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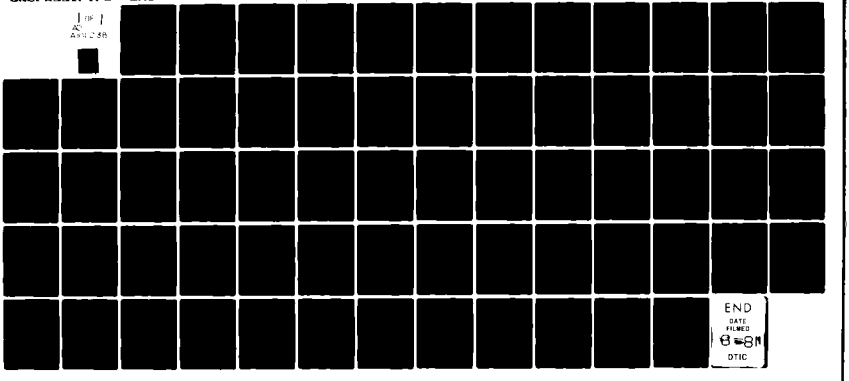

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ARMY ELECTRONIC EQUIPMENT SUPPORT OPTIONS: ASSESSMENT OF MAINTENANCE COMPLEXITY

Working Note ML904-2
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Frans Nauta
Lucas Bragg

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20. ABSTRACT *(Continue on reverse side if necessary and identify by block number)*

The report describes an approach to quantifying maintenance complexity. The approach entails application of a taxonomy defining the indicators predictive of the criterion measures of three components of maintenance complexity: inherent complexity (factors related to equipment design); job complexity (factors related to job design); and apparent complexity (factors representing the gap between skill requirements and those possessed by an individual).

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Research conducted in these subject areas is referenced. Steps required to validate the proposed approach are identified. Potential applications of the approach are in the defense system acquisition review process and in the manpower/personnel/training policy and plans area.

PREFACE

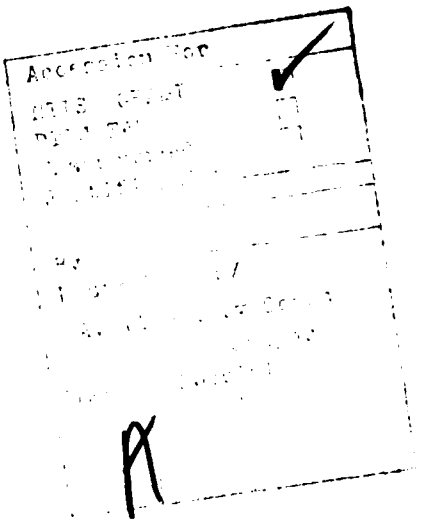
This working note is part of a study conducted for the Office of the Assistant Secretary of Defense (Manpower, Reserve Affairs, and Logistics). Its objective is to assess the feasibility of alternative maintenance support concepts for Army electronic equipment that would reduce the requirement for highly skilled technicians.

A previous report (1) documented an "analytic baseline" for the air-defense-peculiar electronics community. It showed that the required numbers of air defense electronics maintenance personnel would decrease in the 1980s (without changing the Army's planned support concepts). However, the skills required to maintain the new weapon systems were found to be well beyond those required for the currently fielded systems. Additionally, it was shown that the Army is hard pressed to meet even modest peacetime readiness requirements for the current systems due to a variety of factors. One of them is a lack of maintenance skills, but the singular impact of this factor on operational availability could not be quantified.

This note explores the issue of maintenance complexity in more detail. The objective is to arrive at quantitative measures of maintenance task/job complexity. Research on this topic has been very limited to date. The proposed approach, entailing a taxonomy of criterion measures and predictors, is thus a first attempt at structuring a methodology for eliciting quantitative indicators of maintenance complexity. Further research will be required to develop the appropriate scales and relative weights for synthesizing the indicators into composite measures or scores which correlate with the criterion measures of maintenance complexity.

Once the proposed approach has been validated, its potential applications are twofold. First, the taxonomy may be profitably applied during the acquisition process to estimate future changes in job complexity for specific military occupational specialties supporting the new system. Quantification of these changes could highlight their repercussions on required skill levels, job design, job aids, training requirements and personnel selection. Second, the taxonomy could be applied in a macro sense to obtain trend data on the composition of the required maintenance skills in each of the Services. Such trend data might provide useful input into defense manpower studies addressing manpower supply, retention, and training problems.

In preparing this report, the authors benefited from the experience of numerous individuals. The contributions by Joseph Wohl (MITRE Corporation), John Folley (Applied Science Associates, Inc.), Edwin Fleishman (Advanced Research Resources Organization), Douglas Towne (University of Southern California), and Gerard Deignan (Air Force Human Resources Laboratory) are particularly acknowledged.



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1. MAINTENANCE COMPLEXITY

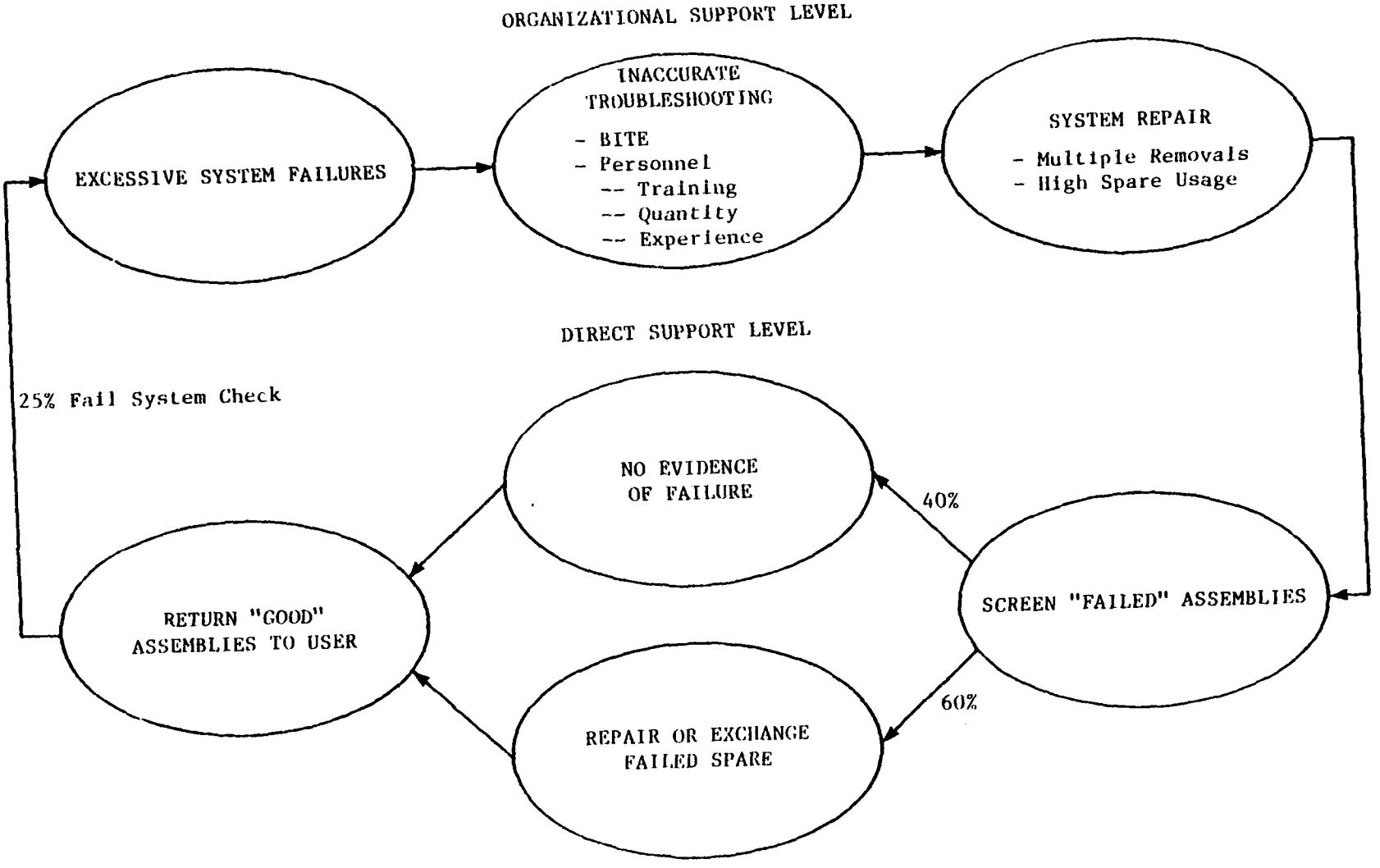
MANIFESTATIONS OF COMPLEXITY

Maintenance complexity is more easily described in terms of its manifestations than defined in a few words. Figure 1-1 illustrates how maintenance complexity can manifest itself in the support of a weapon system. This example applies to the Improved HAWK missile system, but it is representative of problems the Services are encountering in supporting complex electronics systems.

What happens, is that a number of factors interact, resulting in reduced availability of the system, over-consumption of spares, and a significant increase in the maintenance burden. These factors include system complexity, built-in test equipment (BITE) which does not perform as expected, technicians incapable of troubleshooting, and automated test equipment at the direct support (DS) maintenance shop which cannot fully simulate the tactical end item within the same tolerances. The direct consequences are: multiple removals of line replaceable units (LRUs) to correct singular malfunctions; a resulting high no evidence of failure (NEOF) rate for the LRUs sent to the DS shop; an unplanned increase in the maintenance burden of the DS shop, in this case amounting to 25% of the productive man-hours; a high proportion of LRUs returned to the organizational maintenance level failing the system check (FSC) and cycled back again to the DS shop (1).

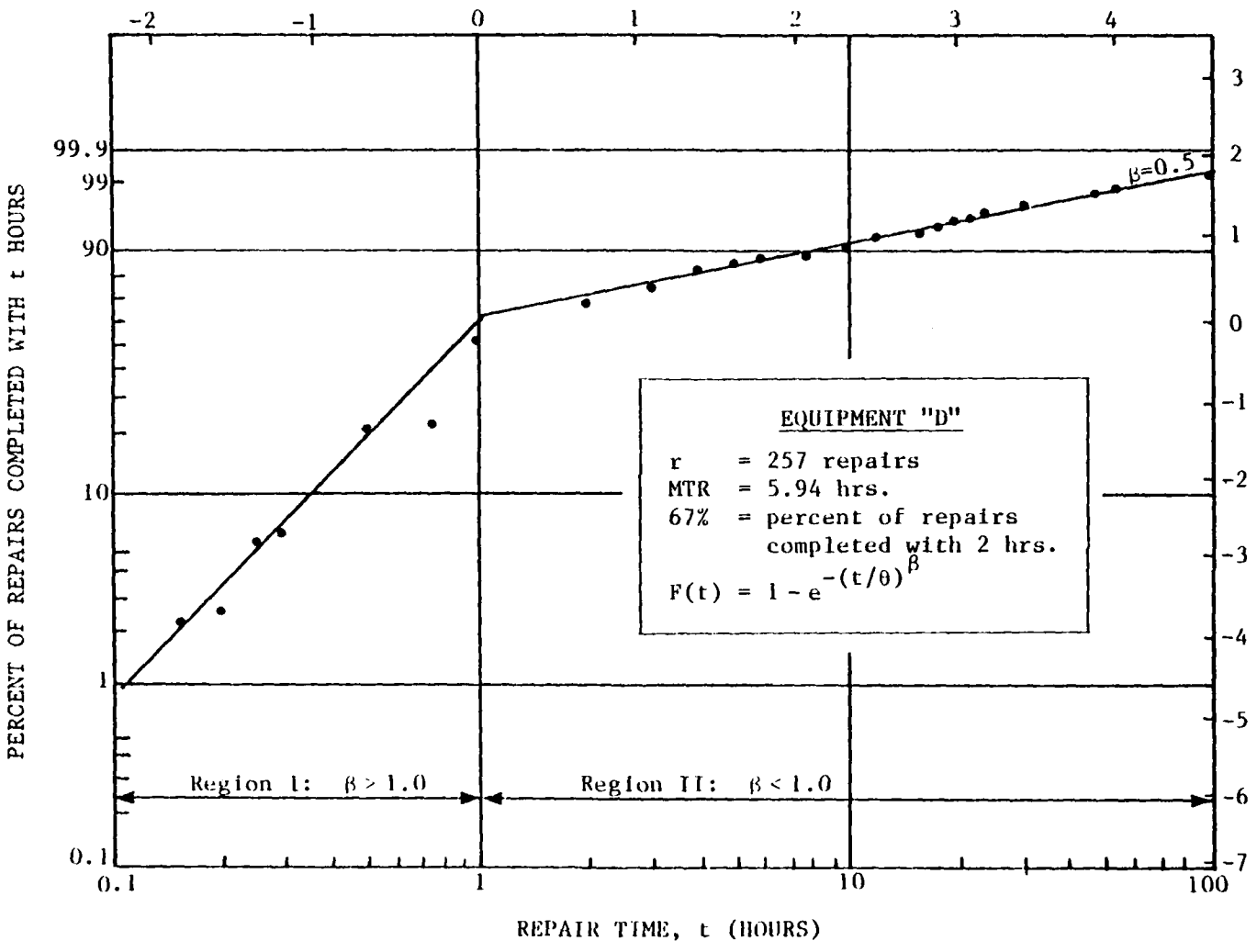
Maintenance complexity also manifests itself in the shape of the frequency distributions of actual repair times. Wohl has performed some interesting research along this line (2). Figure 1-2 is adapted from his

FIGURE 1-1. MANIFESTATIONS OF MAINTENANCE COMPLEXITY



IMPACT:
- Increased Supply Demand
- Increased Maintenance Workload

FIGURE 1-2. CUMULATIVE FREQUENCY DISTRIBUTION (CFD) OF REPAIR TIME FOR EQUIPMENT D, PLOTTED ON WEIBULL PROBABILITY PAPER



Source: "Diagnostic Behavior, System Complexity, and Repair Time: A Predictive Theory," by Joseph G. Wohl, MITRE/Bedford M80-00008, April 1980. Reprinted by permission.

research and illustrates a basic phenomenon of fault isolation. The cumulative frequency distributions of actual repair times for a mix of electronics equipments plotted on the Weibull probability scale have a characteristic shape showing the existence of two distinct fault isolation processes. The majority of repairs (65% to 80% in Wohl s sample consisting of equipments first fielded in the late 1960s) are completed within a short time (about two hours), thanks to traditional methods of maintainability design (BITE, self-test and self-diagnostics, troubleshooting aids, modularization, and equipment packaging). The remaining repairs require a much longer time to complete due to diagnosis and isolation difficulties; i.e., some of the system's malfunctions "escape" its maintainability features.

Importantly, as Wohl points out, the low slope ($\beta < 1.0$) of this portion of the curve indicates a decelerating process in which the probability of fault isolation during a given interval decreases with time, suggesting increasing rarity of failure mode, increasing difficulty in symptom interpretation, or increasing circuitry complexity. (Wohl's analysis is based on validated maintenance data from a special data collection effort. The data consist of active repair times by well-motivated military maintenance personnel.) Clearly, the specific location of the "breakpoint" in this graph for a given equipment is an indicator of maintenance complexity manifesting itself in a long tail of the repair time distribution.[1]

MAINTENANCE COMPLEXITY VERSUS MAINTAINABILITY

NEOF rate, FSC rate, and tail of repair time distribution are the key manifestations of maintenance complexity. For our purposes, maintenance complexity is defined as the product of all man-machine interface factors

[1]Wohl notes that he has found the same phenomenon for almost all complex electronics under field conditions, with the sole exception of flight-line maintenance of highly modularized avionics for which $\beta = 1.0$ (i.e., exponentially distributed).

which influence the effectiveness of a technician's job performance as measured in terms of NEOF rate, FSC rate, and tail of repair time distribution (region with slope less than 1.0 in Figure 1-2). Thus, included in our definition are such factors as equipment design, maintainability design, test equipment performance (built-in or off-line), quality of maintenance diagnostics software, adequacy of job performance aids (especially for troubleshooting), and the technician's ability to do the job. Unfortunately, this type of definition virtually precludes the possibility of expressing maintenance complexity in terms of a simple mathematical relationship of the underlying factors. Instead, complexity will have to be expressed in terms of multiple scales; i.e., a taxonomy or checklist.

Quantitative assessment of maintenance complexity is important, not as a solution to current maintenance support problems, but to give the issue more visibility in the acquisition process. The inherent complexity of a piece of equipment is normally determined by the operational requirements of the weapon system. In certain mission areas, the enemy may have a quantitative superiority, and U.S. policy has been to compensate by ensuring qualitative superiority. The result is increasingly sophisticated and complex equipments. Exploitation of the built-in operational capabilities of those equipments depends on the skills and training of those operating and maintaining them.

The objective of focusing on maintenance complexity in the acquisition process would be to ascertain that equipment complexity is adequately compensated for by (1) a systematic allocation of diagnosis functions between BITE and technician, (2) effective troubleshooting aids for the technician, (3) a job (MOS) design which does not require the technician to perform an impossible variety of tasks across different technologies and subspecialties, (4) a trainer guarantee of certain personnel aptitude and training standards, and

(5) a user guarantee of certain managed on the job training standards. What is clearly needed is a more sophisticated scrutiny of maintainability than afforded by just focusing on mean time to repair. Otherwise, current maintenance support problems are bound to grow worse with the influx of more complex electronics systems in the 1980s. While in peacetime any maintenance capability shortcomings may be compensated through the supply system (increased stockage or pipelines of spares, intensive management of supply, use of readiness floats), wartime sustainability depends on effective use of available spares and/or cannibalization which requires maintenance skill proficiency (36).

APPROACH TO QUANTITATIVE ANALYSIS

The proposed approach entails development of a taxonomy of maintenance complexity indicators. Following review and acceptance of this taxonomy, the second step would be to develop specific scales and weights to permit indicators to be compared between weapon systems as well as combined into composite measures. Following validation of these data, the third and final step would be to institutionalize evaluation of maintenance complexity in the system review process.

On a more near-term basis, an abbreviated version of the taxonomy could be validated and applied on a macro level. The objective of this exercise would be to gain a more precise understanding of evolving trends of maintenance complexity in a mission area or Service aggregate, given the current and planned inventories of weapon systems and associated support concepts. Such a macro analysis of maintenance complexity could illustrate shifts in skill requirements and the resulting repercussions in terms of skill level distributions, training requirements, and aptitude/ability prerequisites.

2. OVERVIEW OF PROPOSED TAXONOMY

INTRODUCTION

The ultimate criterion of maintenance job performance is the availability and/or wartime sustainability of the weapon system. Criterion measures of availability are varied and depend on the purpose of the evaluation (mission-capability, maintenance man-hours, or supply requirements). Two standard measures are operational availability (A_O) and inherent availability (A_I), conventionally defined as follows:

$$A_O = \frac{MTBF}{MTBF + MDT} \quad \text{and} \quad A_I = \frac{MTBF}{MTBF + MTTR}$$

where: MTBF = mean time between failures

MDT = mean downtime

= MTTR + MLDT + MADT

MTTR = mean time to repair

MADT = mean administrative delay time (i.e., waiting for maintenance personnel with requisite skills or test equipment)

MLDT = mean logistic delay time (i.e., waiting for parts)

A distinction must be made between predicted and actual values of these measures. A_O should be based on empirical field data to have practical meaning. A_I is more a design measure; it assumes instant availability of the requisite maintenance personnel, test equipment and spares, and is based on predicted MTTR defined as the "mean value of the probability distribution of times to complete active corrective maintenance over all predictable unscheduled actions weighted by the relative frequencies of occurrence" (28).

MTTR prediction is typically based on the following assumptions: failures occur at predicted rates; only single, "hard" (catastrophic) failures occurring randomly are included; maintenance is performed in accordance with established procedures by technicians with appropriate skills and training; only active maintenance time is counted, excluding administrative/logistic delays, fault detection, and clean-up time. As a result, actual MTTRs determined from field data are invariably larger than predicted MTTRs using standard MIL-HDBK-472 or related (25, 26) techniques.

For example, Phaller (29) reports differences by a factor of 2.5 to 5.8 for a mix of Air Force equipments, with 80% of the difference due to operational factors beyond the purview of MIL-HDBK-472 prediction techniques. (The most significant factors identified by the study include: preparation and clean-up times; unavailability of tools, test equipment or spares; cannot duplicate rate; training shortcomings; and differences between actual vs. predicted failures). Nevertheless, a substantial increase in actual MTTR from the predicted value may have little impact on equipment availability if the reliability (MTBF) is high.

Maintenance complexity, by our definition, affects repair time and quality of repair. Four criteria are proposed to measure the impact of maintenance complexity: NEOF rate; FSC rate; percent failures not included in the high slope region ($\beta \geq 1.0$) of the cumulative frequency distribution (CFD) of repair times (Figure 1-2); and the complement of the slope in the low slope ($\beta < 1.0$) region of the CFD.[1]

---

[1]The Air Force terminology for NEOF is Retest OK(RTOK). Another phenomenon encountered in the Air Force is the inability to duplicate on the ground a failure detected while the aircraft is in operation. This cannot duplicate (CND) rate is an additional candidate criterion measure of maintenance complexity. This phenomenon also occurs in complex ground equipment but is not usually recorded.

An increase in maintenance complexity results in an increase in any or all of these four measures, everything else being equal. The impact on A_0 is through an increase in MDT: MTTR increases due to a longer tail of the frequency distribution of repair times; MLDT increases due to increased parts consumption (unless the effect of NEOF and FSC is compensated for by increased stockage and pipeline supply); MADT may increase due to increased occurrences where special skills are required (unless this effect of complexity is compensated for by upgrading the capabilities of maintenance personnel).

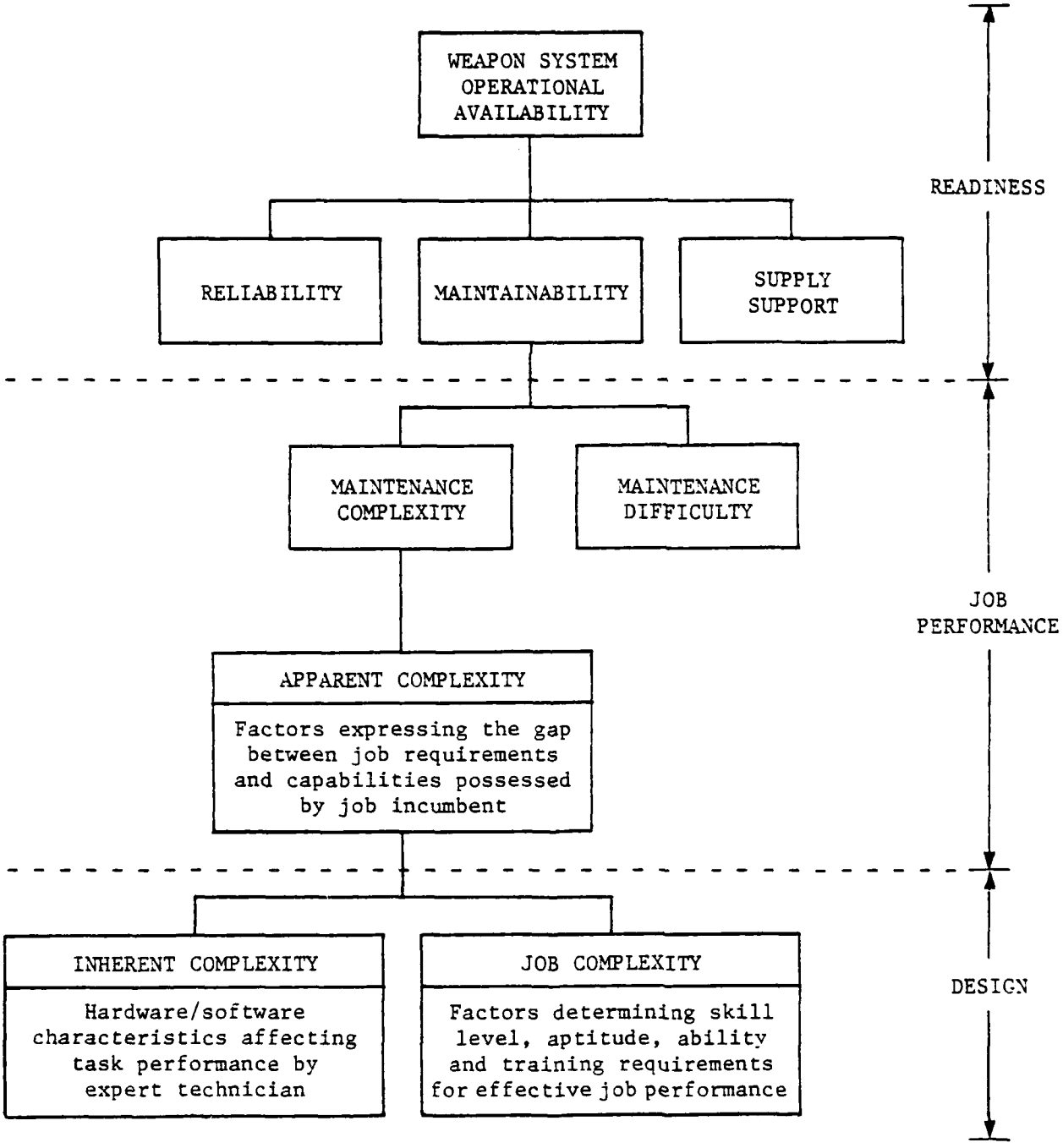
The precise impact of maintenance complexity on A_0 cannot be assessed apart from a variety of operational and logistics factors. Specifically, maintenance complexity does not determine, by itself, the level of effectiveness of maintenance performance as measured by the above four criterion measures. One has to be careful when equating a high NEOF rate (observed from field maintenance data) with a high degree of maintenance complexity. The real cause might well be unavailability of tools or test equipment, or any one of a number of environmental factors beyond the domain of maintenance complexity.

Thus, maintenance complexity must be measured in its own terms, separate from, but predictive of, the four criterion measures.

STRUCTURE

The man-machine interface factors determining maintenance complexity may be classified in terms of three categories as shown in Figure 2-1: factors which are equipment related (inherent complexity); factors associated with the job design, including the maintenance concept (job complexity); and factors expressing the gap between job performance requirements and the technician's capabilities (apparent complexity).

FIGURE 2-1. FRAMEWORK FOR ANALYSIS OF MAINTENANCE COMPLEXITY



Inherent Complexity

This component of maintenance complexity contains the factors which identify equipment complexity, including the design characteristics for maintainability. Some of the factors are known once the failure modes and effects analysis (FMEA) has been completed, diagnosis tasks have been allocated between man and machine, and BITE/maintenance diagnostic software (MDS) specifications have been determined. Other factors remain unknown until the system has been fielded, because neither the FMEA nor maintenance demonstrations can accurately simulate operational conditions. That is, validation of the BITE and MDS prior to fielding of the weapon system is currently not possible.

Job Complexity

This component of maintenance complexity contains the factors identifying the complexity of the job which the technician is required to perform. These data are not normally under control of the program manager. In addition to the types of data commonly provided in the qualitative and quantitative personnel requirements information (QQPRI) or similar manning estimate documents based on the logistic support analysis (LSA), this component includes factors pertaining to other aspects of the technician's job: other end items to be supported, quality of job performance aids, etc. In other words, assessing job complexity's contribution to maintenance complexity in the Army will require an early tentative MOS decision and involvement of TRADOC and MILPERCEN.

Apparent Complexity

This component of maintenance complexity contains the factors which cause the actual job to be more complex for an individual than planned. Potential causes include improper selection/classification procedures, a poor

approach to training, absence of managed OJT in the field, no standards of performance, and improper personnel utilization (lack of practice).

Difficulty vs. Complexity

The distinction between difficulty and complexity seems moot, but is a basic one. Difficulty refers to physical attributes such as lifting a 200-pound LRU, working in a cramped space, or probing connections under adverse conditions (darkness, rain, freezing or tropical temperatures). Task difficulty probably affects time to repair in the sense that a difficult task may take longer to complete than a simple task. In contrast, task complexity refers to some type of mental requirement. In the behavioral sciences, complexity is normally treated as subordinate to difficulty: a complex task is normally difficult, but a difficult task is not complex per se. In Figure 2-1, we elect to treat difficulty and complexity as separate components of maintainability to emphasize the distinction between the two for the purposes of this study. Difficulty may affect MTTR but should not exhibit itself in a task time distribution characteristic of complexity (Figure 1-2).

EVALUATION MEASURES

The intended uses of the taxonomy are to compare the complexity of different weapon systems and associated maintenance jobs (micro analysis for DSARC purposes) or to illustrate overall trends in maintenance job complexity and maintenance capabilities (macro analysis for manpower, personnel, and training program purposes). These intended uses suggest the need for an overall measure of maintenance complexity predictive of the four criterion measures. While an anchored, benchmark scale could be used to measure overall maintenance complexity, such a single measure, however, would not provide insight into what causes complexity. Thus, we propose that weapon systems be compared in terms of inherent complexity; maintenance jobs be compared in

terms of job complexity; and maintenance job performance be compared in terms of apparent complexity (see Figure 2-2).

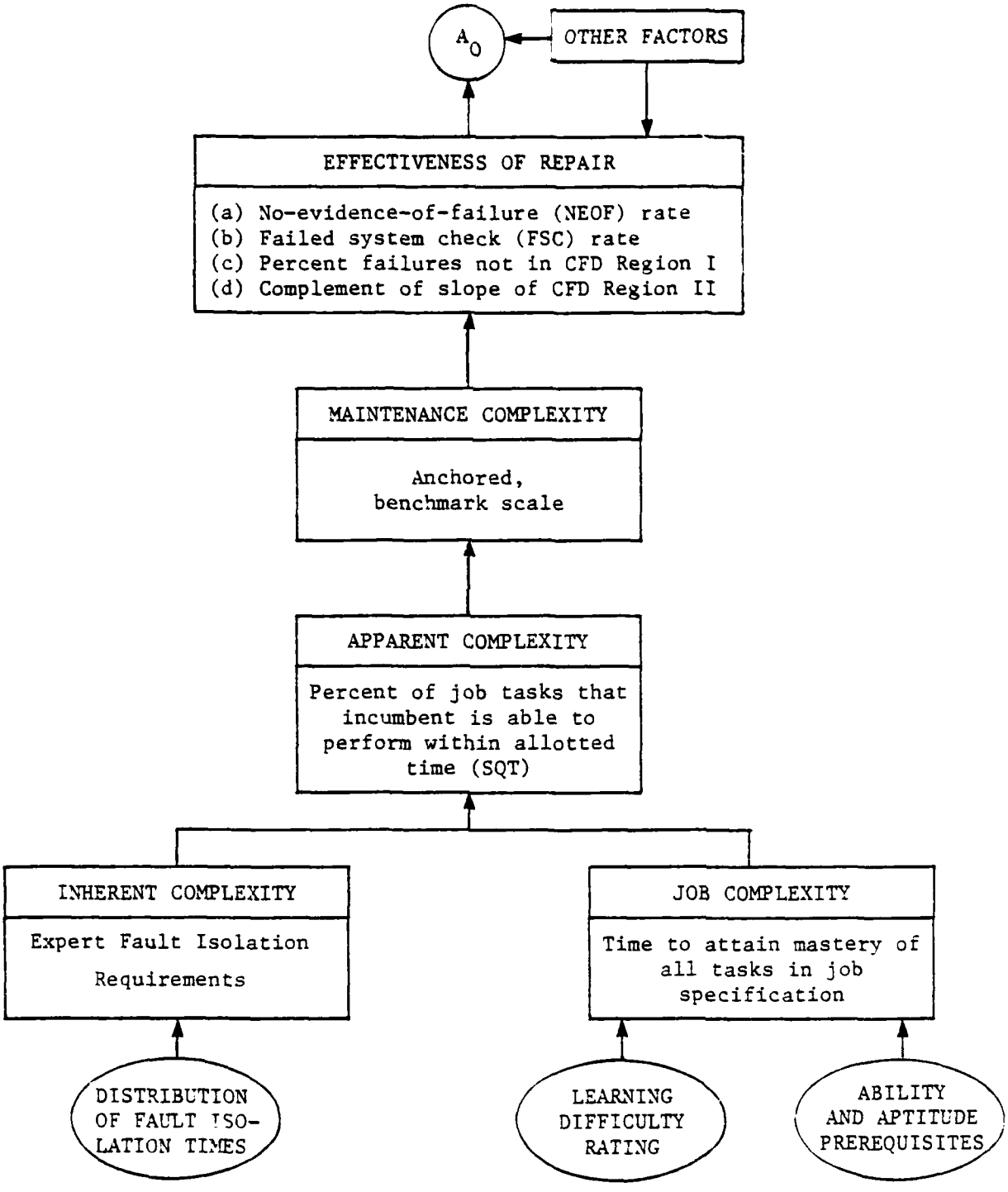
Inherent Complexity

Current maintainability measures utilized to evaluate inherent complexity are expressed in terms of MTTR or derivatives thereof. These measures, however, are imprecise as they reflect both the maintainability characteristics of the hardware (complexity as well as difficulty) and the capabilities of maintenance personnel (including quality of aids). To alleviate some of these measurement problems, an earlier, unpublished version of this document proposed the following criterion measure: the ratio of maximum repair time, M_{max} (95 per cent), to MTTR as demonstrated by expert (contractor) technicians in a maintenance demonstration (M-demo). Further analysis, however, suggests that this ratio is not a useful measure because its validity is limited to conditions where repair tasks are homogeneous in terms of the percent of repair task time expended in fault isolation. In reality, the corrective maintenance tasks associated with a given weapon system or equipment show a wide range in the percent of repair time required for fault isolation, so that the repair time distribution is not indicative of the fault isolation time distribution. Consequently, interpretations based on analysis of repair times may be misleading.

For example, conventional engineering rule of thumb used in preliminary design is to assume that the ratio M_{max} (95 percent)/MTTR) is 3 (27). If the overall repair time is lognormally distributed, the ratio follows from the following equation:

$$\frac{M_{max(\emptyset)}}{MTTR} = \frac{e^{z_{\emptyset}\sqrt{\ln(1+\eta^2)}}}{\sqrt{1+\eta^2}}$$

FIGURE 2-2. MEASURES OF MAINTENANCE COMPLEXITY



where: $z_{\emptyset}$ = table value for standard normal distribution ($z_{.95}$ = 1.64)

η = coefficient of variation = σ/MTTR

Pliska (28) reports a wide range of values for the coefficient of variation based on formal maintenance demonstrations of various equipments. (For example, the largest η value reported in that study is 1.63 for display equipment; the smallest value is 0.42 for data converters; the weighted average for the equipments sampled is 0.864.) The study suggests that for prediction purposes in preliminary design, η values be based on these sample data in lieu of the value of 1.07 in MIL-HDBK-472. The latter is based on older technology (mid-1960s); the suggestion is that η decreases as the degree of equipment modularity and fault isolation automaticity increase. Wohl's data (2) would indicate that this is not necessarily true.

An explanation of this disparity in statistical interpretations is provided by our earlier statement that repair tasks are not homogeneous, but show a wide variation in the percent of task time spent in fault isolation. This is the reason why our previously proposed measure of inherent complexity must be rejected. Instead, the proper criterion measure is an equipment complexity index based on the distribution of fault isolation times for all equipment failures, when fault isolation is performed by expert technicians. It is recognized that this index may be unavailable prior to fielding of the weapon system because failure modes of the fielded system may differ from those established through analysis (FMEA) or encountered in the laboratory (development testing and M-demos). Measurement of this index thus requires follow-on test and evaluation.

Job Complexity

Two measures of job complexity are proposed: (1) the time required to attain mastery (journeyman-level capability) of all tasks for the "average" qualified individual in the "normal" Service environment, and (2) the basic abilities and aptitudes required to attain mastery. The first measure is widely accepted in the literature, but it depends on expert raters--an approach which exhibits certain well known problems (35).

The Air Force is currently engaged in a major research program to develop a job complexity index for all jobs based on this first measure (10). The approach is based on a 25-point, anchored, benchmark scale of learning difficulty for each of a representative sample of tasks. Occupational survey data (including the percent of time specific tasks are performed in each job) are used to obtain an overall measure of difficulty for each Air Force specialty, referred to as the "average task difficulty per unit time spent". Once these indices have been obtained, the objective is to use them as an empirical basis for aligning aptitude requirements across specialties. A similar rating approach would be necessary in the Army for validating the proposed taxonomy.

We see this job complexity measure more as a measure of job design (number and diversity of tasks allocated to a billet) indicating experience or skill level requirements than as a measure implying aptitude requirements. It is fair to say that the Army ignores job complexity in developing manpower requirements for a new weapon system: maintenance tasks are allocated so as to minimize the number of billets required, and paygrades are authorized as a function of the number of billets via standard grade authorization tables. For example, if estimated maintenance man-hours do not justify more than one

or two billets, a grade of E-4 (perhaps one E-5 for certain MOSs) is typically authorized, with little regard to the individual's ability to perform the job.

Field data indicate that even in the Navy (which probably does the best job of classifying and training maintenance personnel) the average maintenance technician (somewhere between E-4 and E-5) is capable of performing only 65% of his work center's nontroubleshooting tasks, with a much lower percentage for troubleshooting tasks; and that, on the average, 3.7 years experience is required (following entry-level training) to achieve the MTTR of a group of experienced technicians for those tasks that the apprentice is capable of performing (30). The latter data are in close agreement with the data reported by RAND on job performance for a mix of occupational specialties (33). Electronics troubleshooting proficiency cannot be expected from technicians with less than nine years experience. The typical E-5 with over four years experience can only fault isolate two out of three failures (24).

Some of these job performance problems are, of course, independent of job complexity and will be returned to in the next section on apparent complexity. In any case, a job complexity measure as proposed is clearly related to the ultimate criterion of the taxonomy, effectiveness of job performance. If institutionalized in the Services, this measure would also lend itself for remedial action in the job design and grade authorization process.

The second and more fundamental measure proposed for job complexity consists of the basic abilities and aptitudes required to attain proficiency. At present, no satisfactory measure is readily available for this purpose. The Armed Services Vocational Aptitude Battery (ASVAB) is used to screen candidates, based on their Armed Forces Qualification Test composite score, and to determine their qualifications for assignment to specific occupational specialties, based on aptitude composites. Area aptitude composites differ among

the Services; the Air Force uses 4, the Marine Corps 7 , the Army 10, and the Navy 11.

Both the ASVAB subtests and the aptitude composites have changed from time to time. For example, with the introduction of the new ASVAB (Forms 8/9/10, October 1980) the electronics aptitude (EL) composite (which happens to be the same for all four Services) comprises general sciences, arithmetic reasoning, mathematics knowledge, and electronics information. The previous ASVAB version used an EL composed of arithmetic reasoning and electronics information.

All Army electronics maintenance MOSs use a cutting score on the EL as the single selection standard (prerequisite). There is no scientific method for determining the "right" aptitude prerequisite for an MOS. Cutting scores have been changed in the Army many times without a change in MOS skill requirements. Such changes are made on the basis of academic attrition experience in entry-level school training and actual or expected difficulty in meeting training quotas.

Empirical data show that EL is predictive of academic success: trainees with a higher EL score have a lower probability of academic attrition. In those cases where different services have identical equipment and job descriptions, selection standards typically differ. For example, for Improved HAWK maintenance personnel, the Army currently requires an EL of 105 for organizational maintenance MOSs and an EL of 100 for direct support maintenance MOSs. (The Army uses standard scores on a scale from 40 to 160.) For the same jobs, the Marine Corps requires a GT of 110 and an EL of 120.

A great deal has been written about the ASVAB, but we have not been able to locate any data showing a relationship between aptitude and job performance (other than written skill tests). Instead, much of the research

published over the last 15 years shows that lower aptitude personnel, given different training and job aids, are capable of better maintenance job performance than higher aptitude personnel trained conventionally with conventional aids (8). While this does not disprove that high aptitude personnel may indeed perform better, the data suggest that caution is warranted in using MOS selection standards as a proxy measure of job complexity.

Aptitude tests fail to predict job performance because they do not tap the basic abilities and personal traits which are predictive of job performance. Some of the most useful research in this area has been performed by Fleishman and his coworkers (9). This research demonstrates that effective performance of a complex, cognitive task such as electronics troubleshooting depends on a number of cognitive and psychomotor abilities which can be measured and tested. These basic abilities are permanent individual attributes. The implication is that persons without these abilities cannot be expected to become proficient at certain jobs regardless of a high aptitude score, unless the tasks are fully procedurized in a job aid which is 100% accurate.

In summary, given the current absence of valid measures of both learning difficulty and aptitude/ability requirements, there seems little choice but to use an anchored, benchmark scale to measure job complexity--a scale which must be developed by experts.

Apparent Complexity

This component of maintenance complexity is probably peculiar to the Services. It refers to a second-order effect resulting in an increase in job complexity as perceived by the person doing it. What this component represents is the gap between job requirements (abilities, skills, knowledge, experience) and the individual's capabilities. Some of the factors involved -- job design, pay-grade authorization, classification --have already

been mentioned. Another factor is the quality of training maintenance personnel receive. An obvious measure of this is the percentage of tasks the technician can perform satisfactorily. When the Army's Skill Qualification Test has become a more reliable and valid measure of job performance, its results will provide a readily available measure of apparent complexity.

The DoD-wide "rationalization" of technical skill training in the mid-1970s under the Instruction System Development program may have been a good concept, but its implementation has been disappointing. One reason for this may be that resource constraints have limited the quality of the required front-end analysis. As a result, individual skill training still does not meet requirements (11). A more important reason is the absence of an effective managed-on-the-job training (MOJT) program for any of the Army's electronics maintenance MOSs we have examined.

Once again, resources are the issue. No MOJT billets (instructors nor trainees) are authorized in the Army's force structure. There is a shortage of NCOs possessing both technical and instructor skills. Lack of maintenance training simulators minimizes the extent of troubleshooting taught at TRADOC schools. Overseas, readiness is perceived as more important than maintenance training so that time and equipment for hands-on training are limited. In FORSCOM also, maintenance training has to compete with many other operational requirements. And excessive personnel turbulence makes any MOJT program difficult to implement. Even in the Air Force, which does have an MOJT program conducted by Field Training Detachments, there are serious problems with the quality of OJT (3). Clearly, budgetary considerations rather than requirements have affected the level of skill training.

To counteract this problem (as well as to open these MOSs to lower-aptitude personnel) much research over the past decade has been devoted to job

or skill performance aids (JPAs or SPAs) (7, 8, 14, 17 - 23). This research has focused primarily on specific formats for troubleshooting and nontroubleshooting JPAs and experiments demonstrating potentially large savings from implementing JPAs. The experiments conducted in the Services show the following payoffs:

- training time reduced by 60% for troubleshooting tasks and up to 100% for nontroubleshooting tasks
- active repair time (excluding fault diagnosis) reduced by up to 33%
- fault diagnosis time reduced by up to 67%
- reduction in false removals (NEOF) by 15%

Westinghouse reports that its experience with JPAs, based on both Air Force and industry standards, shows the following potential savings: MTTR reduced by 40% (including 10% due to less look-up time compared with conventional technical manuals), error rate reduced by 75%, spares consumption reduced by 30%, and training time reduced by 25% (18).

To date, implementation of JPAs has been piecemeal, and the promised payoffs have not been realized. The Services, understandably, are reluctant to implement JPAs on a scale that might ensure that the potential benefits are reaped. Some practical problems related to job structure and personnel management are pointed out by Malehorn (18). Another issue is that JPAs must be accurate; i.e., contractor support might be required in the first couple of years of a newly fielded system until most of the engineering changes have been fielded and incorporated into the JPAs. Also fully procedurized aids for digital troubleshooting have been unsuccessful to date, although a new approach (14) may overcome this shortcoming. Yet another problem is that adequate JPAs are significantly more expensive than traditional manuals. As long as program managers are driven by design-to-unit-production cost rather than

life cycle cost, there is a disincentive to spend much money on the high-quality front-end analysis required for proper JPAs. Folley (18) points out that research should be reoriented towards the program manager's point of view, addressing the question of the most cost-effective mix of aiding/training. Bond and Towne (6) provide an excellent overview of the multi-disciplinary approaches required to solve the troubleshooting problem. They insist that even the most effective aids will not permit finding all failures. Thus, the services would always need expert troubleshooters in addition to JPAs for lower skilled personnel.

At present, a number of pilot programs are underway to assess the potential of JPAs in the context of multi-level training: minimum entry-level, task-oriented training combined with a fully funded JPA program, and advanced technical training for those first-termers who reenlist. If these programs are successful and if JPAs are fully institutionalized in the Services, job complexity could be significantly reduced, and apparent complexity minimized. Until then, apparent complexity will contribute substantially to maintenance complexity and cause ineffective job performance.

3. DETAILED SPECIFICATION OF TAXONOMY

INTRODUCTION

Figure 3-1 provides an overview of the maintenance complexity taxonomy. Each of the three components, inherent, job, and apparent complexity, is made up of factors which are in turn measured by indicators. Indicator values predict component measures, but the specific statistical relations are unknown. We have not developed the necessary scales and weights for the indicators to obtain statistically valid measures. Many of the indicators should probably be measured as indices on a nonlinear scale.

The discussion in this chapter is focused on complexity at the system level and on-equipment maintenance jobs. Some modifications would be required to specify inherent complexity for off-equipment maintenance, though job and apparent complexity specifications would remain the same.

INHERENT COMPLEXITY

Overall Measure

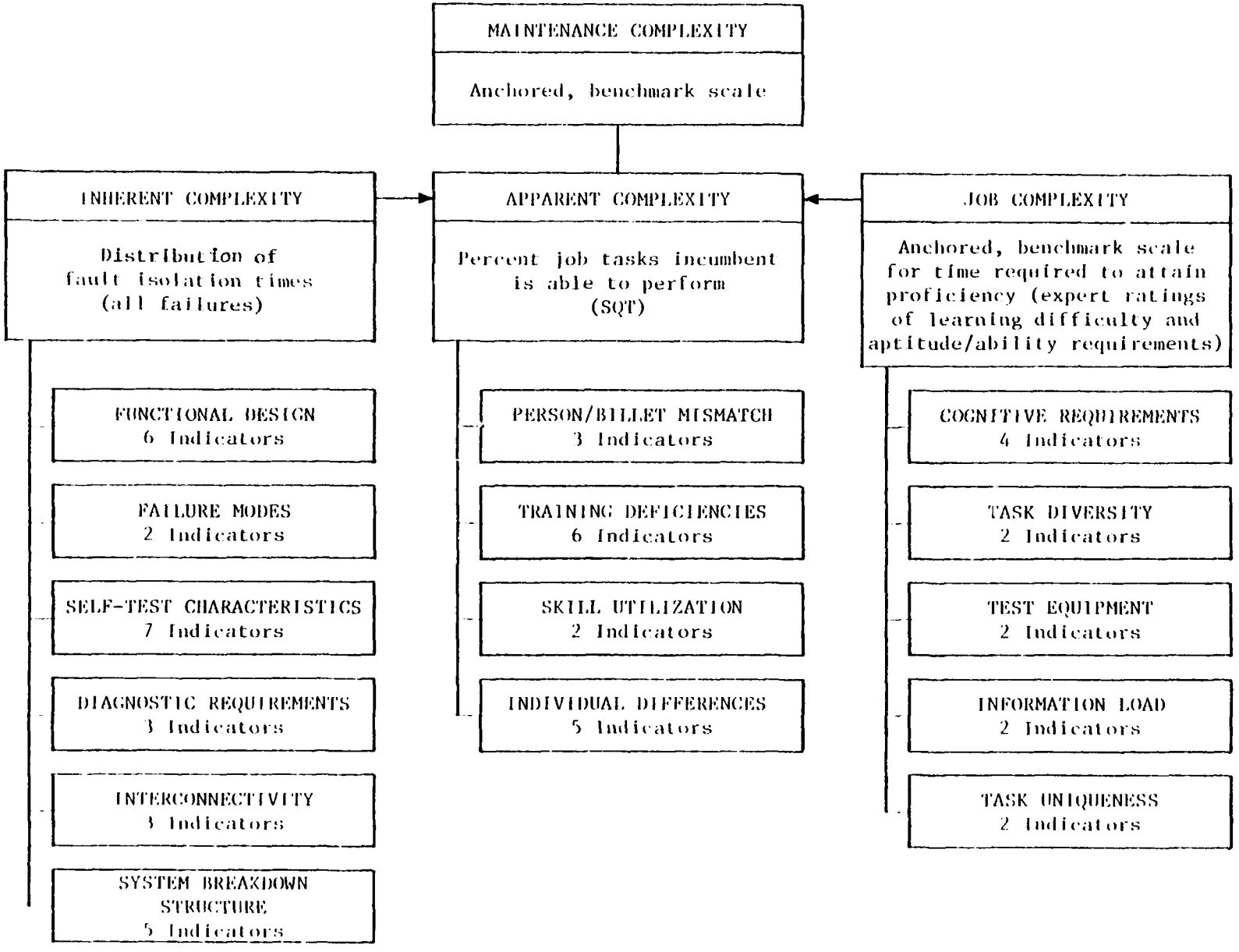
The overall measure of equipment (hardware and software) inherent complexity is the equipment complexity index representing the distribution of fault isolation times for all equipment failures when fault isolation is performed by expert technicians. Obtaining this measure will require changes in maintenance data collection formats.

Factors and Indicators

The factors determining inherent complexity are:

- functional design
- failure modes
- self-test characteristics
- diagnostic requirements

FIGURE 3-1. MAINTENANCE COMPLEXITY TAXONOMY



- interconnectivity
- weapon system breakdown structure

Table 3-1 shows the indicators associated with these factors. Each is explained briefly below. The specific factors to be used for assessing inherent complexity depend on where the weapon system is in the acquisition cycle, which determines the availability of data for quantitative measures.

Functional Design. The first and most important indicator under functional design is the level at which the system is partitioned, physically and electronically. The optimum system from a maintenance viewpoint would be 100% functionally partitioned at the LRU level. This would allow a failure to be identified with a function (receiver, power supply, etc.) and the entire function to be replaced. In contrast, in a fully integrated system, all functions are interdependent. When one fails, the possible number of sources (i.e., the suspect set) becomes very large. The resulting problems for maintenance personnel have been noted in various studies (3).

Many new systems are computer-controlled, which increases inherent complexity. Computer-based systems (e.g., PATRIOT, DIVAD, ROLAND), by their very nature, are integrated. In addition, they generally require a significant amount of built-in instructions or software. The more software (whether operating program or self-test program), the wider the range of possible suspect sets when a failure occurs. A simple indicator of this added complexity is the number of lines of code in high order language (HOL).

The level of derating of components also affects inherent complexity. The actual load as a percent of design capacity not only has a thermodynamic effect on the failure rates of the components, but also results in failures not predicted by FMEA. Such anomalies normally manifest themselves in unpredictable junction breakdowns. Thus, a system with components derated

TABLE 3-1. INHERENT COMPLEXITY INDICATORS

A. FUNCTIONAL DESIGN

1. Partitioning: percent system not functionally partitioned by LRU
2. Derating: Percent components operating above 60% design capacity
3. Tactical Software: lines of code (HOL)
4. Maintenance Diagnostics Software: lines of code (HOL)
5. Number of disciplines (electronics, mechanical, pneudraulics, optics)
6. Mix of technologies (tubes, discrete solid state, IC, LSI)

B. FAILURE MODES

1. Number of failure modes identified by FMEA
2. Percent DT/OT II failures not identified by FMEA
3. Percent DT/OT II failures identified as intermittent

C. SELF-TEST CHARACTERISTICS

1. Ambiguity:
   (a) No Indication: percent failures processed by BITE but not fault isolated
   (b) False Alarm: percent BITE indications reflecting false alarms
   (c) Wrong Indication: percent BITE indications that are wrong
   (d) Ambiguity Group: complement of sensor set evaluation coefficient
2. Interface Requirements:
   (a) Percent identified failures requiring manual isolation (machine-assisted)
   (b) Percent identified failures requiring manual interaction (machine-directed)
3. BITE Hardware Reliability: ratio of system to BITE MTBF

D. DIAGNOSTIC REQUIREMENTS

1. Percent failures requiring remove/replace actions for fault isolation
2. Percent failures requiring peculiar test equipment for fault isolation
3. Percent failures requiring common test equipment for fault isolation

E. INTERCONNECTIVITY

1. Average number of connections among individual components
2. Average number of connections among individual subassemblies
3. Average number of connections among assemblies

F. SYSTEM BREAKDOWN STRUCTURE

1. Number of assemblies
2. Number of subassemblies
3. Number of components
4. Number of subsystems
5. Number of major systems

to a high percentage of design capacity (60% - 75%) will be inherently more complex than the same system with the same components derated to a lower percentage (say, 40% or below) of design capacity.

The final two indicators, disciplines and technologies, only affect inherent complexity if the weapon system involves multiple disciplines and technologies. For example, a fire control system controlling a mechanical gun on a hydraulically driven turret, all controlled by a computer receiving signals from a radar set, crosses several disciplines, making the system inherently complex. The suspect set associated with a failure may be in one of several disciplines, making fault isolation difficult. This effect would be compounded if the job design required one person to work in all disciplines (see section on job complexity).

A similar indicator is the mix of technologies utilized. This refers to the use of tubes, solid state devices, integrated circuitry, or large-scale integration at the component level. The driving factor is not the use of a particular technology, but the use of multiple technologies in a single system.

Failure Modes. Failure modes identified by the FMEA are indicative of inherent complexity. The FMEA never identifies all failure modes complex equipment will exhibit during its life, however. This delta is commonly referred to as failure anomalies. Anamolies have a serious impact on troubleshooting because no procedures have been developed for dealing with them, nor are their symptoms included in the manuals. The number of anomalies may increase with the number of failure modes identified in an FMEA, and this increase may be non-linear. Consequently, the number of failure modes identified by the FMEA is both a first-order indicator of inherent complexity, and a second-order indicator of potential troubleshooting problems.

The second indicator, percent of DT/OT failures not identified by the FMEA, indicates the "quality" of the FMEA performed by the contractor, and also predicts potential troubleshooting problems. The test results are normally used to update technical manuals and job aids, but may also indicate the need for enhancements of BITE hardware and/or software. If testing time is limited, only a portion of all possible failure modes will be encountered in the testing environment, unless a sophisticated failure insertion program is followed. Even then, simulated failure modes will normally be derived from the FMEA. BITE hardware enhancements are notoriously difficult once the detailed hardware design has been completed. For all these reasons, any DT/OT II failures not identified by the FMEA indicate potential maintenance problems.

Some of the failures during testing may be classified as intermittent failures, detected by temporary loss of an operational function with or without a corresponding BITE indication. Systems exhibiting intermittent failures are inherently more complex than those without; their diagnosis requires a high level of proficiency. Intermittent failures are not caused just by immature hardware. Fielded complex systems, especially those with embedded computers, may exhibit this phenomenon too (e.g., PERSHING IA). While the system is in development, intermittent failures will normally be minimized through redesign efforts based on such techniques as "sneak circuit analysis." Apparently, it is in practice infeasible to eliminate all intermittent failures in a complex system. The consequences in terms of operational capabilities and maintenance complexity are unpredictable.

Self-Test Characteristics. The first four indicators listed correspond to different types of ambiguity associated with the self-test or BITE.

The next two indicate the level of human interface required to fault isolate using BITE. The last concerns the reliability of BITE hardware.

During system design, requirements for automatic fault isolation are determined on the basis of reliability predictions and maximum allowable system downtime. Only a selected set of failure modes normally requires automatic fault isolation to bring the predicted MTTR down to an acceptable level (as determined by system availability requirements). The level of BITE (specificity of fault isolation within the system breakdown structure) is determined on the basis of the maintenance concept and cost-effectiveness (MTTR reduction) considerations.

Implementation of BITE may result in four types of ambiguity, three of which, wrong indications, false alarms, and ambiguity group, are widely discussed in the literature. A fourth, percent of failures not resulting in a fault indication, is not.

Wrong indications result from automated diagnostics' incapacity to distinguish between failure modes which they can and cannot accurately diagnose. Thus, if failures occur in such areas as interconnecting wiring, connectors, cabling, or front panel components, the fault indicator will normally be erroneous (27). When the technician replaces the module, the fault indication remains.

False alarms are normally divided into two categories: faults detected during system operation but not repeatable during the fault isolation process (Type 1), and faults detected and isolated to an LRU but not evidenced at the next higher maintenance level (Type 2). Type 1 false alarms include, but are not limited to, intermittent failures. If the indicator used includes these failure symptoms, it replaces indicator B.3 in Table 3-1. Type 2 false alarms are caused by testing conditions such as BITE tolerances. False alarms

can represent a significant factor in assessing maintenance complexity; Pliska (28) shows a range of 0.40 to 1.30 (Type 1) and 0.25 to 0.65 (Type 2) in false alarms (expressed as ratio of false alarms to actual failures) for a representative set of currently fielded electronics systems.

The third type of ambiguity, commonly referred to as ambiguity group, concerns the number of removable items included in the set to which the failure is isolated by BITE. Some failure modes may be cost-effectively isolated to a single LRU; for others, the BITE may not isolate beyond a sizable "suspect set." A measure commonly used for this BITE resolution level is the "sensor set evaluation coefficient," defined as follows:

$$SE = \sum_{i=1}^{n} \frac{1}{i}\left(\frac{P_i}{P}\right)$$

where: P_i = percent of identified failures isolated to a group of i LRUs

P = percent of failures identified by BITE

(Note: Greenman (27) defines this coefficient in terms of failure probabilities; the above format is more suitable for our purposes.)

The higher value this coefficient has (≤ 1.0), the higher the resolution level of the BITE. Thus, the corresponding indicator (C.1.d in Table 3-1) is measured in terms of the complement of this coefficient as an indicator of inherent complexity.

A fourth type of ambiguity, not noticed in the literature but potentially the most critical, is the percent of failures not resulting in a fault indication even though BITE was designed to detect and fault isolate the failure modes involved. Of course, this is not supposed to happen, but anecdotal evidence seems to indicate that it does. Apart from failures in BITE hardware, potential causes may include software inadequacies.

The next two indicators relate to the level of autonomy at which the self-test is implemented. Between the two extremes of fully manual troubleshooting (no self-test) and fully automated fault isolation, several levels of test autonomy may be distinguished. Westinghouse recommends making a distinction between two intermediate levels of test autonomy: machine-assisted, man-directed and machine-directed, man-operated. The former, also referred to as lower-order BITE, would provide little more than fault detection, with fault isolation left to the technician. The self-test would not fault isolate below two levels above the LRU level in the system breakdown structure and would give no further troubleshooting assistance. The latter (higher-order BITE) would provide machine prompting to assist in troubleshooting. Both levels of BITE typically might require manual test probing; but the lower-order BITE would not direct the technician, whereas the higher-order BITE would.

The corresponding two indicators in Table 3-1 are phrased somewhat more generically, the lower level connoting manual intervention (requiring more cognitive skills), and the higher level manual interaction (requiring fewer cognitive skills but the ability to follow instructions precisely). Failures in either category increase inherent complexity.

The final indicator of the contribution of self-test characteristics to inherent complexity is BITE hardware reliability (MTBF). A failure in BITE hardware may cause various ambiguities, including no indication. For this reason, BITE hardware reliability should be an order of magnitude higher than the tactical hardware. The ratio of the two is an indicator of inherent complexity.

Diagnostic Requirements. All failure modes not addressed by fully automated BITE impose a diagnostic burden on the technician. The percent of

failures requiring off-line test equipment (common test, measurement and diagnostic equipment (TMDE) or system-peculiar special test equipment (STE)) clearly indicates inherent complexity. Common sense would suggest that failures requiring STE are more complex to troubleshoot than failures requiring TMDE; hence Table 3-1 includes an indicator for each.

The proper measure for these two indicators, however, should reflect both the percentage of failures involved and the number of different test equipments required. That is, a nonlinear scale is needed to permit comparison of the diagnostic requirements for two systems; for example, one system with 10% of the failures requiring, on the average, 5 pieces of test equipment (the remaining 90% of failures representing 40% of the failure modes are solved by fully automated BITE), and another system with 30% of the failures requiring 2 pieces of test equipment (the remaining 70% of the failures being solved by fully automated BITE).

Another diagnostic technique often required is the removal of multiple LRUs (typically circuit boards) to isolate the failed component. Procedures needing this technique may be viewed as increasing the complexity of troubleshooting. This technique is typically required within ambiguity groups called out by BITE (see previous section on self-test characteristics). It is often necessary in fault isolating failure modes not covered by BITE: complex failures (difficult to test) with a very low frequency are seldom addressed by BITE as the increased cost would not pay off in reduction of MTTR.

Interconnectivity. The interconnectivity of weapon system parts is a basic indicator of inherent complexity. The higher the interconnectivity at each level of the system breakdown structure, the larger the "suspect set" associated with a failure symptom. In manual troubleshooting, perceptual and

problem-solving complexity increase with interconnectivity; in self-test diagnostics, software complexity (logic and lines of code) increases similarly.

Interconnectivity can be measured in different ways. Wohl (2) applies a circuit complexity index at the component level, defined as the average number of components connected to a component. As stated earlier, his research suggests that this index is predictive of the tail of the repair time distribution. Rouse (5) demonstrates that two different measures, "number of relevant relationships" and an information theoretic measure are predictive of fault isolation time. (He also demonstrates that parts count, by itself, is not a good predictor.)

The interconnectivity indicators in Table 3-1 are expressed in terms of Wohl's measure, which turns out to be closely related to Rouse's number of relevant relationships. Interconnectivity at the lowest three levels of the system breakdown structure, i.e., the component (smallest removable item), subassembly (smallest field replaceable unit, e.g., PCB), and major assembly (smallest field repairable unit, e.g., LRU) levels, may be most predictive of inherent complexity.

System Breakdown Structure. Counts of the weapon system's physical components (printed circuit boards, number of piece parts, number of cables, etc.) provide an indicator of inherent complexity. For example, PERSHING II is being touted as much easier to maintain than PERSHING IA. This expectation is based on a significant reduction in the number of "things": PERSHING II has 53% fewer major items and 77% fewer cables than PERSHING IA.

The indicators listed in Table 3-1 are expressed in a generic terminology for the indenture levels of the system breakdown structure. The top level (first indenture below weapon system) is referred to as the major

system. This is broken down into subsystem, major assembly, subassembly and component. For a specific weapon system, the actual number of indenture levels may be more or less. The maintenance concept determines which are LRUs and which are shop replaceable units (SRUs). The relative impact of the counts by indenture level (or sequence of indicators listed) is probably a function of the maintenance concept. The sequence given in Table 3-1 presumes that assemblies are LRUs and subassemblies SRUs.

Comments

The above indicators clearly overlap. Specifically, the effects of interconnectivity (factor E) and system module counts (factor F) are reflected in the number of failure modes (indicator B.1) and ambiguity measures (indicator C.1), while diagnostic requirements (factor D) may have little to add to interface requirements (indicator C.2). Thus, if measures for the first three factors were available, the last three would contribute little else to the overall measure of inherent complexity. However, no measures are available for factors B and C until completion of full-scale engineering development. This suggests that different indicators be used to assess the maintenance complexity of new systems at different stages of the development cycle (see Chapter 4).

A second point which may need clarification is the absence of certain design concepts from the list of indicators. For example, a "soft fail" design (also referred to as "on-line sparing") permits automatic switching over to spare circuitry when a failure occurs in a specific circuit. This concept permits repair of the failed circuit during scheduled maintenance. The prime effect is a significant increase in A_0. Greenman (27) suggests that soft-fail design also facilitates fault isolation. This is not necessarily true; the concept may be subject to the same ambiguity problems as BITE.

Another missing concept is design for testability, which is concerned with accessibility of identified test points, and a host of other issues. A good overview of testability requirements as they affect maintenance complexity is provided by a draft standard for testability (16). (Reportedly, this reference is used as a pilot military specification for testability in the Army's AAH program). The net effect of testability, however, is reflected in the given indicators of ambiguity.

Another such design characteristic is the mix of analog, digital, and hybrid modules. These parameters are often used in MTTR predictions using linear regression, but are not believed to affect inherent complexity as such.

With regard to BITE, Table 3-1 does not explicitly include as an indicator the percentage of failures fault isolated by fully automated BITE (or its complement). Instead, the effects of BITE (apart from ambiguity) are represented in terms of the percentage of failures fault isolated semi-automatically (indicators C.2). It may be of interest to note that past attempts to use regression models in predicting MTTR have shown little sensitivity of MTTR to the percentage of failures automatically fault isolated by BITE (28).

JOB (MOS) COMPLEXITY

Overall Measure

The overall measure of job complexity is the time required to attain job proficiency at the journeyman level, as measured by an anchored, benchmark scale combining learning difficulty and aptitude/ability prerequisites.

Factors and Indicators

The factors determining job complexity are, in order of importance:

- cognitive requirements

- task diversity
- test equipment required
- information load
- task uniqueness

Table 3-2 shows the indicators associated with each factor. Some indicators refer to the number or percent of tasks, which presumes that a complete list of the tasks allocated to the job (MOS) is available. (The list should include all tasks allocated to a billet in the logistic support analysis record (LSAR) or QQPRI even if that billet ultimately is not included in the draft plan TOE; i.e., tasks that may be overlooked when a tasklist is prepared from a contractor-delivered task and skill analysis).

TABLE 3-2. JOB (MOS) COMPLEXITY INDICATORS

A. COGNITIVE REQUIREMENTS

1. Percent tasks with incomplete information in job aids
2. Percent tasks requiring technician to make decisions
3. Percent tasks requiring technician to interpret information
4. Percent tasks requiring pattern recognition ability

B. TASK DIVERSITY

1. Number of different end items supported
2. Number of area specialties required (see Appendix)

C. TEST EQUIPMENT

1. Number of system-peculiar test equipments required
2. Number of common test equipments required in job

D. INFORMATION LOAD

1. Average number of instructions to complete a task
2. Total number of pages of TMs and other job aids

E. TASK UNIQUENESS

1. Number of tasks occurring infrequently
2. Percent of infrequent tasks without fully procedurized aid

Which non-mission-essential tasks to include is a matter of judgment. For example, at a direct-support-level MOS, maintenance tasks on the special test equipment used to check out LRUs are not normally coded mission-essential. However, for our purposes, such tasks should be included in the counts driving some of the indicators. A logical rule would be to include in the task list all maintenance tasks for all end items the MOS is responsible for, and to exclude such nonactive maintenance tasks as supervision, supply duties, and instruction.

Many MOSs merge at the higher pay grade levels, broadening the variety of end items the person is responsible for, primarily as supervisor. Thus, "journeyman proficiency" must be taken generically: the intent is to limit ourselves to active maintenance tasks at the E-5 level, but to include those which may have been allocated to higher pay grades, including warrant officers (e.g., troubleshooting tasks). The Army recognizes five skill levels for enlisted personnel; they are identified as skill level 10 through 50 by the last two digits of the 5-digit MOS code. Skill level 20, which is the journeyman level, is defined as pay grade E-5; higher skill levels essentially add supervisory and instructional duties to the technical skill requirements of the MOS.

A brief review of the factors and their indicators follows.

Cognitive Requirements. The primary factor determining job complexity is the level of cognitive skills required for successful performance. Troubleshooting tasks are more complex than other types of maintenance tasks because they require problem-solving, perceptual, and information-processing abilities in addition to a functional understanding of the system and its subsystems. A job (MOS) specification with no troubleshooting tasks implies a simpler maintenance job than one with troubleshooting tasks.

The required level of cognitive skills is a function of inherent complexity (see Table 3-1) and the level of detail and accuracy of the aids provided to the technician, be they built-in software diagnostics, display-aided maintenance (off-line, computer-controlled prompting) or hard copy manuals (technical manuals, extension training materials, skill performance aids, etc.). Even if a specific troubleshooting task is fully procedurized, it normally would demand some cognitive skills.

A typical differentiation of cognitive requirements, as shown in Table 3-2, consists of: decision requirements, incomplete information to determine the next step in a fault isolation procedure, pattern recognition requirements, and interpretation requirements. Given a job task list and the associated aids used by the technician, an industrial psychologist would be able to classify the cognitive tasks involved in terms of these four categories. An appropriate measure for these indicators should take into account the frequency of task occurrences.

Task Diversity. Task diversity is defined by the number of different equipments supported by the same MOS and by the different area specialties involved. Both indicators should probably have a non-linear scale. The number of area specialties should be expressed as a percentage of an established list of such specialties to ensure rating consistency. A preliminary list of electronics specialties is shown in the Appendix.

Test Equipment. Maintenance personnel may have difficulty in using test equipment proficiently. The amount of test equipment required is thus related to job complexity. It is more difficult to acquire the necessary expertise if the test equipment is system-peculiar rather than common. Thus, Table 3-2 distinguishes between the numbers of common TMDE and system-peculiar STE required to perform the job tasks.

Information Load. Page count is a valid indicator of job complexity: the more pages in a manual, the greater the probability of inaccuracies and mistakes. When some maintenance MOSs have a physical count of over 15,000 pages of manuals, there is something wrong with the way jobs are designed. Display aid maintenance which guides the technician through a procedure, step by step, can simplify a task. But again the length of the procedure (number of instructions or steps required to complete the task) is an indicator of potential for errors, both on the part of the technician and the aid; and, the greater the potential for errors, the greater is the time required to attain job proficiency.

Task Uniqueness. Frequency of task performance is a basic indicator of a technician's proficiency. With the increasing reliability of electronics modules, this indicator may become even more important. Tasks occurring infrequently must be fully procedurized.

Defining an infrequent task is difficult. It depends on the proficiency decay curve, which is a function of skill level and the discipline or area specialty involved. Little research has been found on this subject in the literature. The ARTS (12) suggests that maintenance proficiency decays rapidly, requiring roughly the following levels of on-the-job reinforcement:

- remove/replace tasks, mechanical adjustments: once per year
- mechanical troubleshooting: once per quarter
- electronic troubleshooting: more frequently

These average frequencies apply to a situation where tasks are carried out under strict supervision; without supervision, the frequencies required to maintain proficiency would be higher. We suggest that, in the absence of fielded maintenance training simulators, any electronics troubleshooting tasks occurring less than six times a year should be fully procedurized.

Obviously, there is a relationship between proficiency decay and the individual's aptitude and cognitive abilities, but we have not located any pertinent studies. Further research will be required to define the implications of task uniqueness precisely.

Comments

The maintenance concept affects job complexity indirectly through its impact on the indicators just described. Defined by the maintenance allocation chart, the maintenance concept indicates what tasks are to be performed at each echelon of maintenance (including what the removable items are at each indenture level). The complexity of these tasks is affected by the system's self-test characteristics (Table 3-1) and off-line aids such as JPAs (for off-equipment repairs the test programs available on automated test equipment affect task complexity). The allocation of these tasks to specific MOSs through job design affects job complexity. All three, maintenance concept, job design, and aids are interrelated and should be part of the same design process. Traditional occupational analysis conducted by the services using standard survey questionnaires and the Comprehension Occupational Data Analysis Program (CODAP) is not specific enough to permit assessment of job complexity. Foley (39) has recommended specific formats for collecting additional data required to better integrate the front-end analysis process (task and skill analysis, instructional system development and JPAs).

Job complexity can be controlled by assigning the most complex tasks such as troubleshooting to a separate cadre of experienced technicians outside the enlisted MOS structure, e g., warrant officers. This implies, incidentally, that assessment of maintenance complexity should not be limited to enlisted personnel requirements. Chapter 2 has commented on the practical and theoretical limitations of JPAs in reducing task complexity; specifically,

fully procedurized aids for digital electronics troubleshooting have so far not been successful, though recent research shows promise (14).

Finally, whether or not mission criticality should influence task and job complexity is a matter of debate. We have elected to avoid this issue by proceeding on the assumption that all active maintenance tasks specified for the job are equally important.

APPARENT COMPLEXITY

Overall Measure

Apparent complexity applies to a specific individual in a specific billet. It is determined by the gap between the skills, knowledge, and abilities required by the job and those possessed by the person. If selection, training, and personnel utilization were perfect, maintenance complexity would be the combined outcome of inherent and job complexity. Apparent complexity is the increase in job complexity caused by shortcomings in personnel selection, training, and utilization. The proposed measure of apparent complexity is the percentage of job tasks the technician can perform correctly within set time standards.

Factors and Indicators

The problems related to specifying indicators of apparent complexity were discussed in Chapter 2. Indicators such as the difference between skills/ knowledge required and training standards, and between basic abilities required and possessed, are unknowable without meaningful training standards and a knowledge of basic ability-job relationships. We have defined a number of proxy indicators of apparent complexity which are associated with the following factors:

- person/billet mismatch
- training deficiencies

- skill utilization deficiencies
- individual differences

Table 3-3 lists these factors and indicators. A brief review of each factor follows.

TABLE 3-3. APPARENT COMPLEXITY INDICATORS

A. PERSON/BILLET MISMATCH

1. Duty MOS differs from primary MOS
2. Incumbent does not possess ASI required by billet
3. Incumbent's skill level less than required by billet

B. TRAINING DEFICIENCIES

1. Managed OJT deficiency
2. Unmanaged OJT deficiency
3. Apprentices per NCO during (M)OJT
4. School practice deficiency
5. Non-availability of training equipment
6. Functional theory deficiency

C. SKILL UTILIZATION

1. Diversions from MOS-related work
2. Time since last worked on equipment

D. INDIVIDUAL DIFFERENCES

1. Reading level less than required
2. Aptitude less than required
3. Psycho motor abilities less than required
4. Cognitive abilities less than required
5. Number of times recycled in technical training

Person/Billet Mismatch. Imbalances between job requirements and personnel inventory and the administrative lead time required for assignment often cause mismatches between persons and billets. None of the Services exercises centralized control over assignments. Units periodically receive replacements matching as closely as possible projected vacancies (= authorized billets minus on-board personnel) in terms of primary MOS, additional skill

identifier as needed, and skill level. The closeness of the matches is subject to the logic of the assignment system, imbalances between billet authorizations and deployable personnel, and unpredictable events occurring between the assignment decision and the assignee's arrival. The actual placement of a person in a billet is the commander's prerogative.

Mismatching may also be done deliberately, for example to facilitate cross-training and the acquisition of secondary and tertiary MOSs. Mismatches are not necessarily bad, but they do affect job proficiency.

Training Deficiencies. Lack of an MOJT program is a prime cause of enlisted personnel's inadequate maintenance capabilities. Informal OJT (as indicated by the time a technician spends on learning tasks spelled out in his manuals) might compensate for this to some extent, if enough skilled NCOs were available to help the apprentice.

To quantify the contribution of MOJT and OJT shortcomings to apparent complexity, their requirements must be known. Unfortunately, a training plan developed under the instructional system development approach does not normally spell out these requirements beyond identifying the critical tasks not taught in school and developing the corresponding extension training material for use in the field. The Army does not have a training cadre for conducting OJT; there is no MOJT program for any of the electronics maintenance MOSs we have studied; and it is doubtful in any case whether novices can learn complex tasks solely through serving as helpers on the job. Pending further research, any attempts to quantify (M)OJT deficiencies would have to be based on expert judgment.

Potential causes of school training (AIT) deficiencies include: lack of hands-on training (equipment is often down for maintenance or supply); lack of the theory required to understand cause-effect relations within a

system; more emphasis on rote learning than on cognitive skills; and deviations from the program of instruction (POI). These indicators could be quantified in terms of actual versus required time, assuming that the POI defined the requirements. However, since most of the entry-level courses are self-paced, the material completed will be in accordance with the given POI. The question then becomes whether the POI reflects the "true" training requirement. In the absence of indicators predictive of POI quality, this question can only be answered through analysis of observed values of the criterion measure, actual job proficiency. However, Mallory and Elliot (13) show the potential of using a hardware-free test for assessing a student's troubleshooting skills.

Skill Utilization. In the field, MOS diversions and improper use of personnel in response to operational requirements may detract from job proficiency. For example, field data suggest that an Army maintenance technician (skill level 20 and below) typically may spend 30% of available time on non-MOS related duties (1). This obviously limits the opportunity to gain technical proficiency. Or there may be such specialization within an MOS that the technician loses proficiency in other tasks related to that MOS. For most MOSs responsible for a variety of end items, the items at the duty station determine what equipment the technician will be working on. Upon reassignment to another duty station where different end items are fielded, that technician may be less proficient than the skill level would suggest.

Individual Differences. Of the indicators listed under "Individual Differences" in Table 3-3, only reading level is both measurable and valid in terms of apparent complexity. If an individual's reading level is below that for which the job manual was written, the apparent complexity of the job will

be affected. The other indicators either are available but have poor validity, or have demonstrated validity but are currently unavailable.

The only measures of aptitude now available are obtained from the ASVAB. The electronics aptitude composite (EL) is the single selection standard for all Army electronics maintenance MOSs, with cutting scores ranging from 90 to 110 depending on MOS (the Army uses a standardized scale of 40 to 160 with aptitude scores of 100 representing the mean). The EL currently combines the following four subtests with equal weights: general sciences, arithmetic reasoning, mathematics knowledge and electronics information; thus, it is both an aptitude and a knowledge test. However, as previously discussed in Chapter 2, the EL does not predict job performance (37). (Nor does the reading level which correlates well ($r = 0.8$) with the ASVAB composite tests (38).) The need for better selection test batteries is well recognized (34).

Each MOS has an EL prerequisite which is seldom waived, but its validity is suspect (see previous discussion of job complexity). Thus, neither aptitude as measured by ASVAB, nor deviation from stated prerequisites is necessarily indicative of apparent complexity.

Basic task-performance-related abilities are currently not recognized nor tested for in the Army, even though research has shown their validity (9, 32).

Data on recycling in AIT are difficult to obtain. Recycling may be caused by aptitude and motivation problems predictive of future job performance, but may also be caused by basic learning problems which could be overcome by teaching students how to learn (15).

Comment

Apparent complexity receives little attention in weapon system acquisition. Its consideration during the design process is limited to

"target audience" descriptors normally provided by the user community to the system developer. Apparent complexity is not a primary responsibility of the program manager, but of the TRADOC and the user commands.

Apparent complexity must be monitored to ensure that the planned support system is not defeated through poor implementation. Consider, for example, what has happened to the support of the common FM radio, the AN/VRC-12 family. The design of this radio was based on modularization, with components replaceable in the field. MOS 31V (radio mechanic) was to do most of the repairs at the organizational level, while MOS 31E (radio repairer) would check out and repair the LRUs at the direct support/general support levels. The failure of this rational maintenance concept over the past decade would take longer to document than space permits. Briefly, the basic causes were as follows:

- The test equipment for the 31V did not perform as planned.
- The TMs included incorrect procedures for troubleshooting.
- The training of the 31V was deficient.

As a result, the standard operating procedure both in USAREUR and FORSCOM for the past several years has been to by-pass the organizational level, and to evacuate the faulty radios to direct support (in FORSCOM units most radios end up at the civilian Director of Industrial Operations support organization at the post). While corrective actions are being implemented, recent surveys have demonstrated that most of the radios were in non-operative condition and probably had been so for many years. What should have been a very simple maintenance job (low scores on inherent complexity and job complexity) became a nightmare in terms of apparent complexity due to inadequate operational testing and monitoring of job performance.

Quantitative measures for most indicators of apparent complexity are simply not available. Instead of attempting to predict apparent complexity, efforts should be focused on further improving its measurement by means of job task performance testing.

4. VALIDATION AND APPLICATIONS OF TAXONOMY

INTRODUCTION

The preceding two chapters have described a methodology for assessing the maintenance complexity of weapon systems. Maintenance complexity consists of three major components: inherent complexity, comprising factors which are purely equipment-related; job complexity, comprising factors associated with the maintenance tasks allocated to each MOS; and apparent complexity, comprising factors representing the gap between the capabilities required by the job and those possessed by the person assigned to it. A criterion measure was defined for each of the three complexity components. For each of the contributing factors, a set of indicators was identified, permitting assessment of the contribution of each factor to the first two of the criterion measures.

Much more needs to be done to convert the taxonomy into a useful tool for assessing maintenance complexity. First, research is required to develop the criterion measure of job complexity: an anchored, benchmark scale combining expert ratings of learning difficulty and aptitude/ability prerequisites for each maintenance job in the Army. Second, institutionalized job proficiency measures such as job task performance tests (e.g. the Army's SQT) must be validated before they can be used as criterion measures of apparent complexity. Third, the given indicators of inherent and job complexity, their metrics, and their relationships to the two associated criterion measures must be tested and validated.

Once this work has been accomplished, the taxonomy could be applied as a standard, analytic tool to predict, identify or measure logistic support

deficiencies caused by the inability of maintenance personnel to perform their maintenance tasks as planned.

VALIDATION APPROACH

Validation of the proposed taxonomy would be a major undertaking, requiring full cooperation and participation from the Service involved. The Army, faced with the largest jump in hardware complexity through the force modernization planned for the 1980s, would benefit most from a serious analysis of maintenance complexity.

Validation would entail the following efforts. First, the job complexity scale must be developed with ratings of difficulty to learn and aptitudes required for a sample of maintenance jobs. The Army Research Institute would be the logical organization to lead this effort, which could build upon the related work performed by the Air Force (10). Second, quantitative data must be collected on all indicators of inherent and job complexity (Tables 3-1 and 3-2) for the same sample of MOSs and associated weapon systems. This effort would require participation by DARCOM and TRADOC. Third, the sample data must be subjected to statistical analysis to determine the relationships between criterion measures and indicators. The appropriate scales or metrics for the indicators must also be determined. Fourth, additional sample data on other MOSs and weapons systems must be obtained, repeating the first two steps. Using the equations determined earlier, predicted values of the criterion measures must be compared with the actual ones for this second sample. Due to the relative "softness" of some of the data, the process may have to be iterated until an acceptable confidence level has been obtained.

It may be advisable to start off with a few pilot applications of the taxonomy, prior to a full-scale validation program, to ascertain whether the taxonomy makes sense and is capable of explaining variances in maintenance

capabilities. In view of the limited sample data available in such a pilot effort, statistical analysis may need to be supplemented with expert judgment. One could convene a select group of senior NCOs or warrant officers with the requisite technical experience, supplemented with representatives of the schools where the MOSs involved are taught, and MILPERCEN. Using a DELPHI-type of approach, average values of the relative weights of the indicators could be obtained from the participants' assessments. Such an expert panel would also be helpful in reviewing the taxonomy and determining the appropriate scales for the indicators. On the other hand, using technical experts to directly quantify job complexity, skill level and training requirements based on an early engineering data package (without the aid of a taxonomy as proposed here) results in inconsistent, invalid estimates (31).

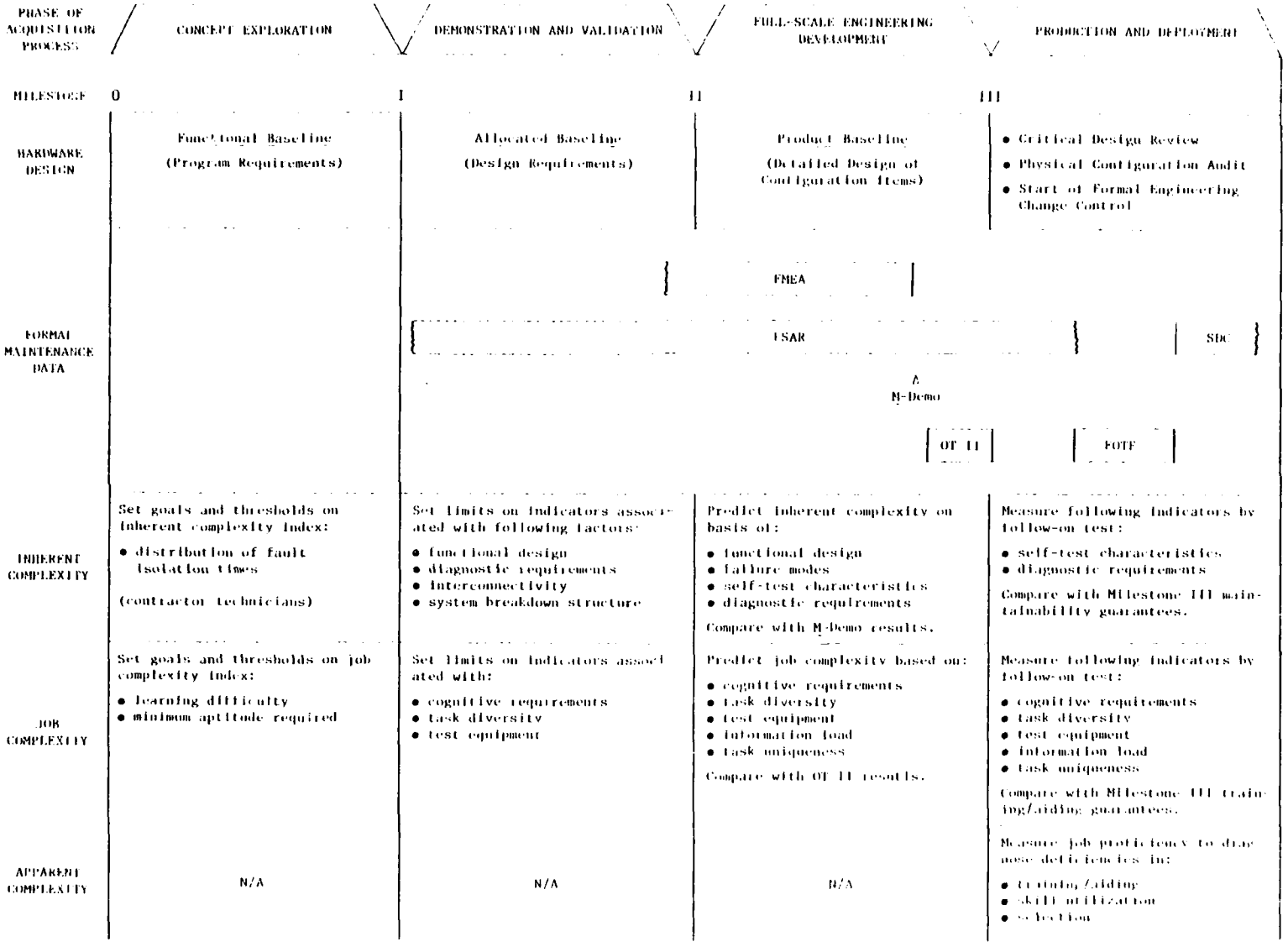
APPLICATIONS

Potential applications of the taxonomy are twofold: (1) micro analysis of the maintenance complexity of a new weapon system as part of the acquisition review process, and (2) macro analysis of maintenance complexity for MOS, mission area or Service aggregates. Each application focuses on different aspects of the taxonomy. Both types of analysis are comparative. Macro analysis identifies trends in maintenance complexity over time; micro analysis compares the maintenance complexity for a new system with that of the system it will replace or with that of another, comparable system in the inventory.

Micro Analysis

Figure 4-1 illustrates the potential use of the taxonomy in the weapon system acquisition process. The bottom portion of the figure identifies the factors on which the review process should focus--factors limited to inherent and job complexity.

FIGURE 4-1. MICRO ANALYSIS OF MAINTENANCE COMPLEXITY

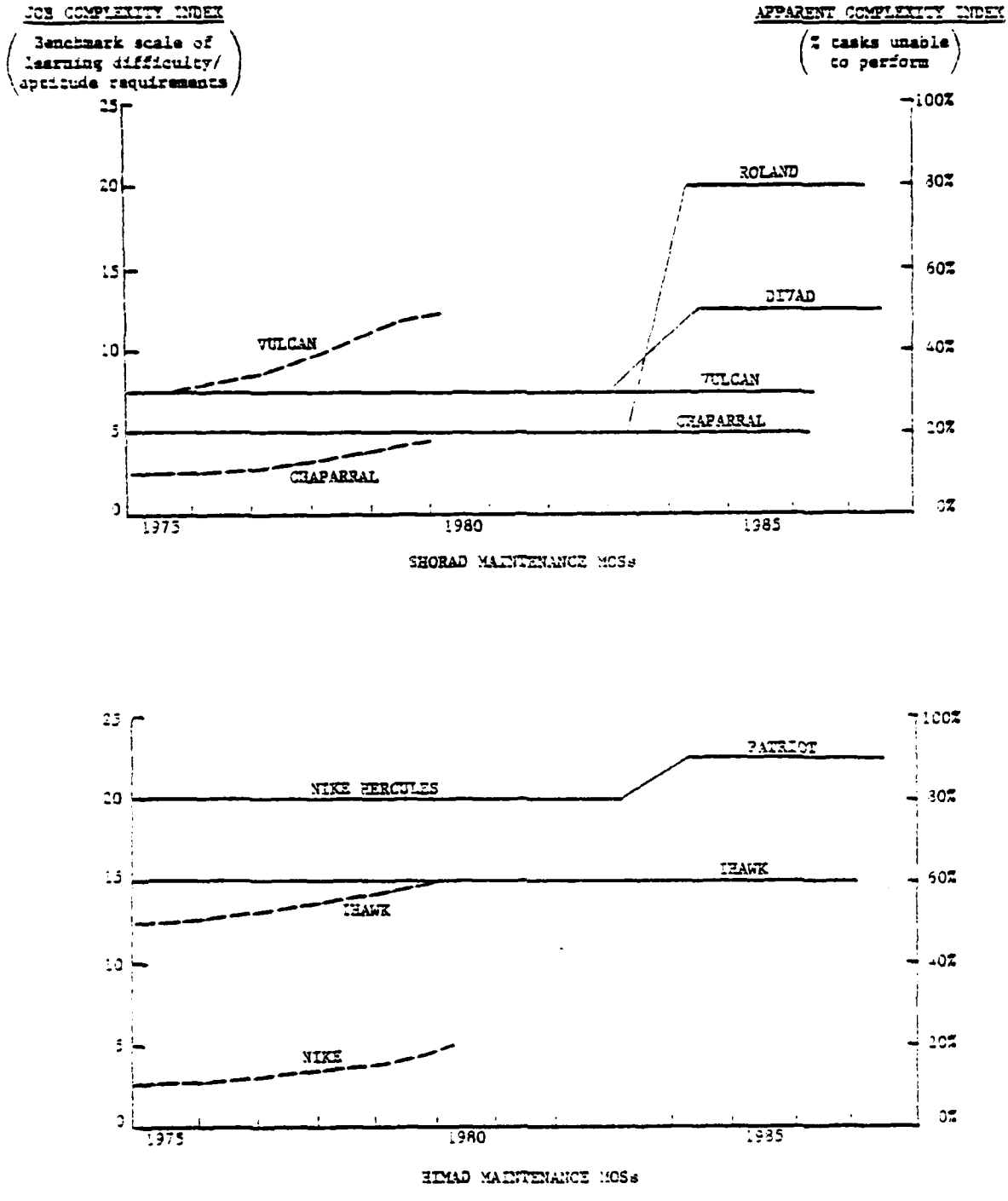


Macro Analysis

Figure 4-2 illustrates a potential application of the taxonomy in assessing trends in job complexity within a selected set of MOSs. The curve depicting trends in apparent complexity as measured in the past, in combination with estimated future changes in job complexity, may suggest needed improvements in personnel selection, training, or support concepts.

FIGURE 4-2. EXAMPLE OF MACRO ANALYSIS OF MAINTENANCE COMPLEXITY

(Hypothetical Data)



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APPENDIX

EXAMPLE OF AREA SPECIALTY LIST

Task diversity is one factor influencing the job (MOS) complexity index. One indicator of task diversity is the number of different area specialties which the MOS must master (Table 3-2). To use the taxonomy, it would be desirable to have a complete list of area specialties within each discipline (electronics, mechanical, pneudraulics, optics, etc.). Compilation of such a list is probably best left to subject area experts. An example of an area specialty list is shown on the following pages. It lists the subject areas identified in the Air Force's Electronic Principles Inventory (EPI) program which is used in their occupational survey work (4). The EPI program recognizes 1,257 "electronics principle items" classified into 62 "subject areas" and 21 "duty groups."

TABLE A-1. EXAMPLE OF ELECTRONICS AREA SPECIALTIES

Duty Group	Area Specialty	Number of EPI
A	1. Mathematics	14
	2. Direct Current and Voltage	9
	3. Resistance	28
B	1. Multimeter Uses	9
	2. Alternating Current	6
	3. Inductors and Inductive Reactance	25
C	1. Capacitors and Capacitive Reactance	36
	2. Transformers	43
	3. Magnetism	14
D	1. RCL Circuits	44
	2. Series and Parallel Resonance (Time Constants)	10
	3. Filters	22
E	1. Coupling	12
	2. Soldering	22
	3. Relays	19
F	1. Microphones	13
	2. Speakers	15
	3. Oscilloscopes	12
G	1. Semiconductor Diodes	50
	2. Transistors	24
	3. Transistor Amplifiers	49
H	1. Solid-State Special Purpose Devices	6
	2. Power Supplies	29
	3. Oscillators	27
I	1. Multivibrators	16
	2. Limiters and Clampers	10
	3. Electron Tubes	44
J	1. Electron Tube Amplifiers and Circuits	7
	2. Special Purpose Electron Tubes	16
	3. Heterodyning, Modulation, and Demodulation	6
K	1. AM Systems	28
	2. FM Systems	19
	3. Numbering Systems	10
L	1. Logic Functions	13
	2. Boolean Equations	25
	3. Counters	24

TABLE A-1. EXAMPLE OF ELECTRONICS AREA SPECIALTIES (Continued)

Duty Group	Area Specialty	Number of EPI
M	1. Timing Circuits	12
	2. Use of Signal Generators	10
	3. Motors and Generators	29
N	1. Meter Movements	10
	2. Saturable Reactors and Magnetic Amplifiers	16
	3. Waveshaping Circuits	11
O	1. Single Sideband Systems	30
	2. Pulse Modulation Systems	39
	3. Antennas	39
P	1. Transmission Lines	31
	2. Waveguides and Cavity Resonators	50
	3. Microwave Amplifiers and Oscillators	76
Q	1. Registers	7
	2. Storage Devices	9
	3. Digital to Analog Converters	14
R	1. Phantastrons	1
	2. Schmitt Triggers	3
	3. Cable Fabrication	2
S	1. Input/Output Devices	3
	2. Photo Sensitive Devices	1
	3. Synchronous Vibrations (Chopper Circuits)	9
T	1. Infrared	27
	2. Lasers	34
	3. Display Tubes	14
U	1. Programming	21
	2. DB and Power Ratios	3