A SYSTEM EFFECTIVENESS MODEL FOR SHIP WEAPON SYSTEMS

BY

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Although easy to forget in time of peace the ultimate purpose of our service in the Royal Navy is to contribute to winning a war at sea. To do this our weapons must destroy any enemy when and where required. From E.M. to admiral with varying degrees of understanding we know just how complex a challenge this presents and how enormous is the system of which we are a part. As I sit in my T.S. or M.C.R. or at my damage control station in a great web of events, people and equipment, what is my small contribution achieving? It is helpful for all of us at least to know that there is an answer to this sort of question.

At the other end of the scale, it is vital that those directing the higher affairs of the Navy, operating its flotillas, designing its warships or responsible for manning them with officers and men fitted to fight, should have a clear and comprehensive vision of all the ingredients involved. Ashore and afloat they must be able to see each of the elements which contribute to the primary purpose in its proper perspective and to recognize their many interactions. Within the Navy Department they should ideally be able to quantify them, to through-cost them and then to arrange the overall balance to give maximum effect for money spent. As, for example, they face such a major decision as the optimum choice of platform for deploying air power at sea, they must seek the most cost-effective design of an enormously expensive command cruiser, that which our American friends would say gives the 'biggest bang per buck'.

For those of us concerned with the training of the officers and men responsible for the machinery and weapons of the Fleet, it is necessary that we too should see where our contribution fits in the overall pattern, to design our training to match the other elements and to execute it economically to the standards required. Similar perspectives are needed in their various spheres by commanding officers, project managers, application officers, naval stores officers and 'Jack Dustys', technical authors—indeed all who shape or control any part of the total system.

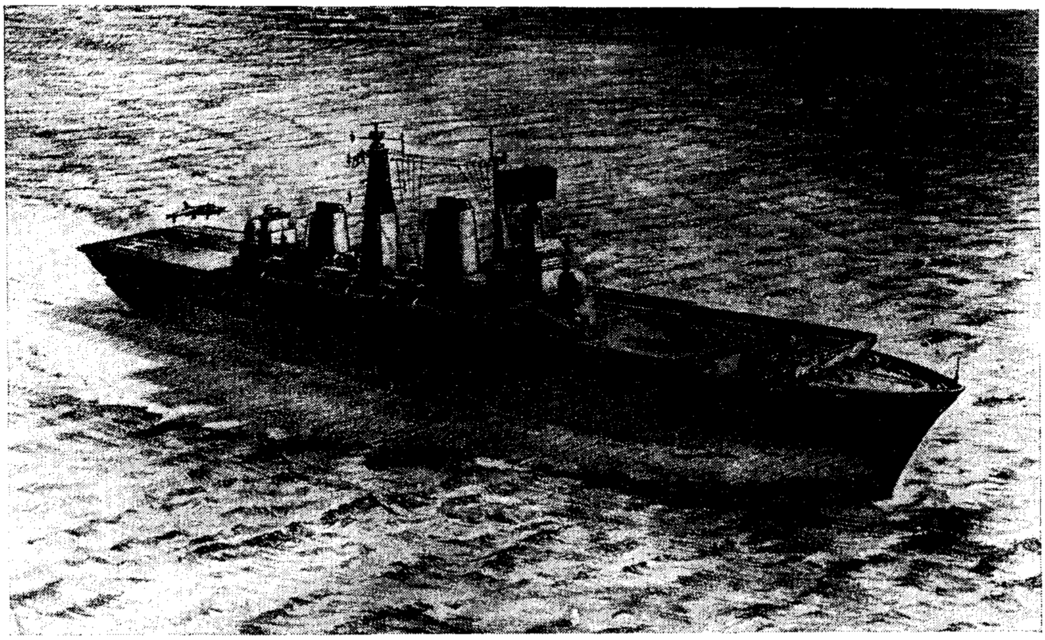

FIG. 1—BIGGEST BANG PER BUCK

Purpose

The purpose of this article is to analyse the factors contributing to effective performance of our ship weapon systems at sea and to show some of their inter-relationships. It will propose a basic System Effectiveness Model.

System effectiveness can be defined as 'a measure of the extent to which a system can be expected to complete its assigned task within a specified time and under specified operational conditions'.

Note: The U.S. term is *systems performance effectiveness*; anglicization can yield a more cost-effective use of words!

Observe that the word 'measure' occurs immediately. It cannot be too strongly emphasized that every attempt must be made to put figures on the parameters identified. What Gallileo pronounced in the 16th century should be written over the desk of each officer on the Naval Staff and project manager in the Procurement Executive:

> 'Count what is countable; measure what is measurable and what is not measurable make measurable.'

This is an ideal, and let us recall that Mr. MacNamara has said: 'We cannot and should not expect ever to develop a complete set of numerical criteria to measure military effectiveness'. 'Ever' is strong, but we must seek to approach the ideal as nearly as possible. If absolute values are elusive relative figures should be sought and in those areas which now defy quantification it is just as necessary to identify clearly the variables concerned if decisions are to be soundly based.

A MODEL

The first step is to break the concept of system effectiveness into primary parameters at the highest scalar level. Three such quantities can be identified:

Performance — P
Availability — A(t)
Utilization — U

They are illustrated in FIG. 2.

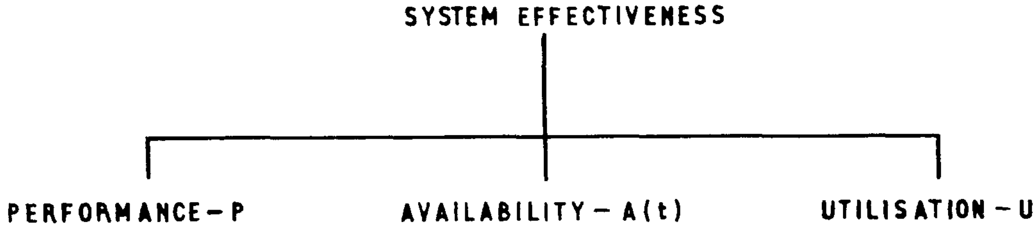

FIG. 2—PARAMETERS OF SYSTEM EFFECTIVENESS

Performance

This is the designed performance of the system. In the more controlled situations, e.g. a missile engagement, it can be expressed explicitly as a *kill probability*. In many other situations it is not readily possible to do this and it may be necessary to rely on a *figure of merit* relative to some standard. The performance of our gunnery systems is commonly measured in an intermediate fashion by establishing a percentage of TTB's and this can be done with some precision. Propulsion machinery performance can be measured in terms of shaft horse power and fuel consumption, radars by use of standard targets, etc.

Much planned maintenance is devoted to upholding the specified performance standards.

Availability

To realize designed performance, it is necessary that the system should be available for use at the place and time required. Various definitions of availability will exist depending on whether or not the system is maintained and on the duty cycle adopted—the short mission of a fighter aircraft must, for example, be treated differently from the continuous base-load operation of a main generator.

With seaborne systems the specified operational time can vary widely. When considering Fleet Availability (3), there may be up to several years between one operational date and another. At the other end of the spectrum it may be necessary to consider a period of a few days with scheduled downtimes specified in minutes and intermediate deployment durations, e.g. 28 days, are common. Times between failures are typically measured in hundreds of hours and times taken to repair in hours or minutes.

When the operational conditions can be regarded as stable it is often convenient to consider *steady-state availability*, sometimes known as *up time ratio* (UTR), which is a probability point estimate defining the proportion of the operating time that the equipment is providing its designed performance.

Those concerned with data collection and processing should note particularly the very wide range of times which must be handled. The units of measurement best suited to the various decisions to be taken will therefore also vary widely—typically from minutes to weeks; in such cases the accuracies needed would range over four orders of magnitude. It is most unlikely that any single type of extraction system could cover such a span effectively, and certain that no one system can cover it economically.

Availability may be further broken down into the two components of Reliability and Maintainability—see later.

Utilization

Given that the system will provide the necessary performance and given that it is available when required to do so, it must be properly used; the *utilization factor* expresses the probability that this will happen.

Mathematical Note

The mathematically inclined will note that the combination of these three factors can express the compound probability that the task for which the system was designed will be achieved in specified conditions within a specified time. It is the product of the three (assumed independent) probabilities identified and

$$SE = P.A.U$$

The simplicity and essential validity of this statement should not seduce us into thinking that a printout of victory probability is within our grasp!

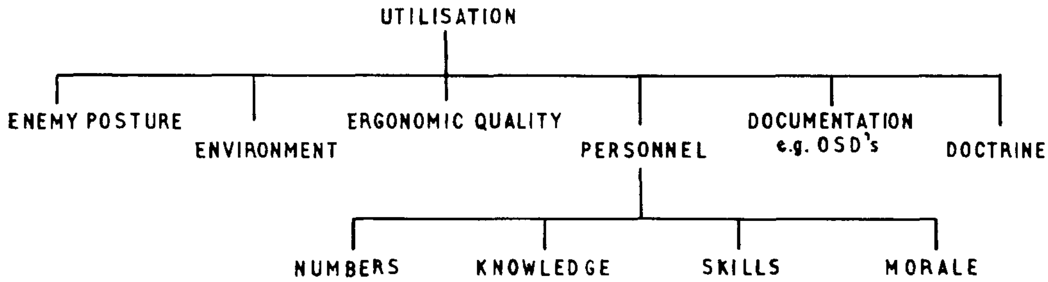

FIG. 3—COMPONENTS OF UTILIZATION

Components of Utilization

The factors governing the probability that the system will be used effectively are set out in FIG. 3.

Enemy posture is fundamental since this reacts on our own decisions and actions. The quality and quantity of his ships and weapons, the morale and training of his men, etc. must be studied, and the old adage 'know your enemy' is even more true in this scientific and computerized age since we can today program our system response to embody the characteristics of his weapons.

System effectiveness was defined as being measured 'under specified operational conditions'. The *environment* factor is indeed specific and practical since, for example, haze may affect the use of optical systems and anomalous propagation that of radar; temperature, sea states, the ECM environment, etc. must be taken into account. Surrounding conditions will also react on maintainability (q.v.) and on personnel, possibly for some of us through *mal de mer*!

Everyone knows intuitively that some equipments are easier to use than others, some cars easier to drive, and in demanding conditions such a factor can be crucial. The man/machine interface must therefore be studied and, although a specialized aspect of design, the *ergonomic quality* of the system deserves mention for its contribution to utilization.

Good *documentation* of the user function must be available, both of the enemy posture and as to doctrine and drill; this is necessary for initial and also continuation training. Recent work by the Naval Manpower Utilization Unit in the application of logic flow analysis to drill procedures (operational sequence diagrams) contributes to this end.

The strategic and tactical *doctrine* under which the battle is fought will have been analysed previously and rehearsed in synthetic situations ashore. There are many examples in warfare of faulty doctrine bringing defeat and the not-uncommon gibe that the military man is always 'fighting the last war' is a reminder of the importance of clear doctrinal thinking. In modern warfare, doctrine too will probably be programmed as well as written in FOTI's and the like, and whether the principal warfare officer of the future is the master of his software or merely its monitor is in this context an issue of importance. If he becomes simply a dispenser of pre-digested situational thinking the flexibility of use of the system will be degraded and the utilization factor lowered; the converse will also apply and a proper balance must be struck.

The final factor in utilization is *personnel* and this ingredient may be seen as having four elements:

FIG. 4—THE MOST IMPORTANT SINGLE FACTOR

Numbers—our ships must be manned with the right number of officers and men under action, defence and damage conditions.

Knowledge—each man must have the requisite level of knowledge required to do his job: it may be of RT jargon, of the fire-main layout, of the ship's sea-keeping capacity or of the complicated workings of an action data automation system.

Skills—Knowledge without skill in its application is useless and a high level of manipulative skill is generally necessary for a user. We all know the meaning of *drill* . . a basic form of skill acquisition nonetheless crucial today. Further types of skill are discussed below in the context of maintenance.

Morale—given that the ship is manned with the right numbers of sailors possessing the knowledge and skills required to use their weapons effectively, they must be able to continue so to use them in face of difficulty, fear, pain, hunger, etc., in short under all the constraints which may exist in a man-of-war. A man's ability to produce his optimum performance in such conditions can be assessed by the state of his morale and here one can do no better than to repeat the famous axiom of Field-Marshal Montgomery:

> *'The morale of the soldier (sailor) is the most important single factor in war'.*

The factors conducing to high morale are well known; *leadership, motivation* and *authority* are the functions necessary to ensure it.

Components of Availability (FIG. 5)

Its two basic components are:

Reliability — S(t)
Maintainability — M(t).

Reliability—S(t)

Reliability is defined as 'the probability that a system will survive for a specified period of *time* (or more) when providing a specified performance under specified operational conditions'. It is commonly called the *survivor function* and hence the symbol S(t) is used to describe it, conveniently leaving 'R(t)' for *repairability*.

Reliability is an inherent system or equipment characteristic which again the designer can control or certainly influence. It is possible to determine a *reliability function* for each equipment; this is the cumulative distribution of

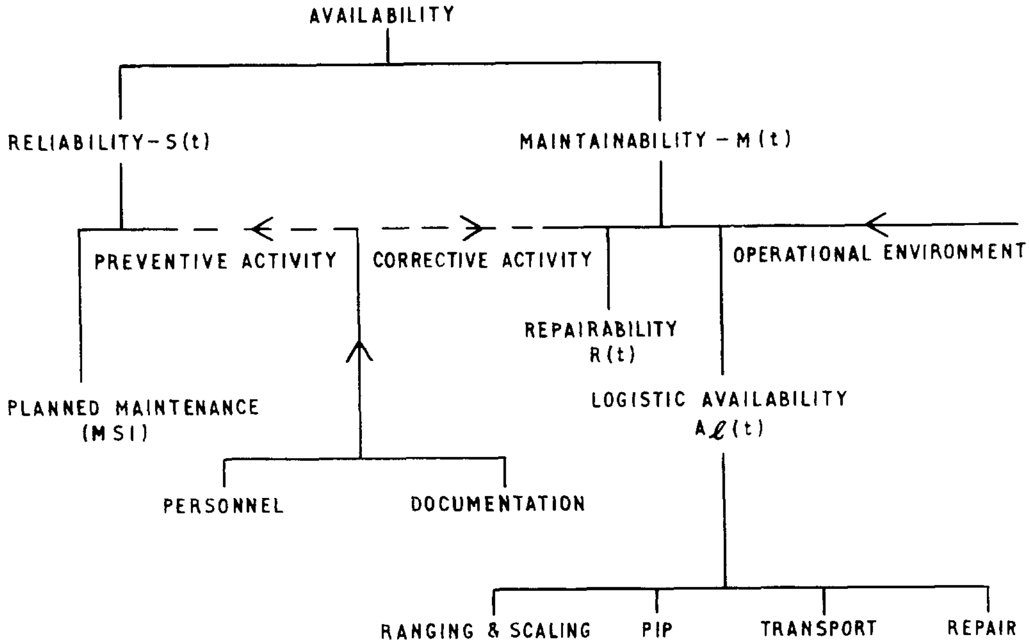

FIG. 5—COMPONENTS OF AVAILABILITY

times to or between failure and its mean is known as *mean time between failures* (MTBF). The reciprocal of MTBF is *failure rate* (λ).

The 'specified operational conditions' include the amount and quality of the upkeep given to the equipment and planned maintenance therefore appears at the next scalar level as an ingredient of reliability. Attempts have been made to quantify this factor and here the idea of a *maintenance support index* is sometimes used.

Maintenance support index or maintenance ratio has been defined as:

$$\frac{\text{Total active maintenance manhours} \times 1000}{\text{Total operational hours}}$$

It varies typically between 0·25 and 10.

Reliability also depends on factors such as the documentation available and the characteristics of the personnel conducting the maintenance. These factors affect the quality of both the premeditated and unpremeditated work.

Maintainability—M(t)

Maintainability is generally defined as 'the probability that a failed equipment will be restored to the operational condition in a specified down *time* (or less) when the repair is carried out under specified conditions'. The specified down time is sometimes called the *maintenance time constraint* and here again it is necessary to specify conditions if the related data is to be meaningful. In practice, this means the use of specified tools, test gear, documents, etc. by maintenance men of the specified calibre working in specified environments and with known urgency. The latter condition can have significant effect on repair time—an operation, for example, carried out by a chief artificer to meet the deadline of a firing slot could take many times as long if given for experience to an apprentice in harbour. Data relating to emergency repairs carried out to a lowered standard will also have to be excluded statistically.

A *maintainability function* can be determined for each equipment operating under the specified operational conditions; this is the cumulative distribution of down times and its mean is known as the *mean time to repair* (MTTR). The reciprocal of MTTR is *repair rate* (μ).

Relationship between Reliability, Maintainability and Availability

Since, when considering steady state availability, total time equals up time plus down time, this triumvirate (the . . . ilities!) is inter-related as follows:

$$\text{Availability} = \frac{\text{Up Time}}{\text{Up Time} + \text{Down Time}}$$

$$= \frac{\text{MTBF}}{\text{MTBF} + \text{MTTR}} = \frac{\mu}{\lambda + \mu}$$

Maintainability of equipment is dependent on factors which are partly inherent and partly external. The first is:

Repairability—R(t)

Repairability may be defined as 'the probability that a specified repair action will be completed in a specified active repair *time* (or less)'.

Like reliability, repairability is therefore an inherent characteristic of the equipment and its installation; it is governed by factors such as access, test facilities, tools and material provided, etc. We know to our cost of cases where Repairability has been lowered because, for example as in the 4·5 in. Mk.6 Turret, access to a resetter magslip could only be achieved by removing a steel plate secured by 27 nuts!

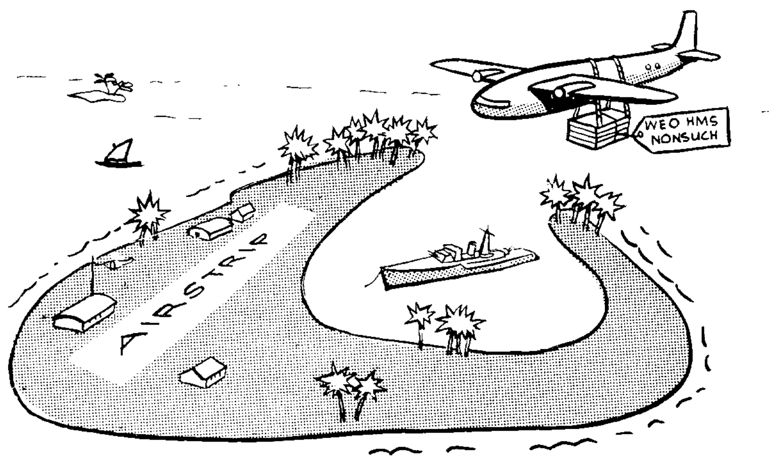

FIG. 6—LOGISTIC WAITING TIME

Equipment may be designed for a high degree of repairability but if the necessary skill or spares or opportunities to work or test are not available when required it will remain unserviceable. The difference then arising between down time and active repair time is called *waiting time* and it may arise for reasons of administration, logistics, etc.

It is necessary therefore at this level to consider the further factor of:

Logistic Availability—Al(t)

Considerable thought is given to provision of spares at the right place and time but this does seem a situation which could be more precisely analysed, indeed no definition of logistic availability is known. One could be offered as: 'the probability that any specified item of stores or spare gear needed for repair in a mission of duration T is made available within a specified *time* (or less)'. Alternatively it could be stated as 'the proportion of time during a mission of duration T that all items of spares needed for repair were made available within a specified *time* (or less)'.

Logistic availability in its turn depends on four factors:

Ranging and Scaling—this is the process of providing the correct range of spares at the various places where they may be needed and then arranging the scale of provision to match the need.

Packaging, Identification and Preservation (PIP)—These processes seek to ensure that the item nominated is maintained in good condition during storage and that it can be found readily when required by the user.

Transport—Since all spares cannot be carried on board, an adequate system of transportation by land, sea or air is also a component of maintainability.

Repair—Defective items replaced may in some cases be repaired on board and recycled, thus adding to effective stocks. The nature and sophistication of much modern equipment is tending to reduce this possibility.

Operational Environment

A feed-in from the operational environment appears at this point. It may not be possible, for example, to gain access to engine-room equipment because of the need to keep steaming, or to test a system because radio silence must be kept. Operational waiting times may therefore also arise to widen the gap between intrinsic repairability and realized maintainability.

Personnel and Documentation

Personnel and documentation are two key factors contributing to upkeep, i.e. both to planned maintenance activity and to repair or corrective work. Their elements are illustrated in FIG. 7.

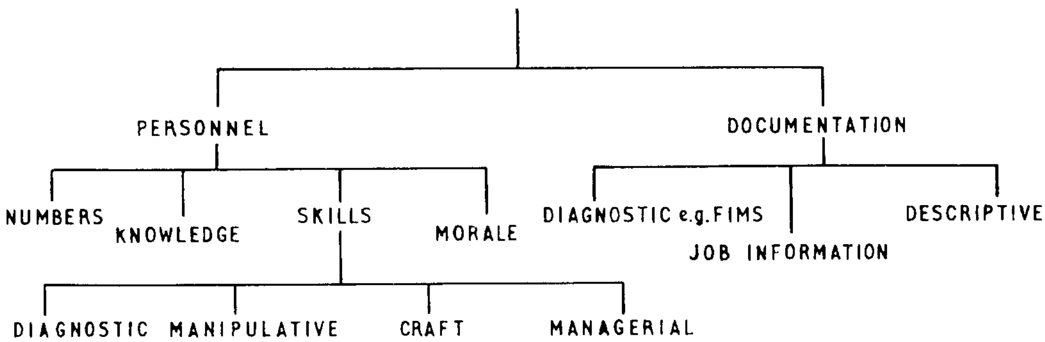

FIG. 7—PERSONNEL AND DOCUMENTATION

Documentation is needed for:

Diagnosis—it is here that work in H.M.S. *Collingwood* on the Functionally Identified Maintenance System (FIMS) has a significant and immediate relevance.

Giving Job Information—Job information cards were produced some years ago but fell out of use; they have recently been revived and, while mainly applicable to the premeditated type of maintenance, can make a contribution both to Reliability and Maintainability.

General Description—this is essential as a continuing basis for understanding and education and for dealing with novel fault conditions.

Personnel

The factors contributing to the overall personnel input to upkeep are essentially the same as those noted under Utilization. We must man the ship

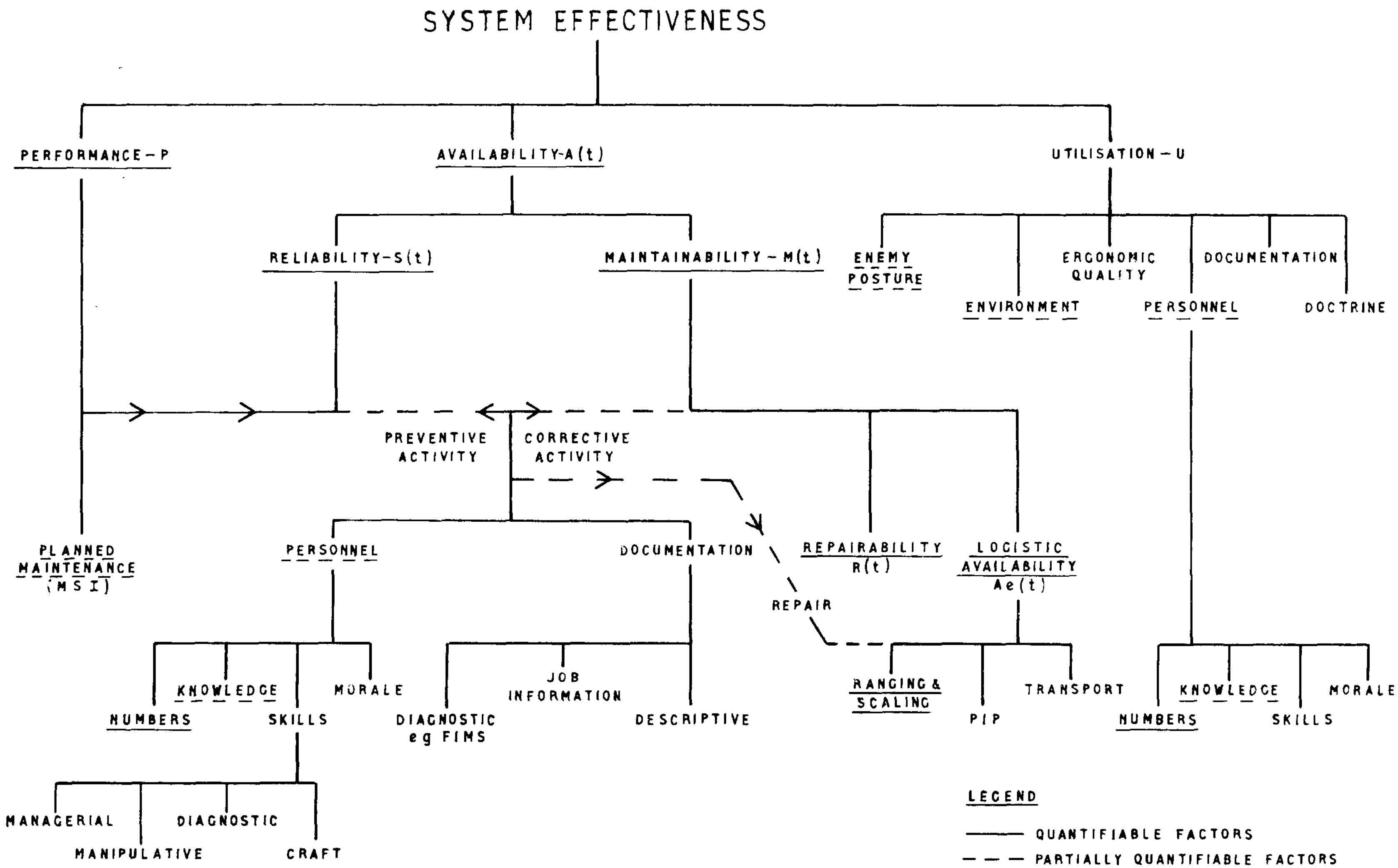

FIG. 8—A SYSTEM EFFECTIVENESS MODEL

with the correct number of men and these men must have the requisite level of knowledge. Their necessary skills however are more sophisticated and have four components:

Diagnostic, i.e. the ability to think through problems and identify faults;

Manipulative, i.e. skill in handling tools, in setting up equipment and in adjusting it;

Craft, i.e. the skill of hand necessary to carry out planned and unplanned tasks;

Managerial, i.e. the ability to arrange and use resources to best advantage in achieving a desired aim.

Morale is equally important in this field although it should be noted that the temperamental and psychological requirements for the sustenance of a maintainer's role are often different from those of a user; this is a matter which seems to require investigation.

The Overall Model

The overall model is built up from various components discussed and is shown in FIG. 8. In doing so, it is important to remember that it represents the salient factors only and to keep the scalar levels correct.

SOME DISCUSSION ARISING

Each interested party will use such a model from his own point of view and expand and interpret it for his own purposes. The following points are offered for disussion but are in no way seen as comprehensive.

The Procurement Process

During the lengthy process from concept formulation through statement of staff requirements and proceeding to design specification and development, factors such as performance, reliability and repairability will be determined. They will ideally have been chosen so that the overall system offers optimum quality, i.e. that balance of attributes agreed as giving maximum system cost effectiveness.

The production, inspection and installation phases must be conducted so that this quality is realized in the ship setting, i.e. that it is followed through in quality of conformance. The various factors requiring attention during procurement are monitored in the activity shown as *quality assurance*. The Navy has been well in the lead in this field through ideas such as GRAQS and SCITS and the growing impact of the Defence Quality Assurance Board is now significant and encouraging. In parallel, the other contributory functions such as manning, training and storing will be proceeding.

The values and states of the model can then be seen as representing the state of affairs at a given point in time, e.g. on commissioning; changes in parameters may subsequently be made (with varying time constants) by post design processes.

Definitions

Reference (3) laid useful ground by defining a series of terms relevant to system effectiveness and among them are definitions of availability referred to earlier. In this Instruction, reliability and maintainability are defined subjectively although the option of expressing maintainability 'as a probability' is offered. It can be seen from the model, however, that since these quantities are the components of availability they too should be defined probabilistically and amendment is therefore needed to DCI 926/70; the definition of *predicted reliability* is in fact that which should preferably be used for *reliability*.

It is noted also in passing that the definitions there given for MTBF and MTTR, while valid up to a point are potentially misleading. These statistics must be recognized as the means of their respective distributions and not simply as deterministic ratios. The stated definition of MTBF is often called *mean life* to emphasize this distinction.

Quantification

It was emphasized earlier that wherever possible the parameters of the model should be given numerical standing. Those which it is possible to quantify have been underlined and where partial quantification only seems possible broken lines are used. What must be confessed as depressing is our apparent lack of progress in this direction. A key problem is that of data and there exists a pressing need to gather a necessary minimum of information so as to quantify the various elements in the model and attach confidence limits to them. As Commander Venton of H.M.S. *London* (whose work in this field still remains the best our Navy has produced) urged in 1967 that we really must *inter alia* take 'the essential step of establishing with reasonable accuracy the defect (and repair) rates for each individual equipment'. Techniques to enable this to be done are available. (Refs. 1 and 2.)

The SUIS project is operating to this end and it is much to be hoped that its efforts will lead to the clothing of such a framework with numerical reality in specific cases of need and importance.

User/Maintainer

It is of interest to observe that when stated in general terms the essential ingredients of the contribution of Personnel to utilization and to maintenance are the same. A fruitful line of investigation into user/maintainer policies might therefore be to seek to match the requirements for knowledge and skills in identifiable user and maintainer tasks. Some pattern of optimality might be revealed; alternatively incompatibilities could be shown. As noted earlier the psychological demands of these roles may differ.

Logistics

Ranging and Scaling

Reference (4) contained an interesting approach to ranging and scaling which sought to relate the level of holding to failure rate and mission duration

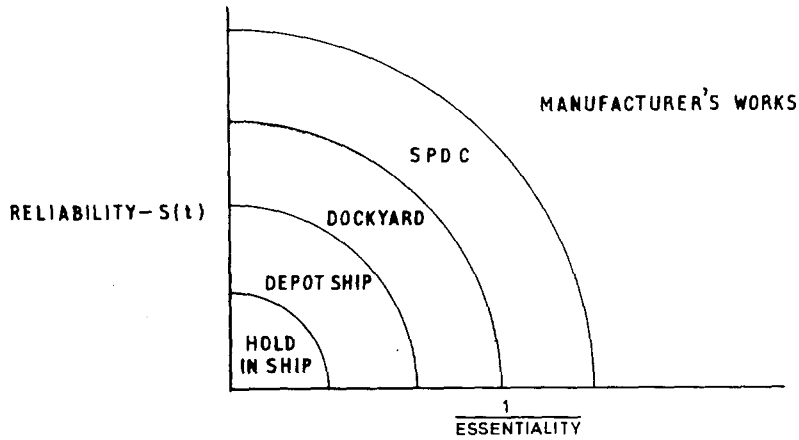

FIG. 9

so as to give an acceptable level of 'logistic availability'. This can only be done practically when reliability data has been generated at lower scalar levels, e.g. for components or assemblies, but the inter-relationships of the system effectiveness model suggest that it is a logical and fundamental approach. DFM has some work in hand on these lines.

The idea can be extended as indicated in FIG. 9. The more reliable an item the less the need for it to be held in the ship and the more acceptable for it to be further away, in a depot ship, a dockyard or even in embryo at the manufacturer's works. Conversely the more important an item to operational performance the more important it is to have it on board. The two factors of reliability and reciprocal of 'essentiality' could be quantified or certainly ranked, and together suggest a basis for progressively disposing spares.

Work is known to have been started on such a system but no results have been seen.

Adjustment of Stocks

Once initial ranging and scaling has been carried out, ships' officers do from time to time review stocks on a usage basis, but this does not necessarily optimize holdings or seek to improve logistic availability.

Much data which might assist in this exists in the form of stores demands (S145 and signal), Opdefs, etc. but since the demise of the Electronic Spares Usage Data return in the 1950's no comprehensive usage record for any type of stores is known to be available.

In view of the impact logistic availability will have on system effectiveness, it would appear that this is a field which would repay attention both operationally and economically.

H.M.S. 'Collingwood'

In considering our individual contribution towards System Effectiveness, it is particularly relevant to the writer to examine briefly the role of H.M.S. *Collingwood*. The factors which this establishment can influence concern mainly the levels of knowledge and skill of the members of the WE Branch. To a substantial extent the establishment also conditions the morale of its members, but this of course is also affected by many other factors both Navy-wide and in individual ships.

Attention is therefore being devoted to the analysis and quantification of knowledge and skills. In this connection, important work is in progress in the Training Assessment and Training Requirements Departments where conscious efforts are being made in conjunction with the Naval Manpower Utilization Unit and the Fleet to analyse in detail the jobs to be done at sea. From these analyses can be derived the levels of knowledge and the skills required by each man at different stages of his career.

In the case of knowledge, this work is being followed through by the development of an extensive computer bank of examination questions. More than 5000 objective questions suitable for junior ratings are now in store and they can be grouped to test desired levels of knowledge or to discriminate among its totality.

The measurement of skills is a much more difficult problem but preliminary steps are being taken and a consultancy contract has been let to examine it further.

As to morale, a tentative move has been made in the even more intangible search for quantified assessment and some indicators are now embodied in the *Captain's Management Guide*. An improvement objective has been stated for the Executive Officer to determine by the end of 1975 the possibility of more precise measurement or indication of morale, but for the present we must rely on the imperfect though sensitive traditional methods.

The re-organization of the establishment in 1970 leading to the establishment of the Schools and of smaller Divisions, together with a closer integration of the instructional and executive roles and the employment of senior ratings as divisional officers has had as a main aim improvement in morale. Gain happily has been made and here too the 'whole man' policies introduced by Admiral Law are being vindicated.

The work on improvement of maintenance methods, notably through the FIMS project has already been mentioned.

Summary

This article began by referring to the complexity of the extensive and interactive nature of our modern ship weapon systems. Let us therefore not delude ourselves into seeking a simple formula to rationalize them, for as pointed out explicitly by Ireson (Ref. 5) and suggested twice earlier, system effectiveness must be a complex multi-dimensional vector and one too which will vary down the time domain; it will not be capable of simple analysis in terms of a small number of clearly defined factors. Against this reality the model suggested is recognized as elementary and several other approaches could be made.

The thinking it illustrates is applicable, however, either in whole or in part at various stages of procurement and use and many techniques varying widely in sophistication can be harnessed in doing so. The model is believed moreover to identify the main factors involved in achieving system effectiveness, to show some (only) of their inter-relationships and to provide the basis of a framework which should prove helpful in decision taking at many stages of both development and deployment at sea.

Disclaimer

This paper presents the ideas of the author and does not necessarily represent those being adopted in the Navy Department.

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Note: This book is of uneven level: Chapters 1–4 and 10 might be 'for starters'.

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