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THE RELATIONSHIP AND APPLICATION OF ECONOMIC ANALYSIS
TO HUMAN FACTORS INTEGRATION FOR SHIP SYSTEMS

Henry Solomon

David W. Taylor Naval Ship Research and Development
Center
Bethesda, Maryland

February 1976

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By

Dr. Henry Solomon

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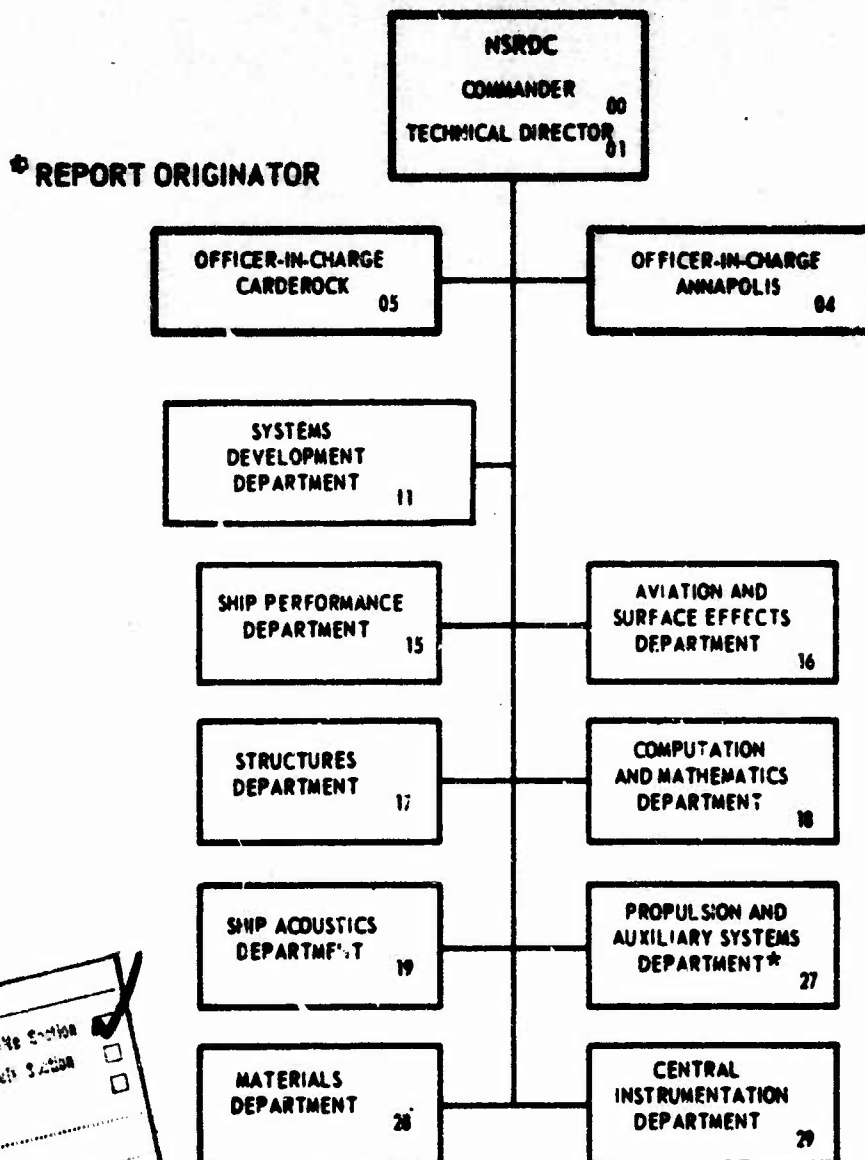
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The purpose of this report is to identify, evaluate, and suggest approaches for the utilization of the economics discipline for human factors integration in the design and development of ship systems. Emphasis is placed on the application of production and cost theory to optimized ship systems.

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THE RELATIONSHIP AND APPLICATION OF
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Dr. Henry Solomon

0. Introduction

A major effort is currently underway by the David W. Taylor Naval Ship
Research and Development Center directed at the development of appropriate method-
ologies for the integration of all human factor engineering related tech-
niques. This effort recognizes the need for an interdisciplinary approach
to ship systems development. It includes relating the disciplines of
various engineering sciences along with the relevant behavioral and social
sciences. This is viewed as necessary since a ship system does not only
consist of a set of equipments with varying degrees of complexity but also
includes manpower who must relate to the equipments and to each other.

The purpose of this report is to identify, evaluate, and suggest
approaches for the utilization of the economics discipline in the pro-
cess of Human Factors Integration for Ship Systems. Since much of the
economic analysis is devoted to optimum allocation and utilization of
scarce resources, it seems clear that the economics discipline can indeed
contribute to the human factors integration process. A major goal of
this process is to increase Navy effectiveness while giving explicit
recognition to the critical role of humans in the operation and mainte-
nance of its weapons systems. Another goal is to achieve a degree of
desired effectiveness with minimum manning levels, or put more appro-
priately, at minimum cost.

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After a close examination of the formal published human factors literature (e.g., Human Factors Journal), there is little or no evidence of identification of economic type problems and, of course, therefore little or no presence of economic analysis. This is not meant to imply that the economic considerations are not implicit; hence the prescribed task is to make these considerations explicit with attempts at resolutions via economic analysis.

There appears to be two principal reasons for the lack of economic analysis in human factors considerations. One is simply the lack of economists employed for this purpose, and the second is the relative narrow horizon of problems viewed as human factors problems. An example of the latter is that human factors engineering has been almost solely devoted to the demand or requirements side of the manpower equation without sufficient consideration of supply, i.e., without viewing the potential future supply of appropriate numbers of personnel with necessary skills and experience.

What follows is a discussion which is intended to provide the dimensions of the role of economics in human factors integration. In this report all topics are not treated with equal depth. Emphasis is given to applications of micro-economic analysis to resource allocations and utilization. Within this emphasis, attention is directed to the possible contributions of production and cost theory.

1. General Navy Manpower Considerations

The size and composition of the Navy has been changing significantly in recent years. In 1968 the Navy had over 900 commissioned ships and the number is expected to be close to 500 in the near future.

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Many of the active ships in the 1960's were old and becoming obsolete in a rapid fashion. Old ships have not been replaced by new ships on a one-for-one basis. The new ships have different and greater capabilities than their predecessors. Of some consequence for the problems addressed in this report are the technological innovations being implemented in the new ships which include greater degrees of automation and must be expected to have considerable impact on manpower requirements. An example is the new destroyer program, i.e., the DD 963 class, which will be discussed later in this report. The exact nature of these impacts is yet to be determined. While automation may certainly be expected to reduce manning levels, some brands of automation may result in the need for highly skilled personnel, while others may require only unskilled or semi-skilled individuals for ship operation and maintenance.

The differential needs for skilled vs. unskilled shipboard personnel has important effects on total personnel requirements. One major reason for this is the need for training of skilled Navy labor. In a report by the Stanford Research Institute [1, pp. 5-6], it was noted that in Fiscal Year 1974, about 20 percent of Navy personnel were in training schools either as instructors or students. The determination of qualitative personnel requirements has a crucial effect on total personnel requirements and total necessary compensation requirements to sustain a high level skill mix. Hence trade-offs of labor and capital requirements affect not only readiness levels but also budgetary levels. Of course other policy parameters affect personnel requirements. Examples are personnel rotation policies, promotion policies, etc.

On the supply side there have been many optimistic projections regarding the Navy's capabilities for attracting and retaining the

appropriate number and quality of personnel. Much of this optimism has stemmed from the establishment of the All Volunteer Force which is to provide the Navy and the other military services the tools to maintain a career force. An example of a major tool for this purpose is the ability to offer financial compensation equivalent to comparable individuals in the civilian labor force. Also it has been supposed that with a larger proportion of careerists, personnel turnover and associated costs (e.g., training costs) will be kept to a minimum, and as a corollary, the productivity of the military work force will be increased [6].

The validity of optimistic future military manpower conditions is somewhat uncertain. While the increase in military compensation has affected the supply of first-term enlistees, it is not clear that it is attracting individuals with necessary qualitative characteristics or that it is influencing careerist decisions. Turnover remains high suggesting that variables other than financial compensation are influencing individual's decisions. It is likely that the civilian and military labor markets are not homogeneous and differential aspects of these markets must be taken into account.

During the next two decades the potential supply of enlistees will decrease. That is, the number of available 18-19 year old males will decrease as seen by Table I.

Table I

16-19 Year Old Males
(Thousands)

Category Year	Population	Labor Force
1970	7,649	4,395
1990	7,045	3,901

Source: Manpower Report of The President April 1975, p. 309.

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Based on evidence at least currently available, the likelihood of males enlisting in the service beyond this age group decreases substantially. Along with problems of personnel acquisition, there remains the problem of retention. Based on some recent studies, the level of education and mental group are among the most important determinants of retention [3]. That is, individuals who have not completed high school and are in the lower mental groups are clearly the ones most likely to reenlist. This becomes somewhat modified by matching of level of education and occupation. For example, high school graduates assigned to technical occupations are much more likely to reenlist than those graduates not assigned to technical occupations. Another point of interest is that individuals who have been in more than one occupation during their first term of service are much more likely to reenlist than those who have experienced only one occupation.

The future decrease in the available pool and the difficulty in attracting and retaining high quality individuals suggest strongly the need for higher capital-labor ratios and the need for selective manpower policies to retain the required personnel. This suggests that greater attention be given to the inter-relationships of humans and equipment in conducting shipboard functions.

2. Systems Functions and The Theory of Production

The human factors discipline is devoted to the examination and analysis of the interaction of man and equipment. Typically this is in the light of behavioral and physiological capabilities and constraints on the part of individuals relating to the equipments. The relationship of man and equipment in the production process is also the concern of

the economist but this has not typically included behavioral and physiological considerations. In the past, the economist has taken what is referred to as the production function as a given and proceeds with the analysis of production from that point on. However, in various contexts, the economist has, for the past 20 years or so, involved himself in the formulation and empirical estimation of the production function.

There are some basic economic concepts and analyses which should be of value to an integrated human factors approach. This value lies in the specification, or at least clarification, of human factors considerations which seem to be absent in the human factors literature. Human factors engineering appears to be devoted mainly to the design of equipment with appropriate account taken of human capabilities and limitations. Also it appears to include consideration of the best use of human beings applied to a given equipment design and function. The issue of taking both views into consideration is to attempt some form of trade-off analysis which suggests, but usually does not result in the use of appropriate economic concepts and measurements.

The best notion for initiating a discussion of economic reasoning is that of the production function.

3. The Production Function

We may consider a ship system or some sub-system as producing one or more outputs or services based on the utilization of one or more factor inputs. The output may be in terms of fire power, speed, etc., and the factor inputs may be aggregate labor, aggregate capital, or may be particular skill services or individual units of capital services, such as computer printouts.

Since a ship is likely to perform more than one function, we may write the production function in general (implicit) form as follows:

$$F(O_1, \ldots O_n, X_{1_j}, \ldots X_m) = 0$$

where

$O_k \geq 0$ are outputs or services $(k = 1,2,\ldots,n)$

and

$X_1 \geq 0$ are factor inputs $(i = 1,2,\ldots,m)$

An important result of this statement is that for a given set of factor inputs, there may be various sets of feasible services. Also to produce a given set of services, there may be various possible sets of factor inputs.

The rather straightforward statement of the production function must be examined in terms of various properties. However, before this is pursued, it may be anticipated that we face important applied problems. The first is how to identify the outputs of the system, hopefully in some measurable form, and the other similar problem is how to identify and measure the inputs. Important methodological questions are the acceptability, feasibility, and suitability of viewing the ship system in total, or the alternative of viewing various possible partitions or subsystems of the total sub-system. These questions must be addressed in part on the basis of judgment, data availability, and cognizance of methodological issues to be described below.

As noted above for the multi-service function, there may be a number of different possible sets of services. One may assign arbitrary values to all but one of these services and obtain the maximum value of

the one service which satisfies the production function. However, it must be emphasized that this maximum value is based on the specification of the designated quantity of factor inputs and the assigned quantities for the other services. Any change in these assigned values will result in a different maximum value for the service under consideration. Hence in partitioning what is really a multi-service system into individual service sub-systems, different results may be obtained in determining the maximum value of each service. The significance of this remark for the problem at hand pertains to the typical multi-mission ship. If the missions are changed or the relative weights or importance of the individual missions are changed, the maximum values of the services or missions may be expected to change.

Before proceeding to the usual analysis relating to the production function, an additional point should be emphasized. In conventional economic analysis from which this production function statement comes, it is assumed that the function has already been specified by the engineers. Needless to say, this is the very problem with which we are dealing. Nevertheless, the notions and properties of the production function will be of assistance.

The first basic and useful notion relating to the production function is that of "marginal product." The exact meaning of marginal product, in our context, is best stated in terms of partial derivatives. That is, the marginal product of, say, product 0_1 , with respect to factor input X_1 is as follows:

$$MP = \frac{\partial 0_1}{\partial X_1}$$

That is, the marginal product of service 0_1 with respect to the factor

service X_1 represents the change in 0_1 due to a small change in X_1, holding all other services and factors constant.

The notion of marginal product is useful for determining maximum output and relating to a productivity concept. By observing the behavior of the partial derivative noted above, we may examine the marginal productivity of each of the factor services. It is reasonable that the marginal productivity of a particular factor may increase at an increasing rate followed by an increase at a decreasing rate, and then decrease. At the point where it begins to decrease for each of the factors, marginal productivity will be zero and output of the service will be at a maximum. While this is not the only condition to be satisfied in order to guarantee a maximum (i.e., a second condition pertains to the second order partial derivatives), it suffices to indicate the importance of behavior of marginal productivity.

Taking an example, which would be unconventional in economic analysis, but illustrative for human factors analysis, reference will be made to a study reported on but not accomplished by McCormick [5] directed at the spacing of knobs. In economic analysis we refer to changes in the quantity of a factor input, but in this example, the changes pertain to spatial arrangement of knobs. This, in fact, could be transformed into quantities of a factor, i.e., amount of space utilized for each arrangement.

The study refers to variations in performance by human operators in different spacings between knobs and differences in knob diameters. As described by McCormick [5, p. 405]:

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"Upon a signal, the subjects were instructed
to operate a knob by turning it until a line on
it was pointing straight up. Four 'prohibited'
knobs were arranged around the one to be operated.
An error was scored if the subject touched one of
the prohibited knobs."

The results demonstrated the relationship of distance between
knobs and touching errors for three sizes of knobs. It was determined
that performance (or output) increased rapidly with increasing distance
between knob edges up to one inch distance, and beyond the one inch dis-
tance, performance increases but at a decreasing rate. Here we see the
notions of increasing and decreasing marginal productivity. (It happens
that at least in the illustration given by McCormick, if not by the
original investigators, marginal productivity begins to decrease at a
smaller distance than one inch, i.e., 3/4 of an inch.)

McCormick then goes on to report that when comparisons are made
between knob centers, rather than edges, performance is more nearly
error-free for 1/2 inch diameter knobs than for the larger knobs. (Un-
fortunately this is not apparent from the results portrayed by McCormick,
if not again by the original investigators, but this is of no great con-
cern for this paper.) What is of interest for this paper is based on
the data shown, performance is about the same for the three different
sized knobs when the distance between knob edges is one inch. Also of
interest is that when the distance of knob edges increases to 1-1/4
inches, the larger knobs yield greater performance, and when the dis-
tance increases even further, say to 1-1/2 inches, performance by the
three different sized knobs gets closer together once again. This is so
because between the distances of 1-1/4 and 1-1/2 inches, the marginal
productivity of the largest size knob is not just decreasing but is

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negative, i.e., total productivity is decreasing.

The observations just offered relate to another important economics notion, i.e., the marginal rate of technical substitution between factor inputs. This is the amount of any relevant factor needed to sustain a given output when another factor is decreased by one unit. It may be viewed as a technical trade-off function among inputs. In the "knobs" example and similar contexts in hum.. factor analysis, this does not appear to be directly addressed.

The notions discussed thus far are implied in various degrees in human factors analysis. However, they do not appear to be utilized ex-plicitly or with sufficient precision. The tools of economic analysis can be used for these purposes and this applies to topics just discussed and those to he discussed.

There is another notion tied to the multi-product production func-tion which is of some value for the problems at hand. This is the mar-ginal rate of product transformation which is represented by the amount of one product or service which can be obtained if the output of another product is decreased by one unit, given that the level of all factor in-puts are at a designated constant level. In the context of designing a ship system including its human and physical capital, in practice the implied trade-off of products presents varying degrees of difficulty depending on how products are to be characterized or defined. Two different products may relate to two different missions which present difficult measurement problems with regard to output. The different products may relate to the same mission but may be directed at, say, speed and firepower, which present somewhat easier measurements problems. Another possibility may be maintenance and operations. Still another

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set of alternatives, which may pertain to some sub-system, is speed and accuracy. These various sets of alternative combinations of outputs represent different questions which may be answered in terms of examinations of marginal rates of product transformation, i.e., given some constant level of factor inputs. It is important to note that for some other levels of factor inputs, the marginal rates of product transformation may be quite different. This will be determined among other things by the amount of redundancy and alternatives of physical and human inputs.

In examining the human factors literature as it relates to the production function, one sees that great emphasis is placed on detailed micro-level combinations of man and equipment. While this is necessary to ultimately assess the interaction of man and equipment on the reliability or other effectiveness measures of the system, there appears to be an open and unresolved question as to human factors strategy for design of ship systems (including equipment and manpower) for the future. Using the jargon of the trade, attention is directed to how to "human factor" an equipment or possibly a sub-system, but little or no attention is given to how to "human factor" a ship at the very preliminary design stage. This is not to be confused with the attention given to the preparation of manning documents at the preliminary design stage which, at most, bears an implicit relationship to the behavioral and physiological aspects of the relations of humans to equipment.

Among the first and very important questions is the feasibility of attempting to "human factor" a ship at the preliminary design stage. It is suggested that to the extent that human factors engineering is not applied at this very early stage, the effectiveness of human factors applications becomes minimized at later stages of design and development.

Hence it is at this stage where there should be an initiation of an interdisciplinary approach to human factors integration. From the point of view of the economics discipline, the formulation of the production function and associated notions should be of value. This cannot be limited to the notions discussed earlier with respect to production theory, nor can it be limited to production theory per se. Augmentation of production function formulation should include viewing a ship as a set of interdependent activities. Also there must be the introduction of cost functions, which have yet to be mentioned.

At the very early stages of design of a ship there is relatively little detailed equipment specification, but there must be some determinations of functions to be performed to achieve mission objectives. Each of these functions may be viewed within the concept of a production function and include some estimates even in aggregate form of man and equipment combinations which may produce the required function. If this can be done, the associated notions can be introduced, e.g., trade-offs of man and equipment, trade-offs of number of men with different occupations and skill levels, trade-offs of different equipment, etc. This is no doubt easier said than done, but represents an opportunity to be tried by an interdisciplinary team. An example which may or may not be appropriate is to take a function, such as fire control, and determine the numbers and amounts of different skill levels which may be combined with different computer configurations.

There is an important methodological question as to what is the best way to characterize a ship's functions so as to permit reasonable estimates and analysis of factor productivity, and various types of technical trade-off analyses. A major consideration here is one that

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is taxonomic in nature. That is how to classify the functions in order to maximize independence from each other. It is sufficiently difficult to examine the relationship of factor services contributions to some reasonably defined single function output. If one or more large equipment aggregates or manpower aggregates are required for two or more functions, major difficulties will emerge in assessing attributions of amounts of factors to outputs.

If only by way of example, we were to give attention to a fire control system, one may then estimate a general system of equipments and estimate performance with alternative levels of manpower and skill mixes. The important point is to attempt to arrive at these estimates prior to exact specification of individual equipments or individual task analyses. Obviously as the design and development stages continue over time, the initial estimates will require revisions and other considerations will have to enter the process. An example of another consideration is the personnel training requirement to operate the equipment. In fact, a process such as training may be considered as a factor input incorporated in the production function. Certainly there must be some trade-off function between level and amount of personnel training and alternative equipments and/or alternative skill levels.

An example of a very different kind of consideration which may affect human factor analysis is the assumed maintenance and repair policies. A shipboard modular replacement policy will have a different impact on necessary personnel than a policy calling for individual repair parts replacements. There does not appear to be any evidence as to where the implied trade-off may be considered at the preliminary design stage. There is even the question of feasibility of these alternative policies.

For example, the consequence of a modular replacement policy may be insufficient storage space for the modules. The consequence of a repair parts replacement policy may be the need for more personnel than the ship can handle with reasonable habitability standards or require a skill mix which may result in less operational effectiveness. If considerations such as these are not given appropriate attention at the initial design stage, the possibility of obtaining improvements in the later stage is minimized. These are pertinent issues for a human factors integration. Following a discussion of cost functions, there will be additional discussions of systems production functions and related notions.

4. Systems Functions and Costs

In the discussion thus far nothing has been said about costs. This is not to minimize the importance of costs, but rather serves conveniently to emphasize that cost analysis must be related to and, in fact, based on the production function. It has been observed that in the human factors literature, while some of the economic concepts of the production function are used at times at least implicitly, even less analysis involving costs are considered. Where, for example, trade-offs are considered, these are most likely to be technical trade-offs as discussed in the previous section. However, in many of the most important applications of human factors analysis, the appropriate objective is minimum cost combinations of men and equipment.

A few of the most basic and important formulations of costs may be discussed very briefly. This may most easily be accomplished by assuming the case of producing a single product or service. This can be extended to the multi-product case.

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In formulating a cost function, which for purposes of simplicity will be taken to be a linear function, the basic data consist of the production function and prices of the factor inputs. Hence, given the following production function:

$$0 = f(X_1, X_2, \ldots, X_m)$$

the resulting cost function is

$$C = P_1 X_1 + P_2 X_2 + \ldots + P_m X_m$$

where P_1 is the price of the ith input, X_1 is the quantity of the ith input, and C is the cost of the product produced.

The typical economic problem is to minimize C for a designated output level 0 . It should be noted that the problem is to minimize cost <u>subject</u> to the production function at a designated level of output. It is not merely to minimize cost. Two economic problems are to minimize cost subject to a production function or to maximize output subject to a cost function. The task of minimizing cost and maximizing output simultaneously is not possible.

Returning to cost minimization, typically accomplished with the Lagrangean multiplier, two important conditions emerge in achieving cost minimization. These familiar conditions are (1) the marginal productivity of the last dollar spent in each factor input must be equal, and (2) the ratio of factor prices for any pair of factor inputs must be equal to the marginal rate of technical substitution among the factors.

These conditions and others which come about in utilizing cost and productions in the theory of the firm (e.g., for profit maximization) should be useful in human factors integration. However, this writer is struck with the need for other considerations which may be judged to be

more useful for the present state of the art in human factors integration.

One important proposition is that the price of a factor input is not necessarily equivalent to its cost. The cost of a factor is a function of its price and productivity. If the price of some factor a is twice that of another factor b but the productivity of factor a is ten times more productive than b , the cost of a is clearly less than b . Although this is a rather obvious proposition, it is too often neglected. This proposition augments one of the first priority needs, i.e., productivity measurements, be it strictly for technical evaluations or for cost analysis.

Another important point is somewhat more complicated. This is to obtain a completely specified production function. Earlier it was suggested that the personnel training process may be included as a factor input. If viewed in this manner, the cost of this input may clearly effect the best combination of man and equipment for a particular function or output. There are alternatives for accounting of this kind of service. One is to consider training as a contributing sub-system, thereby not including it within the ship's production function, but being sure to include the cost of training an individual in the price associated with the individual's service. These so-called indirect costs, such as training, can be extremely significant, particularly for highly skilled technicians. Depending on actual personnel turnover rates, these costs can exceed direct financial compensation rates for selective skills. It is possible that similar conditions may pertain to physical equipment when back-up maintenance and repair costs are considered.

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A related issue to the one just discussed is the question of the time horizon for which optimum man-equipment combinations may be determined. If the expected life of the ship system is five years, the best (i.e., least cost) combination of man and equipment may be quite different than a system with an expected 20 year life span. Also, of course, there is the importance of the degree of utilization of the system within any particular time period on the best combination of men and equipment. This latter point gets much closer to the domain of human factors engineering, where attention spans may have a considerable affect on human performance. Manning a particular equipment under "battle stations" conditions for a 24-48 hour period will require different man-equipment combinations than manning an equipment for 16 hours a day over a 60-90 day period.

What this discussion is intended to suggest is that all cost elements be identified at the preliminary design stage and that human factors integration be applied for estimating a least cost combination of the ships' factors. In the literature examined by this writer, human factors tasks approach this goal but do not seem to achieve it.
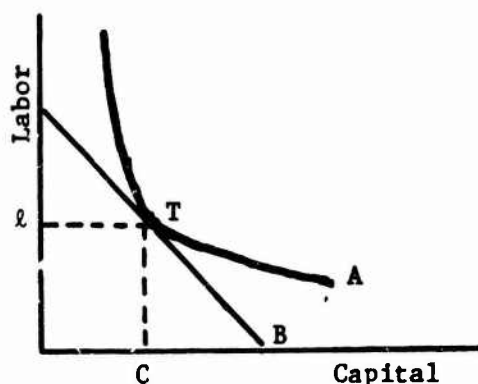
5. More Practical Issues Involving Production and Cost Functions for Human Factors Integration

By way of amplifying the preceding discussions and indicating some strategies for analysis, some elementary economic methodology will be discussed.

Production and cost notions must be brought together. Earlier reference was made to technological substitutability between factors, e.g., capital and labor or trade-offs of labor and capital for a given

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level of output service. There remains the task of deciding what the trade-off should be and to make this determination, the relative costs of the factors must be considered. This is shown in Figure 1.

Figure 1

In Figure 1, curve A is intended to represent the technical trade-offs or substitutability of labor and capital for a given output. Curve B shows the possible trade-offs in expenditures for the two factors where every point on the curve represents the same total expenditures and the slope is determined by the relative prices of the two factors. In this particular illustration, the combination of ℓ units of labor and C units of capital represented by T represents the most efficient combination of factors.

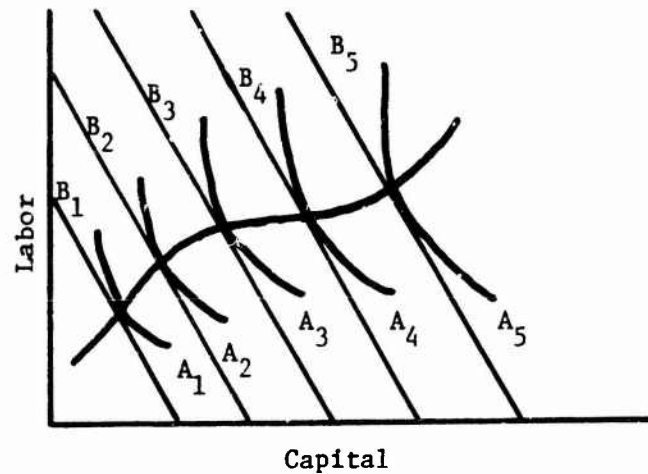A second elementary but major point is illustrated in Figure 2.

Figure 2

Capital

Figure 2 is based on observing the technologically efficient com-
binations of labor and capital for different levels of output. A_1, A_2, ...
represent the technical trade offs for each of the levels of output. B_1,
B_2, ... represent the different levels of total expenditures for the
various levels of output. It should be noticed that the best combina-
tions of input varies as output changes. This is the manner in which the
optimized cost function is developed. Of at least equal importance, it
should also be noticed that if the relative prices of labor and capital
change, the optimized cost function will also change. This change will
be due to the changes in relative prices and the fact that the expendi-
ture curves will be tangent to the technology curves at different points.

It is this type of economic analysis which must be embedded in
human factors engineering. It is clear how important it is to estimate
relative prices. Also it should be clear that it is extremely important
to account explicitly for different output levels. In the case of analy-
sis pertaining to ship systems, these different output levels may be in

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terms of parameters relating to readiness, such as speed, firepower, etc., or may even be viewed as different time frames for ship operations, e.g., different combinations of men and equipment may be necessary for a 90 day independent endurance period vs. a 48 hour combat situation.

It is of some importance to return to analysis relating to the production function, at least for purposes of amplification, and also as a guide to implementation of analysis for human factor integration. For purposes of this exposition, it is useful to draw on a very popular type of production function in economic analysis, i.e., the Cobb-Douglas production function. This function may or may not apply to every situation but it has useful properties and can serve well as an illustration.

The Cobb-Douglas production function is a non-linear function relating capital and labor to output. In general terms it is as follows:

$$O = AL^{\alpha}K^{\beta}$$

when O = output
A = constant
L = labor input
K = capital input.

The function is non-linear because, for example, given constant levels of capital inputs, the relationship of output to labor inputs will be non-linear, i.e., output will increase at a decreasing rate as more labor units are applied. This is equivalent to noting that marginal productivity decreases as inputs are increased.

The parameters α and β are also of great importance for interpretation. These parameters are referred to as elasticities of output with respect to each of the factor inputs, i.e., α is elasticity with respect to labor input and β is elasticity with respect to capital input. For this function, these elasticities are constant. Since each

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elasticity is taken to be less than unity, marginal productivity of the factors will decrease. These parameters are particularly useful for evaluating returns to scale. More specifically, it is the sum of these parameters which indicate returns to scale. That is, if $\alpha + \beta < 1$, $\alpha + \beta = 1$, or $\alpha + \beta > 1$, we have decreasing returns to scale, constant returns to scale, or increasing returns to scale, respectively.

From the above it may be seen that once a production function has been determined, it is possible to determine and interpret its important properties. The parameters noted above indicate the kinds of properties one would use to learn in any context involving production of items or services and this includes viewing a ship system in this manner.

Associated with production function analysis is typically the need for statistical verification and implementation. The data base may include actual empirical observations, simulated test observations, or engineering judgments. If a relation such as the Cobb-Douglas function pertains, the statistical examination would include converting the function into logarithmic form so as to estimate a linear function, i.e.,

$$\log 0 = \log A + \alpha \log L + \beta \log K + \log \mu$$

where μ refers to an "error term" for estimation purposes. Given information on output and factor inputs, one would attempt to estimate the parameters via some form of regression analysis.

Earlier in this report, it was noted that human factors engineering appears to be principally concerned with designing equipment giving due consideration to human capabilities and limitations. Also at times there is consideration given to the best use of humans for the operation and/or maintenance of determined equipment design and function. It

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seems clear and fundamental that neither direction by itself is adequate. The kind of information represented by Figure 2 should be sought, i.e., technological trade-off data and relative costs of the factors. The ability to analyze these trade-offs and implement the most efficient factor combinations depends on the stage of design and development of the ship system. Once the system is beyond the preliminary design stage, the possibilities of trade-offs become limited and one can only resort to the best use of personnel for fixed equipment configurations. Hence, for human factors integration engineering to be most effective, it is essential that this process be embedded in the preliminary design stage of the system. Also while it is usually only implicit, it is essential that expected operational trade-offs be analyzed simultaneously with design trade-offs. For example, the possible personnel-equipment trade-offs should be expected to vary as a function of planned independent endurance periods for the system. This carries with it many implications, not only for manning the equipments operationally, but also the need for explicit logistics support policies such as maintenance, re-supply, etc. In short, a truly integrated logistics support plan based on trade-offs in many dimensions.

6. Ship Manning

A review was made of the issues and procedures utilized for arriving at a Ship's Manning Document. The ship system used for this purpose was the DD 963 Class Ships. The source material was [4].

Prior to a discussion of the procedures, it may be well to view briefly what have been offered as two alternative approaches to manning, which are discussed in [7, pp. 259-60]. The first approach referred to

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as the "Bottom-Up Method" is where the design engineers stipulate the individuals needed to operate and maintain the equipment. This is displayed in a ship (or shore) manning document and through a summing up process, total Navy manpower requirements are determined.

The second approach is the "Top-Down Method" where the total manpower supply is determined by legislation(and/or supply conditions as discussed briefly in the early part of this report) and this supply is allocated as efficiently as possible to meet the Navy's operational and maintenance requirements. While the "Bottom-Up Method" is the dominant practice, in [7] there is some preference given to the "Top-Down Method."

The case used for the discussion in this section, i.e., the Ship's Manning Document for the DD 963 Class is clearly an illustration of the "Bottom-Up Method."

The basic derivation of the manning plan was to take the design of the ship and the Navy's operational requirements as givens and then to determine the size and composition of the ship's crew. In the manning plan, the lack of explicit trade-offs between equipment design, personnel, and operational requirements cannot be over-emphasized.

Considerations are given to maintenance manning (using peak maintenance workloads rather than average workloads), operational requirements (e.g., watches) under various readiness conditions, other personnel requirements such as Utility Tasks (e.g., messengers) and administative support personnel. The essential result of this is a manning display with the kinds of information elements as given in Table I1.

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Table II

Manning Requirements

1) Billet Identification
2) Billet Number
3) Billet Title
4) Rate
5) NEC
6) Operational Manning Requirement (Weekly Hours)
7) Maintenance Manning Requirement (Weekly Hours)
8) Other Requirements (e.g., Utility Tasks, Training) (Weekly Hours)
9) Allowance: Productivity Allowance
10) Total Weekly Hours

It should be noted that the operational manning requirement is differentiated between a "battle station condition" and an independent endurance period. As would be expected to be the case, there are significant differences in personnel requirements between these two conditions. However, there is little or no evidence as to analysis pertaining to alternative endurance periods.

Maintenance manning requirements are differentiated between preventive and corrective maintenance. The meaning of the "productivity allowance" is not clear except that it appears to account for less than maximum performance.

The whole spirit of the manning approach is that it takes on a deterministic approach to determining billets as a function of a specific set of equipment designs. It does include an attempt at estimating performance curves, i.e., the output of equipments as a function of number of operating personnel which, as may be expected, are some version of an "S" curve.

The use of the estimated "S" curves is not clear. From these estimated curves, estimates of the marginal productivity function can be derived and these may provide a useful comparative analysis among the various equipments. This would be particularly useful in a situation including severe personnel constraints, i.e., allocating scarce personnel so as to maximize overall productivity. Also of at least equal importance, an opportunity is missed in relating the marginal productivity with marginal costs of personnel, permitting more efficient personnel assignments.

While improvements such as those noted above should be attempted and would involve relatively little additional effort, a few of the larger issues discussed previously must be addressed. These are the lack of technological trade-offs between equipment and personnel; the need to derive production functions and related parameters; and the need to arrive at optimized cost functions.

There is another matter discussed earlier which should be considered, i.e., the taxonomy of ship sub-systems. As evidenced from the DD 963 plan, the ship is viewed in terms of its administrative units, e.g., Navigation, Weapons, Engineering, etc. This may or may not be an appropriate classification or framework in which to perform trade-off and cost analyses. It depends on inter-dependence among the ships' sub-systems. The production and cost functions should be as complete as possible in their representations of what is required to achieve a particular sub-system's output or service. Some attention should be given to the creation of a classification of sub-systems which would maximize the representation of independence of each designated sub-system.

7. The Ship System as a Set of Interdependent Activities

As was just indicated in the previous section, trade-off and other associated analyses should be performed within a framework of essentially independent sub-systems. It is likely that the most accurate representation of a ship system is to view the system as a set of interdependent activities. Models to represent this condition of interdependence are more heroic and complex. Of at least equal importance, the data requirements for implementation of these models are very difficult to satisfy and it will take a long time to develop the information.

It is somewhat premature to be specific as to a particular model or class of models, but a likely need is a variant of a mathematical programming formulation. The kind of condition to capture is where each particular factor input is necessary for a variety of activities, i.e., ship system functions, and for different mixes of outputs, e.g., missions. There have been some beginnings of mathematical program applications to manpower planning problems. A very useful set of papers on this subject may be found in [2].

The results of much of what has been suggested in previous sections of this report must be accomplished before adequate programming models can be formulated (e.g., nature of production and cost functions). However a collateral research effort directed at programming formulations may be appropriate while attempts are made to formulate and implement the neo-classical economic models.

There is the useful goal of using formulations of personnel assignment problems. This is what has become known as the optimum assignment problem. This is the special case of the "transportation problem" in mathematical programming literature. The assignment problem refers

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to the case where there are n tasks to be performed by n individuals
and the problem is to determine the assignment of individuals to tasks
which will maximize total value or minimize total cost.

It may be instructive to use a simple numerical example to indi-
cate the intent of the technique. Take the example as portrayed in
Table III.

Table III

Task Person	1	2	3
a	8	5	3
b	3	2	4
c	6	9	7

The data in Table III may be assumed to represent the dollar cost of each
person performing each task, e.g., person b performs task 2 at a cost
of $2.00. If one wanted to choose optimum, i.e., least cost assignment,
it would be the assignment of c to 1, b to 2, and a to 3. No other
set of assignments would result in lower total cost. Of importance here
is to note that c does not perform task 1 at the lowest cost, but to
arrive at minimum total cost, it is optimum that c be assigned to task 1.
The significant principle here is that it may be expected to have indi-
viduals assigned to tasks for which they are not most suited if total
optimization is to be achieved. Hence working at a detailed micro-level
attempting to assign the best person for each job may not at all be
optimum from a total system point of view.

In order to carry out the kind of procedure as outlined
above in the highly simplified example, one must accomplish what has

been suggested in previous sections of this report in effecting a
"Bottom-up" approach to manpower requirements, i.e., to determine the
unit costs or values to individual man-equipment calculations. Then one
must proceed with a "Top-Down" approach to achieve over-all optimization
of a system. Ultimately it is not one approach versus the other but, in
fact, the necessary use of both approaches to manpower requirement deter-
mination.

8. Concluding Remarks

While there is little evidence of utilization of economic analysis
in human factors engineering, some initial steps are undertaken in this
process, e.g., derivation of performance curves of humans interacting
with a particular equipment design. It appears to be readily feasible to
extend the human factors engineers' analysis to include economic reason-
ing and analysis. In particular, the specification of technological
trade-offs between capital and humans should be embedded in the economist's
cost analysis to achieve ship system optimization. Accomplishing this will
require close interaction among design engineers, human factors engineers,
and economists in order to determine appropriate formulations, substan-
tive information, and means for solutions of optimum manning and equip-
ment configurations.

The most effective stage of design and development for the neces-
sary interdisciplinary approach toward human factors integration is at
the preliminary design stage of the ship system. This is where the
results of factor trade-off analysis can be implemented. If it is done
after this stage, then the engineers and analysts can only do as well as
possible under existing equipment design constraints, and the contributions

of human factors analysis at these later stages can only be marginal at best.

In order to accomplish human factors integration at the preliminary design stage, it is necessary to "human factor" large sub-systems which are not yet specified in detail. This lack of equipment specificity presents both a difficulty and an opportunity. The difficulty stems from the vagaries of equipment design and the opportunity is to approximate optimum ship systems design.

The required economic tools of analysis to create optimized ship systems are not complex but, in fact, are those found in conventional economic theory. As the problems are formulated in a more complex manner, e.g., complete accounting of interdependence of sub-systems, so must the economic task become more complex, but great strides can be made from the need for adding these complexities.

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