paper is that some type of

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[*] The question of the domain of resources always needs to be considered. For example, the resources domain could include the mental attitude of personnel. Much of what one does depends on what resources we consider to be 1) important (2) measurable as to magnitudes which a unit possesses and (3) measurable in terms of how inadequacies affect performance.

allocation formula exists and that the eadiness depends on such allocations in a manner to be determined.

Uses of a Readiness Measure

Before embarking on any discussion of the mathematical properties of any function to measure individual mission readiness, it would seem useful to consider how such a measure would be used by the Navy. In discussing possible measures we should consider both the possibility of ordinal and cardinal systems. We shall roughly consider an ordinal measurement system as one which can assign a rank ordering of value to a set of different systems states while a cardinal measurement system gives us relative value information for different system states as well as rank ordering information. While at this point we are unfamiliar with all the possible uses of a readiness measure, we shall list below those which to us seem relatively important and which would be possible if a cardinal measure existed. They are:

1. If a cardinal value could be estimated for one system and compared with one estimated for a potential adversary, the information could be used to indicate the degree to which overall Navy expenditures have to be increased or cut back. Naturally, much estimates would include "confidence intervals" as well as the actual estimates.

2. If a cardinal measure were available, then a marginal rate of change of readiness (either in a continuous or discrete sense) could be developed to indicate the sensitivity of readiness to changes in the levels of various Navy resources and programs. It would also allow the Navy to estimate the potential increase in readiness to be obtained from any new weapons system, as well as the consequences in terms of readiness of foregoing expenditures in various areas.

3. Cardinal measures, if available, can be used as the objective functions for many types of mathematical optimization problems of interest to the Navy. For example, on a short term basis, the optimal redeployment of resources to meet a set of possible new threats to the system can be thought of in terms of maximizing readiness. On a longer basis, the optimum allocation of funds over a period of years could be determined as a solution to a problem whose objective is the maximization of eadiness at the end of the period.*

4. Again, on a long term basis, the readiness of a system will change with time as our resources age and as the threats and strategies of our adversaries change. If a cardinal measure is available and is time dependent, then we can determine how our system's readiness will deteriorate if research, development, and production of new technologies are not undertaken on a timely basis. Thus, the measure can be used to signal when and where R and D expenditures are most appropriate.

5. A cardinal measure of readiness, arrived at by logical considerations and with clearly stated assumptions and limitations, provides a common framework about which differing points of view on construction, procurement, research and development, personnel policies, etc. can be debated and evaluated. It can be used to substitute objectivity rather than hunches and emotions into decisions involving alternatives.

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*Ordinal measures of readiness are also useful and important in quantitative optimization models. See [2] for a recent example.

Mission Specification

Critical to our readiness measurement proposal is the requirement that mission requirements can be expressed quantitatively. We have tried to consider various types of Navy missions with respect to common dimensions which many of them possess. Our feeling is that many mission statements either directly or indirectly involve certain dimensions. These include the mission duration and the location or geographical area where the mission is to be performed. Such aspects are easy to quantify by a time and area specification. However, because of the manner in which many missions are ordinarily stated it is often difficult to determine a variable against which expected successful or unsuccessful completion can be evaluated. Nevertheless, it does seem possible for one to usually be able to transform the given statement to another which is operationally useful (and acceptable to the originator of the statement). Although additional investigation of the above comment is important, consider the below example.

A mission involves the mining of specified enemy ports to prevent the passage of shipping into and out of these ports for a certain period of time. An order creating the mission may be as general as that stated above. In order to determine the readiness of the Navy to perform such a mission by our approach, the statement must be transformed into another quantitative statement (obviously not unique) acceptable to the originator of the order. In the above case an initial quantitative statement might take the form "the probability of a ship entering or leaving any port unharmed for T days should be less than α, where α is specified and where the term "unharmed" is rigorously defined. Different levels of effectiveness of such missions relate to the fact that due to various levels of availability and functioning of the various resources, different expected results from the attempt to carry out the mission are possible. Thus we have expressed the required output of the mission by a scalar value α, the maximum allowable probability of undamaged ship passage. However, it is probably preferable for most missions to express mission performance in terms of quantities or amounts of some physical resource. In the present example, the value α could be transformed into the minimum number of mines, properly placed, that would give the desired value of α. That is we could think of a functional relationship existing between the discrete valued variable "number of mines" and the probability level α.

We feel that if any possibility for realistic measurement of readiness exists, the quantification of missions objectives is of fundamental importance. We also feel that we shall be in a better position to see what can be done in this respect after we have some interaction with Navy personnel who are involved in some of the day to day problems of readiness.

Production Functions

After having considered at length various possibilities by which Navy resources are combined or marshalled to meet the requirements of many important types of Navy mission, we feel that the level of output possible through the use of a set of resources can best be described by a "production function" concept discussed below.

In economic theory, a production function is used to describe how the maximum output of any production process depends on the values of the input ingredients. Assume such a relation can be represented by the mathematical function $y = F(X_1 ---- X_n)$ where y is the quantity of output resulting from the use of input i at level X_i. These inputs can be labor, physical products, or capital items required in the production process.

Technological production functions are characterized in several well known ways. Since these are also of interest with respect to the mission production function which we are attempting to construct, we shall discuss them. First, there is the question of what happens to the quantity of our output product when all inputs increase in the same proportion. In other words if kX_i, $i = 1 --- N$, units of input i are used, how does y change? Economists consider three possibilities: (1) constant returns to scale, (2) diminishing returns to scale, and (3) increasing returns to scale.

In the case where $f(kX_1, kX_2, --- kX_n) = kf(X_1, --- X_n)$ the production function is said to a linear homogeneous production function. This is clearly the situation of constant returns to scale. Although increasing returns to scale may occasionally occur with Navy resources, with respect to the degree of mission accomplishment, diminishing and constant returns are much more likely.

Another aspect of production functions involves the question of substitution of factors. If the function $f(X_1, X_2)$ is continuous in X_1 and X_2, then suppose some level y of output can be achieved through the use of X_1 units of input factor 1 and X_2 units of input factor 2. However, many other combinations of factors 1 and 2 will also produce y units of output. All combinations X_1 and X_2 given by the equation $y = f(X_1, X_2)$ will achieve this result. In other words substitution of X_2 for X_1 is possible. If X_1 were in short supply for some reason, a level of output y could still be obtained by using more of X_2 if additional units of X_2 were available.

With Navy systems and the need to carry out a mission, substitution among factors is sometimes possible and sometimes not possible, and sometimes partially possible. For example, pressure mines may be substitutable for acoustical mines to some extent if there is a shortage of mines of the second type, but many other resources do not have useable substitutes.

Many of the standard production functions are of the form where substitution is possible. For example, some well known ones are the Cobb-Douglas, CES, and the linear production functions [1]. However, there is another type which we must also discuss because of its seeming importance for potential use in measuring mission output. This is the "Leontief" production function which is the type assumed in input-output analysis. Here substitution is not possible.

From our understanding of systems such as the United States Navy it seems that many resources (ships, personnel, material, equipment) must be brought together in certain proportions in order to be effective. As an example, assume carrier based aircraft require pilots on a one to one basis. If we have available 40 aircraft and 30 pilots, only 30 airplanes can be made airborne. If fuel is also considered, say 1000 gallons per aircraft to perform a mission at unit level* then 25,000 gallons of fuel available means only 25 such missions can be performed.

The above concept can be generalized as follows:

Let us assume that the system can perform a mission at each location

*Unit level of mission performance refers to the mission requirement statement.

at varying levels defined on the continuous non-negative real axis.

Let $y_j \geq 0$ = the level at which the jth mission can be performed (assumed continuous).

x_{ij} = the level of resource i allocated to the jth mission.

a_{ij} = the level of resource i needed to support the jth mission at unit level.

Then from the above discussion $y_j = \underset{i}{\mathrm{Min}} \left(\frac{x_{ij}}{a_{ij}}\right)$.

The above is the production function for the jth mission output. Note that it is a linear homogeneous production function with constant returns to scale, where substitution is <u>not</u> possible.

For example in the carrier based aircraft example, assume a unit level of the mission equals the dispatch of one aircraft to a location to provide defense against enemy aircraft attacking ground troops. Suppose there are four resources needed to accomplish this mission - aircraft, pilots, fuel and ammunition. The availability of each for the mission (the X_{ij}) are 40 planes, 30 pilots, 25000 gallons of fuel, and 200,000 rounds of ammunition. Suppose the unit level requirements (the a_{ij}) are 1 plane, 1 pilot, 1000 gallons and 1000 rounds, then the level at which the mission can be undertaken is

$$y_i = \mathrm{Min}\left(\frac{40}{1}, \frac{30}{1}, \frac{25000}{1000}, \frac{200{,}000}{1000}\right) = 25$$

Suppose the quantative statement requirement for this single mission at the location considered is "maintaining a presence of at least 30 carrier based aircraft daily for the protection of ground troops". Then the difference between the mission requirement level and ability to perform level is obviously 5. We shall refer to such functions as the above as mission response functions (MRF's). Their evaluation forms an important part of our approach to determining individual mission readiness.

Many production functions involve the production of more than one output as a result of the production process. Such cases of "joint" production can be considered by imagining that for each output product there exists a production function $y_j = f_j(X_1 ---- X_n)$ so that once the mix of the factors of production is specified, the production of each output produce is uniquely determined.

With respect to mission statements, they may often involve multiple objectives. Thus, the statement that a given set of aircraft support ground combat troops with firepower also have the ability to perform surveilance operations might be characterized by two quantitative requirements both of which involve many common resources. The output of such a mission might best be described by a production function involving joint outputs.

Estimating the Mission Response Function

In this section we wish to suggest some approaches to determining (a) the mathematical form of the MRF and (b) the parameters of the MRF. We are given a mission, which we assume, has been stated in terms of desired levels of numerically valued output requirements (number of mines, rounds of shells, number of missiles or aircraft of ships or men, etc.). Often a mission statement will involve several output variables of the above type. We can think of the requirements as being stated in terms of what we can call "primary resources" which must be delivered to an appropriate location through the use of a hierarchy of other non-primary resources. Thus, the mine laying operation requires, besides the mines themselves, ships or aircraft and pilots and mine laying specialists for the initial delivery, surveilance mechanisms to determine the deterioration, if any, of the minefield, and additional mines, ships aircraft and personnel for replacement purposes during the interval when the operation is to be effective. In order for the above ships, aircraft, and personnel to be employed, the operation would require fuel, maintenance, and other logistics support for the delivery vehicles and personnel. This three level hierarchy seems to be typical for many operations - (1) the item or items to be delivered, (2) the delivery means, and (3) the support of the means of delivery. Of course in considering the resource domain any resource whose inadequacy can adversely affect the mission must be considered.

Now the approach suggested here is to develop the MRF by expressing the outputs in terms of the delivery means in terms of the support resources. Then, in the final form the delivery resources do not appear explicitly in the MRF and the output is expressed in terms of the support resources or more generally, the output is expressed in terms of the more remote resources. For example, if we are considering mines to be dropped exclusively by aircraft over a specified time period we might write that

$$N = \mathrm{Min}\left(M, \frac{A}{a_{11}}\right)$$

where

N = the number of mines appropriately planted

M = the number of mines available

A = the number of flights to the target which can be launched during the specified time

a_{11} = the number of mines which one aircraft can hold

That is, the number of mines which can be planted is limited either by the number of available mines or the number of flights which can be launched.

Furthermore, we might assume that

$$A = \mathrm{Min}\left(\frac{P}{a_{12}}\ \frac{F}{a_{22}}\ .\ \frac{U}{a_{32}}\right)$$

P the number of available manpower

F = the quantity of available fuel

U = the number of available aircraft

a_{12} = the number of flight manpower required per flight

a_{22} = the quantity of fuel required per flight

a_{32} = the number of aircraft per flight ($a_{32} = 1$)

We are neglecting the need for specific manpower classes in the above.

Thus, substituting:

$$N = \mathrm{Min}\left(M, \frac{1}{a_{11}}\left[\mathrm{Min}\left(\frac{P}{a_{12}}, \frac{F}{a_{22}} . \frac{U}{a_{32}}\right)\right]\right)$$

Of course if we are considering the mission over a time interval, then we would also have to consider the degradation of aircraft and manpower due to breakdowns and similar losses. The number of flights will depend not only on P, F, and U but also on flight losses and the availability of spare parts and trained repair crews. Consider the aircraft degradation problem. Suppose U_1 round trip aircraft flights are possible in the period if no breakdowns or losses occur. Suppose the rate of flight degradation due to breakdowns is α_1 and that due to losses is $\alpha_2 (0 \le \alpha_j \le 1)$ so that $\alpha_1 U_1$ and $\alpha_2 U_1$ represent the number of flights lost from each cause. Also suppose that the availability of r spare parts will allow an aircraft that would otherwise break down during the period to be operational. If R spare parts are available, then the number of flights possible is given by:

$$U = \left[1 - (\alpha_1 + \alpha_2)\right] U_1 + \frac{R}{2r} \quad \text{if} \quad \frac{R}{r} < \alpha_1 U_1$$

$$= U_1 + \frac{\alpha_1 U_1}{2} \qquad \text{if} \quad \frac{R}{r} \geq \alpha_1 U_1$$

This function would have to be substituted in the previous equation for U.

The above assumes that any aircraft that breaks down can be repaired immediately using the spare parts and that a repaired aircraft will not break down again during the mission. The need for repair crews is not considered and it is assumed that a repaired aircraft can make one-half as many flights as one which did not break down. Lost aircraft cannot be recovered in any manner.

The above example has been used to illustrate one of a variety of ways in which the mission readiness function can be developed. Specific mathematical functions will of course depend on the nature of the missions. If such an approach appears reasonable we would pursue it in future papers.

Readiness Considerations with Respect to a Set of Missions

What we are trying to measure is essentially the "value" to the unit of having the capability to perform each of its missions at some level of proficiency. The question we must ask is does this value measure depend on how all the missions are performed, on how the most important are performed, on how the mose likely are performed, or on performance applied to some other subset of missions?

Without too much thought it becomes apparent that much will depend on how the missions are related to each other. The performance of certain missions may be affected by successful or unsuccessful performance of others. In this sense, missions may be independently mutually exclusive, or dependent in some manner. For example, assistance of a ship in sea rescue operations or some sort (one mission) may be independent of the ship acting as a spare parts depot (another mission). Or, a mission "shell enemy shore installations" (one mission) can only be accomplished if (another mission) "move to vicinity of enemy shore" is accomplished first. Furthermore, many aspects of whether certain missions are independent or non-independent depends often on how resources are allocated to missions and to how they are defined. We intend to develop a model to describe such mission interactions after first learning more about their nature from Navy personnel.

Missions also may have to take place in either what may be termed a roughly simultaneous manner or what might be termed a sequential manner when a group of missions are to be performed. On a sequential basis there is a possibility of reusing resources or reallocating unused resources from those missions performed first to those performed later. On a simultaneous basis this is not possible. In developing an interaction model such relations must also be considered.

We must stress the fact that any approach will imply that the overall unit readiness will depend greatly on how the unit in question allocates or utilizes its resources with respect to its various missions. If its command decides to spend most of the time of its available manpower training for some one mission at the expense of other potential missions, then we would say that the command is putting the unit into a certain state relative to the potential missions. Our measurement system is merely a device to try to numerically estimate the ability of the unit to react to the missions as a group, given certain assumptions regarding probabilities, importances, and how the missions interact.

The short term readiness problem of the Navy might be compared to that of a general repairman in an industrial setting. The repairman can be called upon at any time to repair a piece of broken down equipment, or engage in repairs involving carpentry, plumbing, masonry work, and possible other skills. From his experience he has learned something about (1) the likelihood of various types of work he will be summoned to perform and (2) the criticality of some jobs (to the smooth functioning of the enterprise) over others.

In order to meet what is perceived as his job needs, varying amounts and types of certain tools and materials have been made available to him. Given that we know the amounts of materials and an inventory of his tools as well as his level of skill and ability in various crafts with which he may be involved, how do we measure his potential ability to respond to the calls and make the necessary repairs?

Although the above simplified situation has many similarities to that of the Navy, there are also obvious differences. However, the example can still be instructive in indicating how to proceed with the more complex situation.

Different observers will consider the repairman's readiness to be satisfactory according to different criteria. Many of these will boil down to considerations involving what proportion of the critical jobs he can be expected to perform satisfactorily, where observers will demand proportions ranging from 1.0 downward. Others will want more than just satisfactory performance on critical jobs but will also demand adequate performance on most non-critical jobs.

An examination as to which criteria are preferable will not be undertaken here. Rather, what we should do is to try to suggest several possible approaches and in conjunction with the repairman and his supervisors arrive at some satisfactory methodology.

From our previous work on individual missions, the mission readiness function is intended to measure the potential performance on a mission and how this compares with the mission requirement. Applied to the repairman, we could now introduce values $\overline{Y}_j$ which constitute what is deemed the minimum of level of satisfactory performance on job j in order for performance to be called "satisfactory". Thus any job for which $Y_j \geq \overline{Y}_j$ is one which can be performed satisfactorily. The value Y_j in the Navy context would represent the MRF for mission j and $\overline{Y}_j$ the required performance for the same mission.

Now with the different jobs, the repairman's ability to perform any job, crucial or relatively unimportant depends to an extent on the frequency with which these jobs arrive. If he becomes overwhelmed with work his ability to perform well will decrease principally because certain of his critical resources, (himself for example) can only be in one place at one time. That is those resources which are essentially required on all jobs can be overwhelmed if jobs come in quickly enough. Thus, we would characterize the repairman's job profile as consisting of job types which use certain common resources. We could set up a job by resource matrix indicating by a "$\checkmark$" in the appropriate cell whether the resource is required by the job in any significant amount (without regard to magnitude). For each resource we could list the number of jobs that require this resource. Such a matrix could be constructed and be useful for any future analysis of mission performance in the Navy. In a following paper we expect to use some of the considerations discussed above to formulate some specific approaches to determine readiness in terms of group of missions. We hope to be able to obtain an initial response from the Navy on some of our ideas while proceeding in this work.

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