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COMPUTER SUPPORT FOR CONDUCTING SUPPORTABILITY TRADE-OFFS IN A TEAM SETTING

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This paper presents the results of a research project that had the objective of demonstrating how the conceptual approach of the Boothroyd and Dewhurst Design for Assembly (DFA) process could be applied to developing products which are more easily supported in the field. In this project, a specific methodology was developed which allows a product development team to make system-level trade-offs between redundant part selection and scheduled maintenance visits in order to achieve both low life cycle cost (LCC) and high operational readiness of the resulting system. This methodology was demonstrated for a subsystem of a ground-based radar and evaluated by participants in the demonstration.

14. SUBJECT TERMS

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PREFACE

This paper is the result of work performed by the Institute for Defense Analyses (IDA) under contract number MDA 903 89 C 0003, Task Order T-D6-554, Amendment Number 2, "Measurement Issues in Unified Life Cycle Engineering." This work was performed for the Air Force Human Resources Laboratory, Logistics and Human Factors Division, and the Under Secretary of Defense for Acquisition (USD(A)). The report addresses development of a methodology for assessing and ranking designs with respect to one or more aspects of supportability and specifically addresses tasks 4.a, 4.b, and 4.c in the task order.

This paper was reviewed by Dr. Jeffrey H. Grotte, of IDA, Dr. Joel Tumarkin, an IDA consultant, and Mr. Frank Roth, of Texas Instruments.

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ACRONYMS

AFHRL	Air Force Human Resources Laboratory
AI	artificial intelligence
CALCE	Center for Computer-Aided Life Cycle Engineering, University of Maryland
CFE	complex functional element
DFA	Design for Assembly
DoD	Department of Defense
FAA	Federal Aviation Administration
FOM	figure of merit
Fr/Mhr	failures per million hours
IDA	Institute for Defense Analyses
JSS	Joint Surveillance System
LCC	life cycle cost
LFE	lower functional element
LRU	line-replaceable unit
MIL-HDBK	military handbook
MTBCF	mean time between critical failure
MTTR	mean time to repair
PWB	printed wiring board
RADC	Rome Air Development Center
ULCE	Unified Life Cycle Engineering
USD(A)	Under Secretary of Defense for Acquisition

EXECUTIVE SUMMARY

A. OBJECTIVE

This paper presents the results of a research project that had the objective of demonstrating how the conceptual approach of the Boothroyd and Dewhurst Design for Assembly (DFA) process could be applied to developing products that are more easily supported in the field.

In this project, a specific methodology was developed that allows a product development team to make system-level trade-offs between redundant part selection and scheduled maintenance visits in order to achieve both low life cycle cost (LCC) and high operational readiness of the resulting system. This methodology was demonstrated for a subsystem of a ground-based radar and evaluated by participants in the demonstration.

B. BACKGROUND

The Department of Defense (DoD) has recently focused on correcting problems within the weapon system acquisition process. Concurrent engineering, an approach to product development, has been advanced as a potential solution to problems in weapon system acquisition related to designs that are difficult to produce and support in the field. This approach involves use of a multifunctional team with representatives from all relevant parts of government and industry (product users, designers, manufacturing engineers, and logistics support specialists) to develop--in parallel--the product design and the associated processes for manufacture and support. Such an approach significantly reduces development cost and lead time and results in products that are easier to make, use, and support and are more reliable in operation.

To successfully implement a concurrent engineering approach, a structured methodology for aiding the multifunctional team in developing the product is needed. In fact, several methodologies are needed, depending on the specific aspects of the product being considered by the team. Quality function deployment, for example, is a useful structured group technique for translating customer needs into design requirements and

tracking the rationale for specific design decisions. Another technique that has proven very useful in helping product developers to improve designs from the standpoint of manufacturing is the Boothroyd-Dewhurst DFA methodology. The key elements of this methodology are

- Product development by a multifunctional team
- Relative assessment of alternative designs with a metric
- Training in fundamentals of the methodology and underlying metric
- A specific procedure for creating alternative designs
- Computer support during team product development meetings.

Ease of assembly is only one aspect of a design that affects its LCC. Product supportability also significantly affects LCC and should be considered by a concurrent engineering team early in the product development process. In this project, the research team investigated how the conceptual approach of Boothroyd and Dewhurst could be applied to the area of supportability. The research team sought to identify certain aspects of supportability that are of importance to DoD and for which specific implementations of the general elements of the DFA approach could be developed and demonstrated.

C. APPROACH

An extensive literature review was initiated at the beginning of the task to identify existing techniques for defining, measuring, and designing for supportability. The goal of this review was to identify aspects of supportability to focus on. As a result, the research team, in cooperation with the sponsor, decided to limit the aspects of supportability considered in this investigation to maintainability, reliability, and logistics support, in this order of priority.

Since maintainability received the highest priority, the research team refined the literature review to focus on maintainability and identify methodologies and guidelines used in design for maintainability.

The literature review established that no universally accepted definition of maintainability exists [Ref. 1]. No concise, manageable set of generic guidelines for design for maintainability could be gleaned from the extensive lists found in various government and industry references. The research team determined that design for maintainability guidelines must be specifically tailored to the product being developed.

This finding prompted the research team to further restrict its attention to a specific design problem.

Maintainability, reliability, and logistics support, are all related and should be considered together in designing a system for supportability. Isolated consideration of one aspect of supportability, such as maintainability, is not a desirable approach. To achieve a good design--in terms of supportability--the design team must be able to analyze the effects of trade-offs among these design attributes.

To more specifically identify the kinds of trade-offs that would be appropriate for consideration in this project, the research team collaborated with academia and industry through a cooperative arrangement with the University of Maryland Center for Computer-Aided Life Cycle Engineering (CALCE). This center, an industry-university cooperative research center sponsored by the National Science Foundation, has as its primary focus development of new techniques for designing electronic products for reliability, maintainability, and supportability. The CALCE center is the only center of its kind in the country that is focusing on design for supportability of electronics. Its director, Dr. Michael Pecht, is a nationally recognized expert in design of electronic systems for supportability.

A number of major industrial defense electronics suppliers are members of the CALCE center--Westinghouse Electric, Texas Instruments, Digital Equipment Corporation, Northrop, General Electric, Allied Signal, and General Dynamics. Westinghouse Electric and Texas Instruments agreed to provide technical support to IDA in the development of the methodology and to participate in a demonstration and evaluation of the methodology at the conclusion of the project.

The ARSR-4 was selected as the baseline system to be used for development of the methodology. The ARSR-4 is a ground-based, long-range 3-D radar currently under development by Westinghouse Electric. The system is being designed to meet the air traffic control and air defense sensor requirements of the Federal Aviation Administration (FAA) and the U.S. Air Force's Joint Surveillance System (JSS). The ARSR-4 was selected for the methodology development because the design information (and designers) needed for the methodology was readily available, and Westinghouse Electric was willing to supply this information to the CALCE Center. In addition, considerations of supportability are playing a significant role in the design of the ARSR-4.

D. METHODOLOGY DEVELOPMENT

The ARSR-4 is being designed by Westinghouse for unattended operation and low LCC. The only support equipment it will require is a limited number of tools on site and equipment already part of the FAA/Air Force inventory. To achieve high reliability and allow continuous operation, redundancy is used extensively in the design of this system. Scheduled maintenance visits are also used to enhance reliability through periodic replacement of failed redundant components.

These approaches to enhancing reliability are not without cost, however. Increasing the number of redundant components increases system acquisition cost, while increasing the frequency of maintenance visits increases system logistics support cost. If a given level of system reliability is required, increasing redundancy allows the frequency of maintenance visits to be reduced, and conversely, increasing the frequency of maintenance visits allows redundancy to be reduced. The net LCC impact of changing both redundancy and maintenance visit frequency will depend on the relative magnitudes of such factors as the cost of the parts being made redundant, manpower and transportation costs associated with maintenance visits, and spares costs.

To minimize the total system LCC, which includes both acquisition and support costs, a method for obtaining the proper balance between redundancy and maintenance visit frequency is needed. To obtain such a balance, the product development team needs the freedom to vary both the level of redundancy and the frequency of maintenance visits, and the capability to estimate the LCC impact of such changes.

In the current government acquisition process for the ARSR-4, the product developer was given specifications that prescribe the number of maintenance visits per year. These specifications also limit the number of maintenance actions that require or cause shut down of the system. In seeking to attain the required level of system reliability, the product developer has the freedom to vary only the level of redundancy in the system, leading to the potential for suboptimal system LCC.

The methodology developed in this project supports analyzing such trade-offs. The methodology was developed by researchers from the University of Maryland and IDA working with personnel from Westinghouse Electric and Texas Instruments.

At the same time the methodology was developed, the CALCE Center researchers developed software that supports a product development team in executing the

methodology. This software, developed in collaboration with IDA, Westinghouse Electric, and Texas Instruments, is an extension of the existing CALCE software package, which is supplied to center members. The extension incorporates many existing CALCE software capabilities such as the parts data base and graphics displays. New features incorporated in support of the methodology include the capability to calculate the reliability of redundant systems with repair and the capability to estimate acquisition cost and life cycle maintenance visit costs for systems with redundant parts.

E. DEMONSTRATION AND EVALUATION

A demonstration and evaluation of the methodology took place on September 20, 1989, at the University of Maryland. Representatives from IDA, the Air Force Human Resources Laboratory (AFHRL), the University of Maryland, Texas Instruments, and Westinghouse Electric attended. The demonstration consisted of a presentation by Dr. Pecht on the theory of redundant systems with repair (which is the theoretical basis for the methodology), a demonstration of how the computer is used to support the group deliberations, a working session in which redundancy and scheduled maintenance were assessed for a subassembly of the ARSR-4, and a discussion in which the methodology was evaluated and recommendations for future research and enhancements were given. The following paragraphs summarize these recommendations.

1. Identifying Where to Add Redundancy in the System

In using the methodology developed in this project, a product development team must rely on the expertise of members in determining which system elements to make redundant. An analytical solution to the problem of identifying locations and levels of redundancy to minimize LCC seems unlikely, especially if the entire radar system is considered. However, rules could be developed to guide the product development team in selecting where to place redundancies, leading to improvements in the resulting designs and a more efficient product development process. Development of such rules should be the topic of future research projects.

2. Initiating and Managing Trade Studies

As additional capabilities are added to the computer support available to the product development team, the number of potential excursions and trade-off analyses rapidly expands, and team members may spend valuable time on issues with limited benefits (or

analyze less viable trade-offs). A structured way to identify specific trade-off analyses to be conducted, based on experience and judgment, is needed to best focus team efforts.

3. Addressing Ramifications of Increased Redundancy

A number of side effects are generated when additional redundancies are added to a system. At present, the methodology does not consider these effects. Additional research is needed to allow such effects to be addressed within the context of the current methodology.

These effects include

- Increased system power requirements when additional active redundancy is added (resulting in degradations in reliability)
- Increased size and weight of the system resulting from added redundant components
- Increased system complexity -- resulting in increased development time and cost
- Increased support equipment required to handle redundancy (switching/voting devices, interconnections, environmental conditioning), leading to increased cost and degradation of reliability
- Increased difficulties in fault detection and isolation resulting from redundancy, leading to increased logistic support costs due to requirements for additional spares and manpower.

4. Assessing Life Cycle Cost

The methodology now handles LCC through use of an LCC indicator comprising separate estimates for parts and maintenance costs. The industry participants viewed this approach as useful and appropriate for assessing LCC. The accuracy of individual components of the indicator, however, could be improved.

For example, the methodology now uses total parts cost to represent the acquisition cost of the system; however, the cost of the parts is only a small portion of the total acquisition cost. The large expenditures for engineering man-hours and overhead are ignored. Thus, one enhancement to the methodology could be developing a more realistic acquisition cost indicator.

The support cost indicator, the maintenance visit cost, could be modified to more accurately reflect the support costs by considering items such as levels of maintenance

(with considerations of, for example, the relative costs of built-in-test versus external test equipment).

While more realistic cost indicators are desirable, the industry representatives strongly recommended that a full LCC model not be incorporated into the analysis. Industry acceptance of the validity of such models is not sufficient to justify their use in the methodology.

5. Recording Team Activities

An audit trail of the various alternatives considered by the product development team during the trade-off process should be provided. A way to save alternative configurations and their associated analysis results is needed. Maintaining the history of a small subsystem would not necessarily require significant computing resources. If the entire radar is modeled, maintaining an audit trail could require significant amounts of storage and entail significant information management problems.

6. Assessing the Entire Radar

While the methodology demonstrates the concept of performing trade-offs of redundancy versus maintenance visits, for such trade-offs to be realistic, the entire radar system must be modeled. This need raises issues related to increasing the computer support capabilities to handle the level of detail required to model the entire system. To address issues such as assessing the relative benefits of changing the quality level of a certain part, which may appear 500 times in a number of separate subsystems, additional computer support capabilities are needed. These capabilities are also needed because the builder of the radar warrants the entire system and is interested in the reliability and maintenance cost of the total system, not just a small subsystem as was used in the demonstration.

F. FINDINGS AND RECOMMENDATIONS

This project has successfully demonstrated how the conceptual approach of DFA can be applied to design for supportability. The findings and research opportunities identified during this project have been grouped into three categories and are presented in the following sections.

1. Organizing and Managing Teams

Having a core product development team that charters specialty teams as needed was the IDA research team's vision of how product development teams could be organized. The organizational issues involved with creating and managing concurrent engineering teams, and in particular, the activities of multiple teams, warrants a substantial research effort. A core team, like the one envisioned for this project, could coordinate the work of the other teams, each of which would be investigating certain problems and conducting trade studies. However, one team could conduct a study indicating that a certain course of action should be followed to realize certain benefits, yet this action may create problems for another team that is trying to achieve other goals. Such conflicts must be resolved.

The most common way resolving such conflicts is through design review boards (which often meet after design decisions are made) and ultimately, by autocratic decisions made by engineering management. This approach often leads to failure to identify and resolve major conflicts until a stage in the design process in which design changes are very expensive. A better way is needed.

During the demonstration of the methodology developed in this project, the group interactions were completely unstructured. However, structured group problem solving methodologies have been shown to make group problem solving more efficient. Identifying promising structured group problem solving methodologies for concurrent engineering is another area for research.

This project has shown that government requirements, such as specifying the number of maintenance visits, can place unnecessary constraints on a product development team. This type of limitation could result in products with LCC higher than necessary. An approach to product acquisition in which the requirements are jointly developed by a team consisting of both government and industry personnel would result in requirements that do not unnecessarily restrict the design freedom of the product development team. The research team did not consider any legal or political issues associated with using such an approach to acquisition. These issues would have to be addressed before such an approach to acquisition could be implemented.

2. Computer-Aided Group Problem Solving

The proper role of the computer in support of group problem solving is an area of growing research. Approaches range from the group sharing a single computer during the

meeting (as was done in this project) to providing a separate computer for each attendee. Other areas of research are concerned with supporting the group when they are working in a distributed environment.

This project demonstrated that software originally designed for a single user can be used in a group setting. Contrary to claims made by some researchers, specific group-oriented software is not necessarily required. The use of other single-user software in group settings should be explored.

How the computer support for the team is developed is an open issue. One approach is to let the product development team build its own computer models using spreadsheets or similar software shells. One advantage of models built by the team is that the team members will be confident of the model's accuracy, since the team itself verified the validity of the approach used in the model.

3. Design for Maintainability

The final area that requires additional research is a developing design for maintainability methodologies and tools. Significant gaps exist in the field of design for maintainability. The review of the research literature found a lack of consensus in the research community on the definition of maintainability and how to design for maintainability. Many of the industry maintainability specialists interviewed during this study defined designing for maintainability as calculating the Military Handbook (MIL-HDBK) 472 attributes of a design, such as mean time to repair (MTTR).

The available measurements of maintainability have not kept pace with advancing technology. For example, the techniques proposed in MIL-HDBK 472 do not properly handle designs in which high reliability is achieved through use of redundancy with repair. In such situations, scheduled maintenance is the key element--not corrective maintenance, which is the only item addressed in the handbook.

G. FUTURE DIRECTIONS

The methodology developed during the course of this project only begins to address the many considerations relating to incorporation of supportability into the product development process. Much remains to be done. However, the results of this project, which was limited in its scope and funding, clearly indicate that there is great potential for improving development processes through use of relatively simple approaches to aid product development teams. The conceptual approach of Boothroyd and Dewhurst, which

has been proven successful in improving the ease of assembly of designs, and has been applied to limited aspects of supportability in this project, can also be applied to many other issues that must be addressed if the goals of improved quality, reduced cost, and shortened development lead time are to be attained. Moreover, such applications need not be costly to develop. The relative benefits from taking such an approach on major weapon system acquisition programs are likely to be great.

I. INTRODUCTION

This paper presents the results of a research project that had the objective of demonstrating how the conceptual approach of the Boothroyd and Dewhurst Design for Assembly (DFA) process could be applied to developing products that were not only easy to assemble in the factory, but also more easily supported in the field. This conceptual approach consists of five elements:

- Product development by a multifunctional team
- Relative assessment of alternative designs with a metric
- Training in the theoretical basis underlying the metric
- A specific procedure by which alternative designs are created and evaluated
- Computer support for the team during product development meetings.

In this project, a specific methodology was developed that allows a product development team using this conceptual approach to make system-level trade-offs between redundant part selection and scheduled maintenance visits to achieve low life cycle cost (LCC) and high operational readiness of the resulting system. This methodology was demonstrated for a subsystem of a ground-based radar and evaluated by participants in the demonstration.

A. BACKGROUND

Unified Life Cycle Engineering (ULCE) was an Air Force Project Forecast II Research and Development program with the goal of developing

> A design engineering environment in which computer-aided design technology is used to continually assess and improve the quality of a product during the active design phases as well as throughout its entire life cycle by integrating and optimizing design attributes for producibility and supportability with design attributes for performance, cost, and schedule. [Ref. 2]

During Fiscal Year 1988, a research team at IDA performed a study under the auspices of the ULCE Program titled *Measurement Issues in Unified Life Cycle*

Engineering. As part of this study, the research team investigated various techniques used by industry to evaluate producibility and supportability in the early phases of the product development process. This investigation revealed that the trend in industry is toward a concurrent engineering approach in which product development is accomplished by a multifunctional team including specialists from all relevant departments in the company (e.g. design, manufacturing, finance, marketing, and product support). Group problem solving is an activity that underlies much of the work of such product development teams. Because the primary thesis of ULCE is that use of computers can facilitate the accomplishment of a life cycle approach to engineering, a question naturally arose as to what extent computers were being used by industry to facilitate the group problem solving process needed in concurrent engineering.

In an attempt to answer this question, the study team surveyed both current industry multifunctional product development team practices and current computer-aided group problem solving methodologies and technologies [Ref. 3]. While the latter methodologies and technologies offer potentially great benefits to product development teams, the study team observed little use of such techniques by industry product development teams. This finding prompted a study team recommendation that the ULCE program be broadened to consider research in applying computer-aided group problem solving techniques to product development processes [Ref. 3].

One notable exception to this finding was the Boothroyd-Dewhurst DFA methodology, which has been successfully used in many companies to support concurrent engineering teams in designing products that can be easily assembled in the factory. Based on the success of DFA, the study team hypothesized that the conceptual approach of Boothroyd and Dewhurst could also be applied to design for supportability. This hypothesis formed the basis of the research project described in the remainder of this paper.

B. ORGANIZATION OF THE REPORT

Chapter II contains a project overview that describes DFA and outlines the approach taken by the research team in arriving at the methodology developed in this project. Chapter III describes the methodology developed during this research project. Chapter IV details the demonstration of this methodology and its evaluation by industry participants in the demonstration. Chapter V presents recommendations for further research based on the findings of the research team and on comments from industry.

Appendix A contains a discussion of historical approaches to consideration of maintainability in the design process and includes various definitions of maintainability and maintainability design rules and guidelines. Appendix B contains an annotated bibliography of research papers, articles, and books treating issues of maintainability in electronics design. Appendix C describes the computer support environment that allows efficient execution of the methodology developed in this project. Also included in this appendix are details of the equations underlying the metrics that are used in the methodology.

II. PROJECT OVERVIEW

The goal of this project was to demonstrate that the conceptual approach taken by Boothroyd and Dewhurst in their DFA process can also be applied to developing more supportable products. To accomplish this, a methodology was developed that addresses considerations of reliability, maintenance scheduling, and logistics support for a ground-based radar system. This methodology provides analyses that facilitate development of alternative configurations of the radar system that exhibit low LCC while meeting minimum requirements for system reliability. In a parallel effort, computer software was developed that supports the product development team in calculating the metrics needed for the methodology.

This chapter provides an overview of the conceptual approach of Boothroyd and Dewhurst and outlines the specific research tasks and findings that lead to the development of the methodology described in Chapter III.

A. BOOTHROYD AND DEWHURST DESIGN FOR ASSEMBLY

Boothroyd and Dewhurst have developed a methodology that supports a product development team in designing products that are easy to assemble [Ref. 4]. The conceptual approach of the DFA methodology consists of the following five elements.

- Product development by a multifunctional team
- Relative assessment of alternative designs with a metric
- Training in fundamentals of the methodology and underlying metric
- A specific procedure by which alternative designs are created
- Computer support for the team during product development meetings.

Bart Huthwaite, a well known instructor in the DFA methodology, emphasizes that the team philosophy is essential for successful implementation of DFM [Ref. 5]. A team composed of members from all of the departments of the company that are concerned with the product under development ensures that each department's perspective is considered. More ideas can be generated when the team works together to recognize weak points in the

design. The team members' creativity is stimulated by shared ideas. A synergy develops within the team.

A quantitative measure (or metric) that is used as a basis for comparison of alternative designs is a key element of the DFA approach. Computation of the DFA metric begins with estimating the total assembly time for the design. To compute this time, the assembly sequence, geometric features, and rough dimensions for the current design must be known. Using this information, the design is rated in terms of the estimated time that will be required for part handling and orientation and for part insertion and securing, and these ratings are used to calculate the total assembly time.

Next, the assembly time for an ideal design having the theoretical minimum number of parts is calculated. This ideal design will generally not be feasible due to constraints such as the economics of manufacture or unavailability of specialized manufacturing equipment to make the more complicated parts needed in a minimum-part-count design [Ref. 4]. Thus the ideal design cannot usually be used as the solution to the design problem.

An assembly efficiency for the current design is then computed by dividing the estimated assembly time for the theoretical minimum-part-count design by that of the current design. This assembly efficiency, expressed as a percentage, is used as the metric when evaluating alternative designs. Designs with higher assembly efficiencies are to be preferred, all other things being equal, to those with lower assembly efficiencies.

The assembly efficiency metric is based largely on the judgment of team members. It must be considered a relative, rather than absolute, measure. Assembly efficiencies should only be compared with other assembly efficiencies calculated by the same product development team.

The theoretical basis of the assembly efficiency is a set of 12 generic guidelines [Ref. 5]. The guidelines and use of the metric, including the proper interpretation of the assembly time estimation attributes, are taught to the team before design alternatives are generated.

The DFA procedure for generating alternative designs is

1. Calculate the assembly time of the current design. (A baseline design must be available to begin this procedure.)
2. Based on the function of each part of the current design, calculate the ideal assembly time for a design that has a theoretical minimum number of parts.

3. Calculate an assembly efficiency rating for the current design as compared with the ideal design.
4. Using judgment based on the design for assembly guidelines and weak points of the current design as identified by the metric, modify the current design to increase the assembly efficiency.
5. Continue this procedure of modifying and assessing the resulting design until the product development team has identified a preferred design or until no more time remains for design activities.

While the team is determining the ratings and establishing the theoretical minimum number of parts, team members share knowledge and insights. Creativity is stimulated, and innovative solutions are proposed. The group identifies problems with the current design and continually explores ideas for improvement.

DFA software allows the product development team to calculate the assembly times and assembly efficiencies for alternative designs. This software resides on a microcomputer that is operated by a designated team member. The computer screen is made visible to all team members. While the assembly time and assembly efficiencies could be calculated by hand, the computer can perform the calculations faster--a valuable feature because the key to consistent measurements made by a group is rapid iteration [Ref. 5].

Using a team for product development is being widely promoted; however, bringing together a team of people from different departments with a range of skills to work for a common goal is not an easy task. Ignoring the logistical concerns, a fundamental problem is communication. A product development methodology such as DFA can provide the common language needed for successful product development team interaction [Ref. 6]. DFA enhances the creativity and experience of the team members, helps the team reach consensus, and enables the team members to make estimates when exact measures are not available [Ref. 5]. The process of using DFA is considered as important as the analytical results derived from its use. The ultimate goal of the DFA methodology is not to calculate the assembly efficiency but to improve the design.

In view of the importance of the process embodied in the DFA approach, the research team hypothesized that this process could be applied to design for attributes other than ease of assembly. In particular, supportability is a design characteristic of considerable interest to DoD that should receive consideration early in the design process. As a first step in demonstrating how the DFA process could be extended to supportability,

the research team undertook to ascertain the current state of the art in methodologies for measuring supportability and for designing improved supportability.

B. LITERATURE REVIEW

An extensive literature review was initiated at the beginning of the task to identify existing techniques for defining, measuring, and designing for supportability. The goal of this broad review was to identify aspects of supportability to focus on. As a result, the research team, in cooperation with the sponsor, decided to limit aspects of supportability considered in this investigation to maintainability, reliability, and logistics support, in this order of priority.

Since maintainability received the highest priority, the research team refined the literature review to focus on maintainability and identify methodologies and guidelines used for design for maintainability. The results of this refined review are included in Appendices A and B. An index of the complete supportability file is also available from IDA.

Incorporating maintainability considerations early in the design process through the team approach is not a new concept. In 1956, Milton J. Marcus of the Human Engineering Laboratory, Rome Air Development Center (RADC), made the following comments at the Ease of Maintainability Conference [Ref. 7]:

> Another factor relating to the inclusion of maintenance considerations early in the equipment development process is the position of maintenance near the bottom of the hierarchy of design requirements, which has contributed to the growth of the problem to its present magnitude. Equipments must be planned to simplify or eliminate maintenance procedures. This requires team-type efforts, with the design engineer and the engineering psychologist working together.

Developing a generic tool to aid teams in designing for maintainability is, however, problematic. The literature review revealed that no universally accepted definition of maintainability exists. No concise, manageable set of generic guidelines for design for maintainability could be gleaned from the extensive lists found in various government and industry references. The research team determined that design for maintainability guidelines must be specifically tailored to the product being developed. This finding prompted the research team to further restrict its attention to a specific design problem.

Maintainability, reliability, and logistics support, are all related and should be considered together in designing a system for supportability. To achieve a good design--in

terms of supportability--the design team must be able to perform trade-offs between these attributes of the design. To more specifically identify the kinds of trade-offs that would be appropriate for consideration in this project, the research team collaborated with both academia and industry.

C. COLLABORATION WITH ACADEMIA AND INDUSTRY

Through a cooperative arrangement with the University of Maryland Center for Computer-Aided Life Cycle Engineering (CALCE), the research team collaborated with academia and industry. This center, an industry-university cooperative research center sponsored by the National Science Foundation, has as its primary focus development of new techniques for designing electronic products for reliability, maintainability, and supportability. The CALCE center is the only center of its kind in the country that is focusing on design for supportability of electronics. Its director, Dr. Michael Pecht, is a nationally recognized expert in design of electronic systems for supportability.

Under the arrangement with the CALCE center, the University of Maryland was given a research grant by IDA to provide technical assistance in developing the methodology for this project. In a parallel effort, the CALCE center undertook an internally funded project to develop software to support a product development team in executing the methodology.

A number of major industrial defense electronics suppliers are members of the CALCE center--Westinghouse Electric, Texas Instruments, Digital Equipment Corporation, Northrop, General Electric, Allied Signal, and General Dynamics. Westinghouse Electric and Texas Instruments agreed to provide technical support to IDA in the development of the methodology and to participate in a demonstration and evaluation of the methodology at the conclusion of the project.

D. SYSTEM SELECTION

The ARSR-4 was selected as the baseline system to be used for development of the methodology. The ARSR-4 is a ground-based, long-range 3-D radar currently under development by Westinghouse Electric. The system is being designed to meet the air traffic control and air defense sensor requirements of the Federal Aviation Administration (FAA) and the U.S. Air Force's Joint Surveillance System (JSS). The ARSR-4 was selected for the methodology development because the design information (and designers) needed for the methodology was readily available, and Westinghouse Electric was willing to supply

this information to the CALCE Center. In addition, considerations of supportability are playing a significant role in the design of the ARSR-4.

E. ARSR-4 SUPPORTABILITY ISSUES

The ARSR-4 is being designed by Westinghouse Electric for unattended operation and low LCC. The only support equipment it will require is a limited number of tools on site and equipment already part of the FAA/Air Force inventory. The use of redundant parts in a system allows failure of one of the parts without failure of the entire system. Thus, to achieve high reliability and allow continuous operation, redundancy is used extensively in the design of this system. Scheduled maintenance visits are also used to enhance reliability through periodic replacement of failed redundant components.

These approaches to enhancing reliability are not without cost, however. Increasing the number of redundant components increases system acquisition cost, while increasing the frequency of maintenance visits increases system logistics support cost. If a given level of system reliability is required, increasing redundancy allows the frequency of maintenance visits to be reduced, and conversely, increasing the frequency of maintenance visits allows redundancy to be reduced. The net LCC impact of changing redundancy and maintenance visit frequency will depend on the relative magnitudes of such factors as the cost of the parts being made redundant, manpower and transportation costs associated with maintenance visits, and spares costs.

To minimize the total system LCC, which includes both acquisition and support costs, a method for obtaining the proper balance between redundancy and maintenance visit frequency is needed. To obtain such a balance, the product development team needs the freedom to vary the level of redundancy and the frequency of maintenance visits, and the capability to estimate the LCC impact of such changes.

In the current government acquisition process for the ARSR-4, the product developer was given specifications that prescribe the number of maintenance visits per year. These specifications also limit the number of maintenance actions that require or cause shut down of the system. In seeking to attain the required level of system reliability, the product developer has the freedom to vary only the level of redundancy in the system, leading to the potential for suboptimal system LCC.

F. SCENARIO FOR METHODOLOGY DEVELOPMENT

In order to place the methodology in context, the following scenario was created. It is assumed that at some point in the future a major technological advance has occurred that has initiated development of the next generation of the ground-based 3-D air surveillance radar, which will be called the ARSR-5. It is also assumed that by the time of the ARSR-5 procurement, the Department of Defense (DoD) has adopted the concurrent engineering approach to system acquisition. Thus, the concept exploration phase of the acquisition cycle, where requirements are set, is now conducted as a multifunctional product development team effort with representatives from DoD (the customer) and design, manufacturing, and supportability engineers from potential contractors. For the ARSR-5 procurement, minimizing LCC while maximizing operational readiness is a key design goal. This goal must be addressed from the outset of the systems engineering process for the ARSR-5. The number of maintenance visits is no longer government specified but is a design variable that can be traded off with the amount of redundancy used in the system design. The methodology developed during this project allows a product development team to conduct such trade-off studies.

G. COMPUTER SUPPORT

At the same time the methodology was developed, the CALCE Center researchers developed software that supports calculating the metrics needed for the methodology. This software, developed in collaboration with IDA, Westinghouse Electric, and Texas Instruments, is an extension of the existing CALCE software package, which is supplied to center members. The extension incorporates many existing CALCE software capabilities, such as the parts data base and graphics displays. New features incorporated in support of the methodology include the capability to estimate the reliability of redundant systems with repair and the capability to calculate system cost and life cycle maintenance visit costs for systems with redundant parts.

In addition, a maintainability prediction capability has been integrated with this methodology. This capability allows the additional consideration of the relative cost effectiveness of improving the maintainability of various subsystems or components of the radar. For example, the benefits of reducing the removal time for a particular line replaceable unit (LRU) at a given investment cost can be assessed relative to the overall expected savings in system LCC.

H. DEMONSTRATION AND EVALUATION

A demonstration and evaluation of the methodology took place on September 20, 1989, at the University of Maryland. Representatives from IDA, the Air Force Human Resources Laboratory (AFHRL), the University of Maryland, Texas Instruments, and Westinghouse Electric attended. The demonstration consisted of a presentation by Dr. Pecht on the theory of redundant systems with repair (which is the theoretical basis for the methodology), a demonstration of how the computer is used to support the group deliberations, a working session in which redundancy and scheduled maintenance were assessed for a subassembly of the ARSR-4, and a discussion in which the methodology was evaluated and recommendations for future research and enhancements were given. The complete results of the demonstration are given in Chapter IV.

III. METHODOLOGY

The methodology developed in this project and described in this chapter addresses the issue raised in the preceding chapter: determining an appropriate balance between redundancy in the radar system and the frequency of maintenance visits in order to meet a system reliability requirement in the most cost-effective manner. This methodology was developed by IDA research staff members working with researchers at the CALCE Center and industry representatives. The conceptual approach of the Boothroyd-Dewhurst DFA process was used as the basis for developing the methodology.

A. THEORETICAL FOUNDATION OF THE METHODOLOGY

A scheduled maintenance strategy coupled with provision for redundancy of critical system elements offers the possibility of designing a system for near failure-free operation. In the methodology developed in this project, it is assumed that during each scheduled maintenance visit, all components that have failed since the last visit are replaced with functioning components. Increasing the frequency of such visits will improve the system reliability, provided redundant components are present. If no redundant components are present, and exponential failure distributions are assumed for the individual components, then scheduled maintenance will not affect system reliability.

There are limits as to how much system reliability can be increased through either increasing maintenance visit frequency or increasing the numbers of redundant components in the system. The limiting case in terms of increasing maintenance visit frequency would be a situation in which a maintenance crew is present and monitors the system continuously, immediately replacing any failed component with a functional one. This approach cannot guarantee continuous, failure free operation of the system, however, because it will take a certain amount of time for the crew to remove and replace a failed component, and during this time there will be a non-zero probability that a sufficient number of other components will fail, leading to a system failure.

With standby redundancy, in which additional components can be automatically activated and made part of the system upon failure of operating components, the time

between maintenance visits is essentially zero. The system essentially repairs itself in real time. However, there are practical limits to what can be achieved in terms of improved reliability through this approach. Redundant components require additional interconnections, and sensor and switching mechanisms are needed for standby redundancies. These additional elements are subject to failure, and their hazard rates must be considered in the reliability calculations. Adding additional redundant components also complicates fault detection and isolation, leading to increased maintenance times.

In a series system (a system with no redundancies) in which only unscheduled maintenance is performed, improving the reliability of the system will, all else being equal (in particular, assuming the cost of each remove and replace action, in terms of spares cost, manpower, etc. is unchanged), lead to a decrease in logistic support costs. The expected cost of maintenance in terms of manpower and spares will be driven by the number of failures that will be experienced, and this number will decrease as the reliability of the system is increased. In the case of a system with redundancies and a scheduled maintenance strategy, such as considered in this project, this relationship between system reliability and logistic support costs does not always hold.

For a given maintenance visit frequency, increasing the system reliability by increasing redundancy will actually increase logistic support costs. This cost increase is because in the interval between maintenance visits, more components in the system can fail (although such failures may not lead to system failure). This increase in the expected number of failures will lead to an increased maintenance workload during each maintenance visit, and an increase in spares requirements (under the assumption that all failed components are replaced during each visit.)

If achieving a given level of system reliability, or system operational availability is desired, then increasing the amount of redundancy can be accompanied by a corresponding reduction in maintenance visit frequency. Whether the net effect of such added redundancy (after visit frequency is adjusted) will be a decrease in logistic support costs will depend in a complex way on factors such as the cost of the components whose redundancy is being increased, their reliabilities, the cost of maintenance manpower, and fixed costs associated with each maintenance visit.

Because of these factors, achieving an optimal balance between adding redundancy and increasing the frequency of maintenance visits is a non-trivial analytical problem. An analytical solution to this problem is not likely to be achieved. Incorporating the many complicating factors into the calculations would be very difficult and lead to considerable

uncertainty regarding the validity of the final results. Thus, a considerable amount of engineering judgment must go into selecting system elements to be made redundant in order to improve reliability at a reasonable cost.

B. MULTIFUNCTIONAL PRODUCT DEVELOPMENT TEAMS

For this project it is assumed that a core team is formed when the product development is initiated. This team consists of members from all of the relevant departments in the organization, as well as customer and supplier representatives. As issues arise during the development, this team charters specialty teams to address the issues. The charter includes the goals, the constraints, and the system the specialty team is to use as a baseline.

To meet the DoD goal of minimizing field support costs while maximizing operational readiness, the core team identifies low LCC and high reliability as high priority design goals. LCC is a function of the acquisition costs and the support costs. The core team recognizes that one way to lower LCC while still meeting reliability requirements is to consider adding redundant elements to the radar to maintain system reliability, while reducing the number of maintenance visits needed per year. While system acquisition costs are increased due to the additional parts cost for redundant components, decreasing the number of scheduled maintenance visits decreases the system support costs. Thus the core team charters a specialty team to address this trade-off between redundancy and scheduled maintenance visits. The specialty team is composed of design engineers, reliability and maintainability engineers, and a DoD (customer) representative of the program manager for the specific system. The team could also include other specialty engineers, such as producibility engineers.

As a result of other team efforts, the requirements for the reliability of the system in series, as mean time between failures (MTBF), and system reliability, as measured by MTBCF, are determined and passed on to this specialty team. The team's job is to develop a set of configurations with varying amounts of redundancy and numbers of scheduled maintenance visits that satisfy these reliability requirements and exhibit a reasonably low LCC.

C. METRIC FOR GOAL ASSESSMENT

In the methodology developed in this project, the metric used by the team to assess whether the goal of low LCC is met by alternative designs is called an LCC indicator. It

includes some, but not all, of those costs that make up the total system LCC. In particular, the LCC indicator is the sum of a proxy for system support cost and a proxy for system acquisition cost.

Since all failed redundant components are to be replaced during scheduled maintenance visits, the spares cost is calculated based on the failure rates of the elements and is included in the cost of a maintenance visit. The repair cost per visit and the travel cost to the site for a maintenance visit are added to the spares cost to obtain the cost per visit. The cost per year for all maintenance visits is discounted over the life of the system to obtain the proxy for total support cost. This cost is added to the total parts cost, which is used in this methodology as a proxy for system acquisition cost, to obtain the LCC indicator value for a given system configuration (redundancy specification for each system element) and maintenance visit schedule.

D. TRAINING

Once the specialty team assembles, the first agenda item is a review of the theory and design principles behind the goals and the analyses required for the trade-offs to be conducted during the meeting. The principles address the various trade-offs to be considered in the meeting (redundancy versus maintenance frequency) and should specify useful methods of achieving the specified goals within the given constraints (creative redundancy modeling). The principles are stated in terms that every member of the product development team can understand, and the necessary analysis techniques are available for review during the session. The metrics used in assessing whether the alternative configurations meet the goal and constraints are also explained to the team, if the team members were not involved in developing the metrics. Verification of the equations and the analyses in the computer software is provided to the team. After reviewing the theoretical basis of the system, the specialty team reviews the baseline system of the product under development.

E. GENERATION OF ALTERNATIVE DESIGNS

As with the DFA process, a baseline design is needed to initiate the activities of the team. Generation of alternative designs is accomplished by changing baseline system element attributes, such as the number of redundancies of an element, and changing baseline system parameters, such as the frequency of scheduled maintenance visits. Modifications are made only with the consensus of the team.

Once an alternative has been modified, element attributes and the system parameters must be recalculated. The MTBF for the series configuration of the design is checked to determine if the MTBF requirement is violated. If the MTBF requirement is exceeded, another modification must be made to the configuration to raise the MTBF until it meets the requirement. Once the MTBF requirement is met, the system MTBCF is calculated as a function of the number of maintenance visits. The minimum number of maintenance visits required to achieve the specified MTBCF can then be determined. The LCC indicator is calculated once the minimum number of maintenance visits is specified. If the alternative is deemed viable (achieves goals within constraints), it can be further modified or another alternative can be selected as a new starting point.

After a suitable number (determined by the team) of viable alternative redundant configurations have been developed, these configurations are evaluated and compared to determine which one best meets the constraints for the lowest cost. If several alternatives have nearly the same LCC, other attributes and design considerations are used in the selection process to determine the best alternative. The specialty team relies on the creativity, experience, and expertise of team members to address those attributes and considerations affected by modifications but not directly considered in the methodology.

F. COMPUTER SUPPORT

Before a design session begins, the specifications for the baseline system must be entered into the computer data base. This information includes, for each possible element in the system, such things as reliability, repair times, and cost. Additional information is also required to compute the constraint and goal metrics. This information includes items such as service life, cost of maintenance manpower, travel costs, and a discount rate for computing the present value of the cost stream associated with a series of maintenance visits extending from initial operational capability throughout the service life of the system.

The software provides the team with the capability to enter, display, and save alternative redundant system configurations and to estimate the reliability of these redundant systems under alternative maintenance visit schedules. It also allows the team to estimate acquisition costs and life cycle maintenance visit costs for systems with redundant elements.

A detailed description of the software supporting the methodology and the equations and analytical assumptions underlying the methodology are given in Appendix C.

IV. DEMONSTRATION

A. OVERVIEW

On September 20, 1989, the methodology developed in this project was demonstrated and evaluated at the University of Maryland. Representatives of AFHRL, IDA, the University of Maryland, Texas Instruments, and Westinghouse Electric participated in the demonstration and evaluation.

The agenda for the demonstration and evaluation is shown in Table IV-1, and the people who participated in the demonstration and evaluation are shown in Table IV-2.

Table IV-1. Meeting Agenda

Time	Agenda Item	Speaker/Participant
0930-0945 hours	Opening Remarks	W. Cralley, IDA
0945-1000 hours	Scenario for Methodology	D. Dierolf, IDA
1000-1015 hours	Break	
1015-1200 hours	Theory behind Assessment Metrics and Representation of Baseline System	M. Pecht, University of Maryland
1200-1330 hours	Lunch	
1330-1530 hours	Alternative Generation	All Participants
1530-1630 hours	Discussion	All Participants
1630 hours	Closing Remarks	W. Cralley, IDA; Cpt. Hill, AFHRL

Table IV-2. Meeting Participants

Name	Affiliation	Position
Mr. Frank Roth	Texas Instruments	Systems Engineer
Mr. Dino Fieni	Westinghouse Electric	Reliability Engineer
Dr. Michael Pecht	University of Maryland	Director, CALCE Center
Mr. Hugh Reinhart	University of Maryland	Graduate Student
Ms. Chu Zhang	University of Maryland	Graduate Student
Mr. B.T. Sawyer	University of Maryland	Software Engineer
Cpt. Ray Hill	AFHRL	Project Manager
Mr. William Cralley	IDA	Project Manager
Mr. David Dierolf	IDA	Research Staff Member
Dr. Karen Richter	IDA	Research Staff Member

B. DEMONSTRATION ACTIVITIES

The background of the research, the conceptual approach taken, the scenario for the methodology development, and the theory, equations, and metrics underlying the assessment capability were explained to the meeting participants. The material presented follows the descriptions given in Chapter III and Appendix C and will not be repeated here. (Appendix C also contains a user's guide to the CALCE software used in the demonstration.)

This section describes the input data required to exercise the software supporting the methodology and the output results provided by this software. It also contains a description of the alternative generation process and an example of this process that illustrates the activities during this portion of the demonstration.

1. Operation of the Software

A design is entered into the computer by specifying a hierarchical description, often called a high-level bill of materials. This hierarchical description identifies the lowest level elements on which repair will be conducted. For purposes of this project, repair is defined as removal and replacement of all elements of the system that are found to have failed at the

time of a maintenance visit. Deferred maintenance of certain failed elements discovered during scheduled or unscheduled maintenance actions is not considered in the methodology developed in this project, although it is a valid maintenance strategy that could be considered in actual maintenance situations.

Each element of the hierarchy has a set of associated attributes, as shown in Table IV-3. All attributes, with the exception of those used for part identification, require numerical values. Some of these values are assigned by the user; the remaining are computed from other attributes and may not be changed.

Table IV-3. Element Attributes

User Defined	Calculated
• Total number of elements present in the system	• Repair time (time to remove and replace an element of the system)
• Total number of elements required for operation of the system	• Element's percent of the total system failure rate
• Duty cycle	• Element equivalent failure rate
• Element failure rate	• Element equivalent failure rate with repair
• Unit cost of an element	

The duty cycle of an element is the ratio of the element's operating time to the total system operating time; it is used in calculating the reliability of the element. The percent of the total failure rate is the failure rate of the element divided by the total system failure rate. The equivalent failure rate is the failure rate that a group of identical elements (including some that are redundant) would have if this group were considered as a single aggregated element. Note that even if each element has an exponential failure distribution, the failure distribution of a group of such elements will not be exponential if redundancy is present. Thus the equivalent failure rate is useful only as a heuristic and is not actually used in calculating the total system failure rate.

Each design configuration has a set of global system-level parameters associated with it. These parameters are shown in Table IV-4. Default values are initially assigned to these parameters. Some global parameters can be changed by the user, while others are calculated and may not be changed. Parameters that can be edited include service life, number of maintenance visits per year, travel cost of a maintenance visit, and discount rate to be applied for determining LCC. MTBCF, system reliability with and without repair, series failure rate, and series MTBF are computed from the other parameters.

Table IV-4. Global System Parameters

User Defined	Calculated
• Service life	• System reliability with repair
• Maintenance visits per year	• System reliability without repair
• Maintenance labor rate	• System failure rate (failures per million hours)
• Travel cost for a maintenance visit	• Series failure rate (assumes all elements, even redundant ones, must be operational for the system to operate)
• Discount rate for computing present value of maintenance visit cost streams	• MTBF (for the series system)
	• MTBCF
	• MTTR
	• LCC indicator

The software supports the selection of elements to make redundant by highlighting those with the highest equivalent failure rates. Two types of redundancy, passive (or standby) and active, can be considered by the team to reduce the LCC of the baseline system.

2. Alternative Generation

The starting point for the demonstration was a baseline configuration for a subsystem of the ARSR-4 with no redundancies (a series configuration for reliability estimation purposes). Table IV-5 shows the attributes of the elements in the baseline configuration. The global parameters for this configuration are shown in Table IV-6. Note that scheduled maintenance does not improve the reliability of a series configuration system (assuming exponential failure distributions). Thus, system failure rate with repair is the same as without repair, and MTBCF is equal to MBTF for this configuration.

In the demonstration, constraining requirements were specified for both minimum reliability for the system in series configuration (MTBF) and for system reliability (MTBCF) for the subsystem of the ARSR-4 being considered. The MTBF requirement was 6,500 hours, and the MTBCF requirement was 100,000 hours.

The following procedure was followed during the alternative generation process:

- Add redundancy to a selected system element
- Check to see if the MTBF constraint is satisfied (if not, no level of scheduled maintenance will suffice to make the design feasible)

Table IV-5. Attributes of Elements in Baseline Configuration

Block ID	Diagram No.	Description	Repair Time (hrs)	Total Units	Required Units	Unit Cost ($)	Unit Fail Rate	Series Fail Rate	% Total Fail Rate	Duty Cycle	Equiv Fail Rate	Equiv Fail Rate With Repair
a1	01	Pulse comparator	0.8	1	1	2000	14.770	14.770	22.3	1.00	14.770	14.770
a2	02	Doppler filter	8.4	1	1	1000	17.230	17.230	26.1	1.00	17.230	17.230
a3	03	Positive detection identifier	2.0	1	1	1000	14.190	14.190	21.5	1.00	14.190	14.190
a4	04	Computer false alarm rate (CFAR)	1.0	1	1	1000	13.340	13.340	20.2	1.00	13.340	13.340
a5	05	Channel interface	2.0	1	1	1000	6.562	6.562	09.9	1.00	6.562	6.562

Table IV-6. Global Parameters for Baseline Subsystem

Service life	43,850 hours
Maintenance visits/year	0
System reliability with repair	0.055126
System reliability without repair	0.555126
Series failure rate	66.09 failures per million hours
MTBCF	15,130.4 hours
MTBF (series)	15,130.4 hours
MTTR	3.21 hours
LCC indicator	6,000 $

- Determine the minimum number of maintenance visits per year needed to achieve the MTBCF requirement (or determine that no number of maintenance visits will suffice, meaning the design is infeasible)
- Determine the LCC indicator for this configuration
- Record details of the configuration and parameter values for reference
- Modify the configuration and repeat the preceding steps.

During the demonstration, the alternative generation process was repeated several times. Dr. Pecht operated the computer for the team during this session.

An account of the various configurations and the results for each one was maintained manually. A sample of these configurations is presented in the following section, illustrating the support the CALCE software provides.

3. Examples Of Alternative Generation

Table IV-7 shows the baseline system with a redundant Doppler filter as the first alternative configuration. Table IV-8 shows the system parameters for this alternative. The addition of the redundant component decreases the MTBF while increasing the MTBCF. With five scheduled maintenance visits per year, the MTBCF is still far below the requirement of 100,000 hours. Even with additional maintenance visits, this configuration is unable to meet the MTBCF requirement.

Table IV-7. Baseline System with a Redundant Doppler Filter

Block ID	Diagram No.	Description	Total Units	Required Units	Unit Fail Rate	Equiv Fail Rate With Repair
a1	01	Pulse comparator	1	1	14.770	14.770
a2	02	Doppler filter	2	1	17.230	3.974
a3	03	Positive detection identifier	1	1	14.190	14.190
a4	04	Computer false alarm rate (CFAR)	1	1	13.340	33.340
a5	05	Channel interface	1	1	6.562	6.562

Table IV-8. System Parameters for Alternative in Table IV-7

Service life	43,850 hours
Maintenance visits/year	5.00
System reliability with repair	0.1147793
System reliability without repair	0.0843560
Series failure rate	83.32 failures per million hours
MTBCF	20,259.30 hours
MTBF (series)	12,001.60 hours
MTTR	4.29 hours
LCC indicator	22,472.30 $
Initial parts cost	7,000.00 $
Total maintenance cost	618.61 $/visit
Spare parts cost	112.02 $/visit
Repair time	0.13 hours/visit
Maintenance person cost	50.00 $/visit
Travel cost	500.00 $/visit
Discount rate	0.0 %

Table IV-9 shows the attributes for an alternative configuration with multiple redundancies. Table IV-10 shows the system parameters for this alternative. The MTBCF requirement of 100,000 hours is met, as well as the MTBF requirement of 6,500 hours. The additional redundancies allow the number of scheduled maintenance visits to be reduced to one every two years. The value of this reduction is shown by the LCC indicator ($15,531), which is less than the LCC indicator of the first alternative, which did not meet the reliability requirements.

Table IV-9. System with Multiple Redundant Elements

Block ID	Diagram No.	Description	Total Units	Required Units	Unit Fail Rate	Equiv Fail Rate With Repair
a1	01	Pulse comparator	2	1	14.770	3.025
a2	02	Doppler filter	3	1	17.230	1.016
a3	03	Positive detection identifier	2	1	14.190	2.815
a4	04	Computer false alarm rate (CFAR)	2	1	13.340	2.519
a5	05	Channel interface	2	1	6.562	0.676

Table IV-10. System Parameters for Alternative in Table IV-9

Service life	43,850 hours
Maintenance visits/year	0.5
System reliability with repair	0.6691264
System reliability without repair	0.3891756
Series failure rate	149.41 failures per million hours
MTBCF	10,160.00 hours
MTBF (series)	6,692.80 hours
MTTR	3.81 hours
LCC indicator	15,531.59 $
Initial parts cost	13,000.00 $
Total maintenance cost	1,012.18 $/visit
Spare parts cost	468.97 $/visit
Repair time	0.86 hours/visit
Maintenance person cost	50.00 $/visit
Travel cost	500.00 $/visit
Discount rate	0.0 %

C. DEMONSTRATION FINDINGS

Following the session, all participants discussed the methodology. Due to cost and schedule constraints, not all issues could be addressed in the implementation of the methodology. The following sections describe the issues that were addressed and the major findings from the demonstration.

1. Identifying Where to Add Redundancy

While adding redundancy to the system element with the highest failure rate (or equivalent failure rate when scheduled maintenance is being performed) seems most logical for improving system reliability, this modification does not always lead to a better solution in terms of LCC. Recall that increasing the level of redundancy increases both acquisition cost and the cost of each maintenance visit (due to the increased opportunity for sub-elements to fail between visits). Whether the increased system reliability that results from adding such redundancy will allow the frequency of maintenance visits to be reduced sufficiently to offset these additional costs is often not intuitively obvious. More economical improvements yielding an equivalent improvement in system reliability may possibly be obtained by adding redundancies to a less costly element.

In addition, an element with a very low failure rate may be critical to the operation of the system. Some subsystems, such as power supplies, are known to be failure prone and are made redundant in systems such as the ARSR-4. Other reasons for demanding redundancy in certain systems include difficulty of fault isolation when a certain component fails or an explicit desire by the customer for redundancy for certain components. The level of criticality of an element is an important factor in determining which elements to make redundant to ensure the system does not fail. The methodology should provide for mandatory redundancy in certain subsystems. For various portions of the ARSR-4, redundancy is impossible because of size, weight, or cost constraints. Consideration should be given to providing for such constraints in the software.

The functional relationship between improving reliability through added redundancy and improving reliability through increased scheduled maintenance frequencies is complex. Identifying the optimal solution in terms of LCC appears to be a very difficult analytical problem. While the CALCE software supporting the present methodology allows the product development team to explore various options, it can only provide general indications as to where to place additional redundancies to improve LCC. Adding redundancy to the system element with the highest equivalent failure rate, for example, often is a good approach, but this approach is not necessarily the optimal approach, as was noted in the preceding paragraph.

Thus, at present, the team must rely on the expertise of members in determining which element to make redundant. While an analytical solution to this problem seems unlikely, especially if the entire radar system is considered, better heuristics could help guide the product development team in selecting where to place redundancies, leading to improvements in the resulting designs and a more efficient product development process. Development of such heuristics could be the topic of future research projects.

2. Initiating and Managing Trade Studies

Trade studies are usually the result of a product development team member's uncovering a particular problem and convincing management that such a problem should be addressed. Trade-off studies are costly and time consuming, and only studies offering significant product improvement should be undertaken. Engineering experience and judgment become critical factors in identifying which of the many possible trade-offs should be conducted, given the limited time available to the team. Methods for identifying and managing such efforts should be improved. As expanded capabilities for conducting

trade-off analyses are added to the software, deciding which options to explore becomes increasingly difficult. The number of potential excursions rapidly expands, and team members may spend valuable time on issues with limited payoff (or analyze less viable trade-offs). A structured way to make decisions requiring experience and judgment is needed to best focus team efforts.

3. Addressing Ramifications of Increased Redundancy

Adding more active redundancy increases system power requirements. Since power supplies are notoriously unreliable, the possibility exists that increasing the reliability of one part of the system through added redundancy could result in a decrease in total system reliability or an increase in total system logistics support burden and cost.

While increased size and weight accruing from more redundancy may not be of considerable importance in a ground-based system, they must be considered in avionics. In the case of high-performance fighter aircraft, increases in weight or space requirements can require a multitude of other design changes, which can cause significant problems.

Increased system complexity resulting from more redundancy will increase system development costs in a manner that is not reflected in the acquisition cost portion of the LCC indicator. In particular, additional funding for design and prototype development and testing will likely be required.

Additional costs may also accrue from the support equipment needed to handle additional redundancies. Such costs are related to the need for additional sensing and switching/voting circuitry, interconnection devices, and added demand for environmental conditioning.

Additional failures may occur due to support equipment needed to handle redundancies. Failures in sensing circuits or interconnections, for example, are not accounted for in the current methodology.

Increased difficulties in fault detection and isolation may result from increased redundancy. This can lead to an increase in false removals, resulting in increased logistic support costs in terms of spares and manpower utilization. Such additional costs are not handled in the current methodology; the methodology assumes 100 percent fault isolation.

Any or all of these considerations should be addressed through additional research to improve the accuracy of the metrics now present in the current methodology.

4. Assessing Life Cycle Cost

Aside from costs resulting from increased redundancy noted in the preceding paragraphs, procedures used to estimate the other costs in the methodology could also be more realistic. The approach taken in the methodology involving use of an LCC indicator and separate estimates for parts and maintenance costs was viewed as useful and appropriate by the demonstration participants from industry. The individual components of this indicator, however, could be more accurate.

For example, the methodology now uses total parts cost to represent the acquisition cost of the system; however, the cost of the parts is only a small portion of the total acquisition cost. The large expenditures for engineering man-hours and overhead are ignored. Thus, one enhancement to the methodology could be developing a more realistic acquisition cost indicator.

The support cost indicator, the maintenance visit cost, could be modified to more accurately reflect the support costs by considering items such as levels of maintenance (with considerations of, for example, the relative costs of built-in-test versus external test equipment).

While more realistic cost indicators are desirable, it was strongly recommended by industry representatives at the demonstration that a full LCC model not be incorporated into the analysis. The analysis results of such models are not viewed credible by many, and industry acceptance of the validity of such models was not considered sufficient to justify their use in the methodology.

5. Recording Team Activities

An audit trail of the various alternatives considered by the product development team during the trade-off process should be provided. A way to save alternative configurations and their associated analysis results is needed. Maintaining the history of a small subsystem would not necessarily require significant computing resources. If the entire radar is modeled, maintaining an audit trail could require significant amounts of storage and entail significant information management problems.

6. Assessing the Entire Radar

While the methodology demonstrates the concept of performing trade-offs of redundancy versus maintenance visits, for such trade-offs to be realistic, the entire radar

system must be modeled. This need raises issues related to increasing the computer support capabilities to handle the level of detail required. To allow addressing issues such as assessing the relative benefits of changing the quality level of a certain part, which may appear 500 times in a number of separate subsystems, additional computer support capabilities are needed. These capabilities are also needed because the builder of the radar warrants the entire system and is interested in the reliability and maintenance cost of the total system, not just a small subsystem as was used in the demonstration.

D. LIMITATIONS OF THE DEMONSTRATION

The overall results of the demonstration suggest that the methodology represents a useful initial step towards supporting concurrent engineering teams. Two caveats must be noted. First, the demonstration was limited to one day. Considerations such as the validity of the equations used in the methodology could not be assessed during the demonstration. Second, the participants in the demonstration, unlike the members of a concurrent engineering team, had nothing at stake in the outcome of this meeting. In industry, the participants in the product development team meeting would represent the views of certain constituencies. These views could lead to conflicts that would have to be resolved.

V. FINDINGS AND RECOMMENDATIONS

This project has successfully demonstrated how the conceptual approach of DFA can be applied to design for supportability. A number of findings and many research opportunities were identified during this project. These findings have been grouped into three categories and are presented in the following sections.

A. ORGANIZING AND MANAGING TEAMS

Having a core product development team that charters specialty teams as needed was the IDA research team's vision of how product development teams could be organized. The organizational issues involved with creating and managing concurrent engineering teams, and in particular, the activities of multiple teams, warrants a substantial research effort. A core team, like the one envisioned for this project, could coordinate the work of the other teams, each of which would be investigating certain problems and conducting trade studies. However, one team could conduct a study indicating that a certain course of action should be followed to realize certain benefits, yet this action may create problems for another team that is trying to achieve other goals. Such conflicts must be resolved.

The most common way of resolving such conflicts is through design review boards (which often meet after design decisions are made) and ultimately, by autocratic decisions made by engineering management. This approach often leads to failure to identify and resolve major conflicts until a stage in the design process in which design changes are very expensive. A better way is needed.

During the demonstration of the methodology developed for this project, the group interactions were completely unstructured. However, structured group problem solving methodologies have been shown to make group problem solving more efficient. Identifying promising structured group problem solving methodologies for concurrent engineering is another area for research.

This project has shown that government requirements, such as specifying the number of maintenance visits, can place unnecessary constraints on a product development

team. This type of limitation could result in products with LCC higher than necessary. An approach to product acquisition in which the requirements are jointly developed by a team consisting of both government and industry personnel would result in requirements that do not unnecessarily restrict the design freedom of the product development team. The research team did not consider the legal or political issues associated with using such an approach to acquisition. These issues would have to be addressed before such an approach to acquisition could be implemented.

B. COMPUTER-AIDED GROUP PROBLEM SOLVING

The proper role of the computer in support of group problem solving is an area of growing research. Approaches range from the group sharing a single computer during the meeting (as was done in this project) to providing a separate computer for each person at the meeting. Other areas of research are concerned with supporting the group when they are working in a distributed environment.

This project has demonstrated that software originally designed for a single-user can be used in a group setting. Contrary to claims made by some researchers, specific group-oriented software is not necessarily required. The use of other single-user software in group settings should be explored.

How the computer support for the team is developed is an open issue. One approach is to let the product development team build its own computer models using spreadsheets or similar software shells. One advantage of models that are actually built by the team is that the team members will be confident of the model's accuracy because the team verified the validity of the approach used in such models.

C. DESIGN FOR MAINTAINABILITY

The final area that requires additional research is developing design for maintainability methodologies and tools. Significant gaps exist in the field of design for maintainability. The review of the research literature found a lack of consensus in the research community on the definition of maintainability and how to design for maintainability. Many of the industry maintainability specialists interviewed during this study defined designing for maintainability as calculating the Military Handbook 472 attributes of a design, such as mean time to repair (MTTR).

The available measurements of maintainability have not kept pace with advancing technology. For example, the techniques proposed in MIL-HDBK 472 do not properly

handle designs in which high reliability is achieved through use of redundancy with repair. In such situations, scheduled maintenance is the key element--not corrective maintenance, which is the only item addressed in the handbook.

D. FUTURE DIRECTIONS

The methodology developed during the course of this project only begins to address the many considerations relating to incorporation of supportability into the product development process. Much remains to be done. However, the results of this project, which was limited in its scope and funding, clearly indicate that there is great potential for improving development processes through use of relatively simple approaches to aid product development teams. The conceptual approach of Boothroyd and Dewhurst, which has been proven successful in improving the ease of assembly of designs, and has been applied to limited aspects of supportability in this project, can also be applied to many other issues that must be addressed if the goals of improved quality, reduced cost, and shortened development lead time are to be attained. Moreover, such applications need not be costly to develop. The relative benefits from taking such an approach on major weapon system acquisition programs are likely to be great.

REFERENCES

1. Book review of *Reliability, Availability, and Maintainability (RAM) Dictionary*, ed. Tracy P. Omdahl, ASQC Quality Press, 1988, appearing in *Quality and Reliability Engineering International*, Volume 5, Number 3, July-September 1989.
2. *Unified Life Cycle Engineering (ULCE) Implementation Plan*, February 1987.
3. Dierolf, David A. and Karen J. Richter, *Computer-Aided Group Problem Solving*, IDA Paper P-2149, February, 1989.
4. Boothroyd, Geoffry and Peter Dewhurst, *Product Design for Assembly*, Boothroyd-Dewhurst, Inc.,Wakefield, RI, 1987.
5. Huthwaite, Bart, "Product Design for Manufacture and Assembly: The Five Fundamentals," *Proceedings of the 2nd International Conference on Product Design for Manufacture and Assembly*, 1987.
6. Burke, Gerald and Jamie Carlson, "DFA at Ford Motor Company," *Proceedings of the 4th International Conference of Product Design for Assembly*, 1989.
7. Marcus, Milton J., "Human Engineering Toward an Increase in Maintenance Capability," *Proceedings of the Second Symposium on Electronics Maintenance: Design for Ease of Maintenance*, May 1956.

APPENDIX A

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MAINTAINABILITY

A. BACKGROUND

An extensive literature review of supportability issues in engineering product development began early in this research and continued throughout the effort. The focus shifted from general supportability issues to consideration of maintainability; this appendix discusses the results of the focused review and survey. Discussions with maintainability experts and review of the literature revealed a lack of consensus on the definition of maintainability [Ref. A-1]. The literature search also indicated that many evaluation checklists and guidelines for design for maintainability exist; however, since no generally accepted definition of maintainability exists, no published guidelines were found to be universally applicable [Ref. A-2]. Furthermore, the relationship between design decisions and maintenance and logistics policy decisions seems poorly understood.

B. HISTORY OF MAINTAINABILITY AS A DISCIPLINE

Maintainability has existed as an engineering discipline since the early 1950s. At that time, the maintainability of a design was considered, but maintainability engineers would receive the design after the main design group was finished with it. At this stage, their ability to influence a design was limited; only minor improvements in the maintainability of the product could be made. Maintainability engineers had no influence in the major design decisions, where the opportunities for product improvement were greatest. In recent years, with the advent of complex systems requiring highly skilled technicians, the importance of considering maintenance during all stages of the design phase has been widely recognized.

As with most engineering disciplines, the need for the study of maintainability preceded its inception as a design discipline. The most significant factor driving the original development of the discipline was the invention of complex electronics systems built with vacuum tubes. The poor reliability of these systems necessitated their constant maintenance and repair. Many of these early systems had mean times between failure

(MTBF) of 20 to 100 hours. The components of these systems were hand soldered in place, with little consideration given to the ease of replacement. Built-in diagnostics or testability were almost unheard of, and the use of designed test points was not extensive.

The natural delay between the development of theory and its practical application was partly to blame for the delay in the use of maintainability theories; however, the emphasis on acquisition costs instead of the more substantial utilization costs probably was a more significant factor. The widespread application of maintainability techniques can be traced to the original issue of Military Standards 470, 471, and 472 in 1966. These standards set maintainability program requirements and demonstration and prediction techniques to be used in developing military systems.

Since then, the development of the transistor and the integrated circuit have spurred major changes in the field. Individual components are no longer isolated and replaced when a fault occurs--entire boards and assemblies are replaced. This modularity has changed the emphasis in maintainability from replacement methods to diagnostics and testability. The improvement in the function of electronics, especially with the introduction of the first microprocessors in 1971, has allowed part of their power output to be dedicated to fault detection and isolation. Automatic fault detection and isolation has simplified the task of the repair technician.

The defense industry has come to realize the importance of maintainability considerations. An Air Force R&M 2000 Initiative guideline specifies that each new generation of a particular type of system should double the reliability and require half the maintenance of the preceding generation system. A recommended goal is the isolation of failures down to the smallest field replaceable unit (FRU) during operation without the use of special tools. The acquisition portion of life cycle cost (LCC), rather than the support portion, is still emphasized in defense procurement. More research is needed to improve current techniques for design for maintainability and encourage their increased use throughout a variety of practical applications.

C. DEFINITIONS OF MAINTAINABILITY

The literature survey revealed that many definitions of maintainability exist in the engineering community. A sampling of these definitions follow.

MIL-STD-1388-1A, *Logistics Support Analyses*

> Maintainability is the measure of the ability of an item to be retained in or restored to a specified condition when maintenance is performed by

personnel having specified skill levels, using prescribed procedures and resources at each prescribed level of maintenance and repair.

Reliability Analysis Center, RADC-GAFB, *Reliability Design Handbook* (also MIL-STD-778)

Maintainability is a characteristic of design and installation which is expressed as the probability that an item will be retained in or restored to a specified condition within a given period of time, when the maintenance is performed in accordance with prescribed procedures and resources.

MIL-STD-1472C *Human Engineering Design Criteria for Military Systems, Equipment and Facilities*

Design for Maintainability involves design considerations directed toward achieving those combined characteristics of equipment and facilities which will enable the accomplishment of necessary maintenance quickly, safely, accurately, and effectively with minimum requirements for personnel, skills, special tools, and cost.

Jones, J. V., *Engineering Design*

The probability that a failed item can be repaired in a specified amount of time using a specified set of resources is called maintainability. Note that this is a statistical prediction, which means that, like reliability, maintainability can be greatly influenced by variables such as availability of resources and environmental conditions where maintenance is performed.

Blanchard, B. S., and W. J. Fabrycky, *Systems Engineering and Analysis*

Maintainability is an inherent design characteristic of a system or product. It pertains to the ease, accuracy, safety, and economy in the performance of maintenance actions. Systems engineers must be concerned with the design and development of a system that can be maintained in the least amount of time, at the least cost, and with minimum expenditure of support resources (e.g., personnel, materials, facilities, test equipment) without adversely affecting the mission of the system. Maintainability is the ability of an item to be maintained, whereas maintenance constitutes a series of actions to be taken to restore or retain an item in an effective operational state. Maintainability is a design parameter. Maintenance is a result of design.

Priest, J. W., *Engineering Design for Producibility and Reliability*

Maintainability is the design discipline concerned with the ability of the product to be satisfactorily maintained throughout its intended useful life span with minimum expenditures of money and effort. The purpose of maintainability is to design products so that they may be easily maintained and kept in serviceable condition. To accomplish this goal the system should be easily and quickly maintained by

- Technicians with minimum skill levels
- The minimal number of special tools, support equipment, and technical documentation
- Requiring minimum scheduled or preventive maintenance
- Developing a system for easy maintenance reduces the number of maintenance hours, skill level requirements, equipment requirements, and storage space requirements.

While all of the definitions are similar, significant differences do exist. Maintainability is defined as a measure, an inherent characteristic of a system, and a design discipline. From these definitions, what is included in maintainability is not clear--for example, preventive maintenance (PM) is included in most, but not all, of the definitions. Those definitions that define maintainability as a statistical measure cannot include many less quantifiable issues, such as safety. As a design discipline, maintainability is concerned with cost effectively maximizing operational availability by minimizing maintenance times and frequency.

D. WORKING DEFINITION OF MAINTAINABILITY

For the purposes of this project, maintainability is defined as an inherent design characteristic of a system that pertains to the ease, accuracy, and cost of maintaining the system. The two primary objectives of design for maintainability are to maximize operational readiness and to minimize LCC. Operational readiness is a measure of how often or how long a system is capable of successfully completing its mission. LCC includes all resources (personnel, materials, facilities, and test equipment) required to acquire and operate the system based on assumed longevity measured in years. Secondary goals include improved mobility and simplified subsystem upgrade.

E. TYPES AND COST OF MAINTENANCE

To maximize operational readiness, system downtime between fully mission-capable states must be minimized, while the probability that nothing will fail during the mission must be maximized. To do this, PM and corrective maintenance (CM) may be considered.

1. Preventive Maintenance

PM is used to keep the system in an operational or available state by preventing system failures from occurring. PM includes servicing, failure inspection and correction, recalibration and tuning, and the repair of parts that have failed without causing system failure. PM is typically scheduled in terms of the specified maintenance tasks and the frequency of the maintenance visits. Proper scheduling of PM requires timely, accurate information on the trends and status of components that are failing or will fail due to aging. PM results in a reduction in the lifetime operating costs of complex systems. Systems with

PM exhibit quasi-constant failure rates. A significant number of operational failures indicate that the time between PM actions is too long.

One form of PM, reliability centered maintenance (RCM), is required by DoD Directive 4151.16; RCM was first used in the commercial aviation industry. Its purpose is "to identify the essential preventive maintenance tasks required to retain the safety and reliability inherent in system design." [Ref. A-3] This method emphasizes identifying the functions with poor reliability rather than the individual parts or assemblies. A PM plan that will improve this functional reliability is then selected. If the plan improves reliability and is cost effective, it is adopted. The process includes

- Identifying functions (not parts) with the worst reliability and the worst failure modes
- Selecting a preventive maintenance plan for this function
- Determining the applicability of the plan--whether it reduces the failure rate
- Determining the effectiveness of the plan--whether it is economical.

To maximize the effectiveness and minimize the cost of PM, the time-to-failure distributions and the hazard-rate trends of the maintained system and its associated parts must be known. For example, if a part in a series system (1 out of N: fail) has an increasing hazard rate, then properly scheduled preventive maintenance will improve the reliability of the system. If a part has a decreasing hazard rate, any replacement of the part will increase the probability of failure. If the hazard rate is constant, as is often considered the case for electronic devices, then replacement will not affect the reliability. In fact, such maintenance actions are likely to induce (real or reported) failures. If the system is composed of redundant parts, scheduled maintenance can be used to improve the system reliability, even if the parts have constant or decreasing hazard rates.

2. Corrective Maintenance

CM includes repair and replacement activities that return the system from a failed state to an operating or available state. The frequency of CM depends on the system reliability and is not scheduled. CM actions can include fault detection and isolation, disassembly, interchange, reassembly alignment, and checkout. Minimizing the time required for corrective maintenance actions and maximizing the probability of successful completion of those actions are key objectives.

3. Cost of Maintenance

The cost of maintenance is determined by the frequency of maintenance, both preventive and corrective, and the cost of the logistics support required to perform the maintenance actions. Maintenance manpower and costs are related to the frequency and difficulty of maintenance actions. Logistics support costs are driven by the total costs to remove, replace, transport, and repair components at all levels of maintenance. The logistics resources include personnel, training, spare parts, test equipment, facilities, and data.

With modern weapons systems, the ratio of design to production to operation costs can average approximately 1:5:15. This ratio indicates that the largest improvements in LCC can be obtained by decreasing the cost of operation. The greatest effect design for maintainability can have on LCC is reducing the system requirements for skilled maintainers. The time required to perform maintenance actions and the complexity of the maintenance actions will influence both the number of maintainers required and their training needs. Good design for maintainability techniques can decrease the number and training of the technicians needed to keep a system running and decrease the logistics requirements of a system, thus decreasing the LCC and improving the mobility of the system.

F. THE ROLE OF MAINTAINABILITY IN SYSTEM EFFECTIVENESS

System effectiveness, as illustrated in Figure A-1, is determined by a number of factors [Ref. A-3--A-5]. Maintainability, reliability, logistics support, and maintenance concepts all affect hardware availability and dependability. Figure A-1 also shows other design-related and policy-related decisions that affect reliability and maintainability. Although the designer could have many options in designing for availability or dependability, initial requirements specifications limit these options. One weakness in product acquisition today is a poor understanding of the relationship between policy and design decisions.

In *Design for Maintainability; What the Government Standards Do and Don't Say*, Captain Donald Loose, Air Force Human Resources Laboratory, uses a figure (reproduced here as Figure A-2) to represent the paths of influence between design for maintainability and the system level trade-offs of LCC and operational readiness [Ref. A-2]. The lines of influence are marked with current models used for making the calculations required in the trade-offs. The lines with adjacent question marks represent the links that are poorly

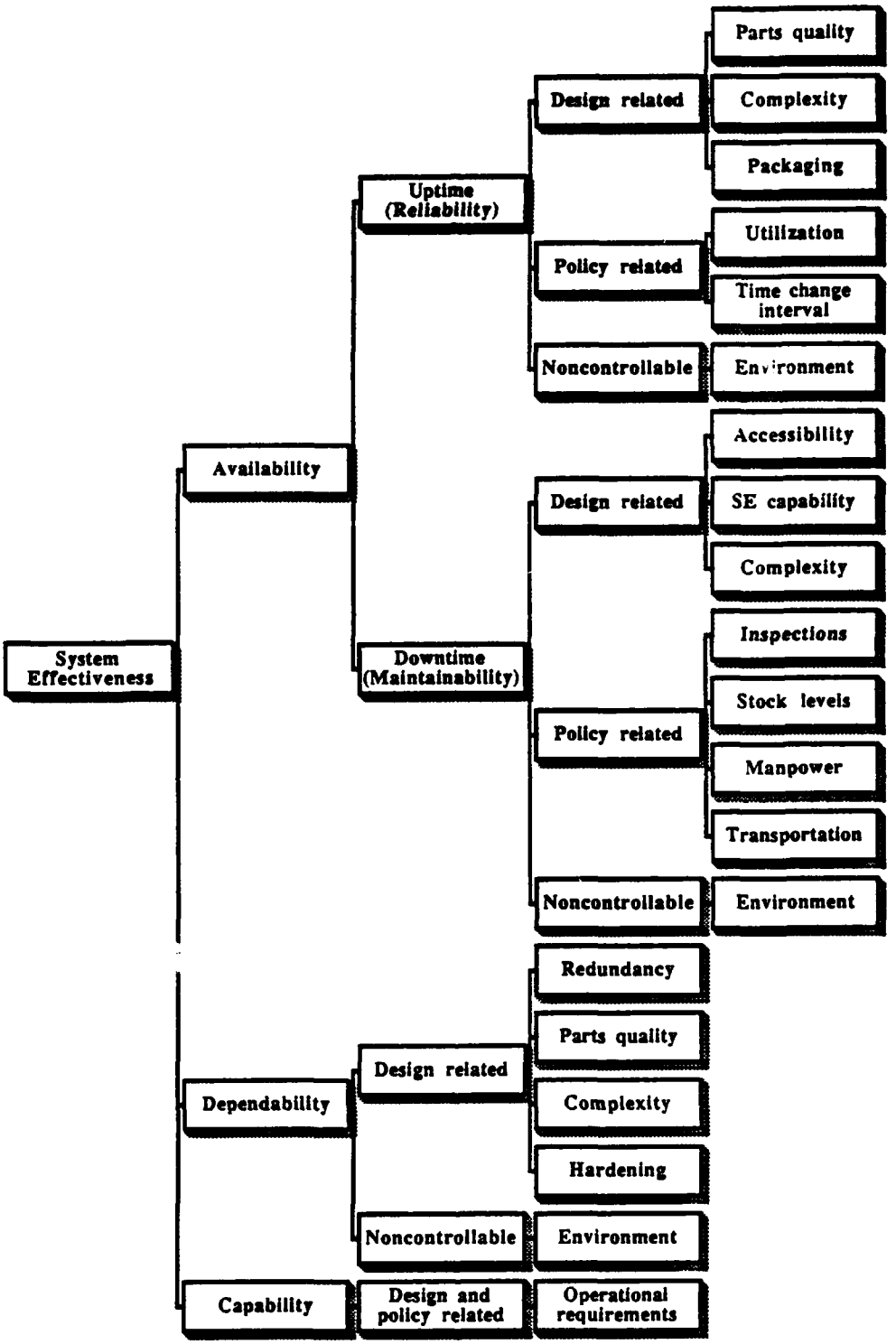
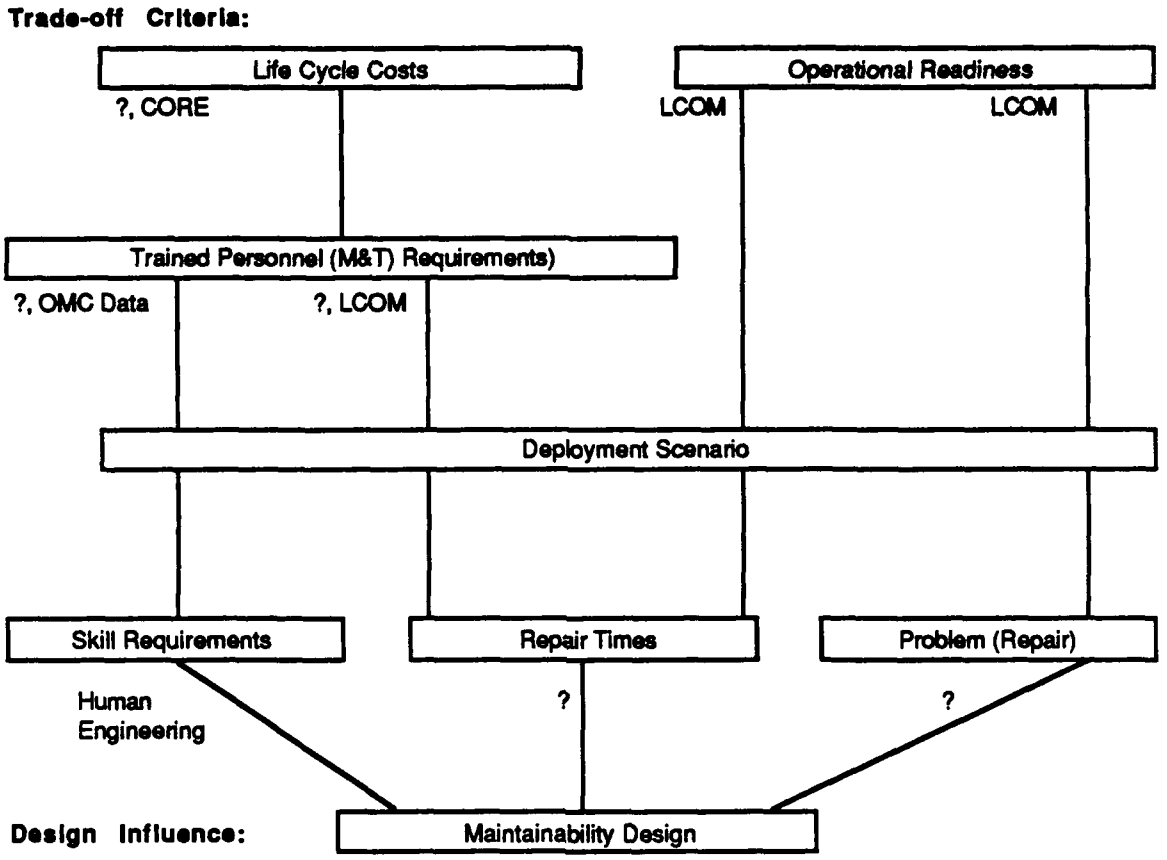


Figure A-1. System Effectiveness [Ref. A-5]



Key: **LCOM** **Logistics Composite Model**
CORE **Cost-Oriented Resource Estimation Model**
OMC **Occupational Measurement Center**

Figure A-2. The Role of Maintainability in Systems Engineering [Ref. A-2]

understood in new design approaches. Maintainability design will also influence operational readiness through provisioning requirements, support equipment requirements, and maintenance planning.

G. FUNDAMENTALS OF DESIGN FOR MAINTAINABILITY

The goal of design for maintainability is to incorporate features into the design that improve the maintainer's abilities to assess and isolate faults and will reduce the time to repair, both preparation time and active maintenance time. Preparation includes accessing the proper maintenance personnel, travel, and tool and equipment collection. Active maintenance includes reading documentation, locating and correcting the problems, and documenting the results. In addition to design-related repair times, logistics delay time (such as waiting for spares once the active maintenance activity has started) is also a large driver of mean time to repair. Policy issues such as spares budgets and number of levels of

maintenance significantly affect the mean time to repair. The total systems engineering process for a weapon system must consider design and policy issues simultaneously if life cycle cost is to be minimized.

1. Issues to be Considered in Designing for Maintainability

To be effective, designing for maintainability must include consideration of various issues. For example, the number of potential maintenance actions must be minimized, and those remaining must be simplified (by lessening the number and skill level of personnel required and lessening the number of special tools required). The status of the system must be made readily available through diagnostics and test, and considerations must be given to existing resources, including the manpower, the skill level of the personnel, and the training available. Improved technology line replaceable unit (LRU) replacement should be permitted to provide for potential system improvements and safety of the maintenance personnel must be made a paramount design consideration.

The amount of maintenance is minimized by minimizing the use of parts requiring maintenance and improving the access to these parts. Use of self-lubricating and self-calibrating parts are two of the techniques used to decrease maintenance. Using snaps instead of screws for covers and ensuring that no assemblies must be removed to access a maintenance point (one deep maintenance) can decrease the time necessary for required maintenance. Modular systems with high quality built-in-test capabilities can speed repair actions significantly. Ensuring that the assemblies with the worst reliability are the most accessible can also help to reduce repair times.

2. Maintainability Design Guidelines

Various sources of design for maintainability guidelines, rules, and questions were consulted in an attempt to derive a concise set of generic design for maintainability guidelines. Military standards and handbooks, checklists, and guidelines used by government, industry, and academia were analyzed for general applicability [Ref. A-6--A-10].

During the course of the research, a number of strawman sets of generic guidelines were developed based on the source material; however, the lists were found to be contradictory and controversial to some extent. The reason for this disparity was given at the 1989 International Conference on Engineering Design by A. L. van der Mooren [Ref. A-11].

> It would be very useful if a set of recommendations could be given, which, when applied to any design, straight on led to a [maintenance centered] MC-object. But on second thoughts this idea doesn't seem feasible. Even if suggestions are not contradictory among themselves, their material realization may lead to incompatibility; more inspection holes in a vessel e.g., may promote the maintainability, but reduce the reliability. Thus only conditional recommendations can be made and the designer should in each separate case decide whether and how to apply them, considering technical and economic consequences.

The research team therefore concluded that in the case of design for maintainability, unlike design for assembly, no concise set of universal basic guidelines could be developed to give to the product development team. The least objectionable set found by the research team appears to be those given by van der Mooren as the "ten commandments" to be generally applied to enhance an object's overall maintenance behavior:

1. Keep the construction simple.
2. Use standardized components.
3. Take care of good accessibility.
4. Take care of good replaceability.
5. Apply modular construction.
6. Neutralize human errors.
7. Neutralize developing damage.
8. Make the condition accessible.
9. Aim for self-help.
10. Provide a maintenance manual.

While these guidelines seem reasonable, they are general and may be of little help when designing a specific system.

The following list of guidelines is included to provide some notion of the types and nature of the guidelines available in the literature. Such guidelines must, however, be tailored to the specific problem being addressed. Not all of these guidelines will be appropriate for all design problems.

- Minimize maintenance downtime by using
  - Maintenance-free design
  - Standard, proven, and modular design and parts
  - Simple, reliable, and durable design and parts
  - Fail-safe features to reduce failure consequences

- Worst-case design techniques and tolerances.

- Minimize maintenance downtime by designing for effective
  - Prediction or detection of malfunction or degradation
  - Failure localization to the affected product level
  - Isolation to a replaceable or repairable module or part
  - Correction by replacement, adjustment, or repair
  - Verification of correction and serviceability
  - Identification of parts, test points, and connections
  - Calibration, adjustment, servicing, and testing.
- Minimize maintenance costs by designing products that minimize
  - Hazards to personnel and equipment
  - Special tools required for maintenance
  - Requirements for depot or contractor maintenance
  - Consumption rates and costs of spares and materials
  - Personnel skills.
- Minimize the complexity of maintenance by designing for
  - Compatibility among system equipment and facilities
  - Standardization of design, parts, and nomenclature
  - Interchangeability of like parts, materials, and spares
  - Minimum maintenance tools, accessories, and equipment
  - Adequate accessibility, work space, and work clearances.
- Minimize the maintenance personnel requirements by designing for
  - Logical and sequential function and task allocations
  - Easy handling, mobility, transportability, and storability
  - Minimum numbers of personnel and maintenance specialities
  - Simple and valid maintenance procedures and instructions.
- Minimize maintenance error by designing to reduce
  - Likelihood of undetected failure or degradation
  - Maintenance waste, oversight, misuse, or abuse
  - Dangerous, dirty, awkward, or tedious repair tasks
  - Ambiguity in maintenance labeling or coding.
- Minimize the frequency of tool failure by
  - Providing accessibility, adequate work space, and clearance
  - Ensuring installation loads do not exceed tool stress limits.

3. Quantitative Metrics for Maintainability

In addition to guidelines, a product development team needs some way of quantifying the relative merits of alternative designs in terms of maintainability. The following metrics have been commonly used for this purpose.

- Mean time to repair (MTTR)
- Maximum time to repair
- Mean time to restore system (MTTRS)
- Mean time to restore function (MTTRF)
- Direct man-hours per maintenance action (DMH/MA)
- Total parts cost per removal (at all levels of repair)
- Probability (proportion) of faults detected
- Proportion of faults isolatable
- Level of isolation in bill of material hierarchy
- False alarm rates
- Maintenance man-hours/flight hours/operating hours.

These metrics can be used in trade studies if the information needed in the calculations can be acquired. For a metric such as MTTR, necessary information includes identification of specific maintenance tasks to be performed for the system and prediction of the time required to perform these tasks. The governing document for maintainability programs in the Department of Defense, MIL-STD 470A (*Department of Defense Maintainability Program for Systems and Equipment*), provides general maintainability task descriptions. This standard is useful in classifying the types of tasks that a maintainability program could consider, although tailoring of the tasks to the specific program is required. The DoD governing document for maintainability calculation and prediction is Military Handbook 472.

As in the case of design guidelines for maintainability, choice of an appropriate metric (or metrics) for maintainability depends on the specific product development problem being addressed. The product development team, as part of the planning of the product development process, must decide how they will address maintainability in conducting trade-offs.

H. CONCLUSIONS

No universal consensus exists for the definition of maintainability. Maintainability is interpreted in various ways by different specialists in the product development process. The systems engineer, the logistics specialist, and the hardware engineer all have different views. The variety of guidelines, some of which are contradictory, that have been published concerning maintainability reflect the lack of consensus on the definition of maintainability.

REFERENCES

A-1 Loose, Capt. Donald R., USAF, *Design for Maintainability, What Government Standards Do and Don't Say*, Air Force Human Resources Laboratory Technical Paper, AFHRL-TP 89-28, Wright-Patterson AFB, OH., January 1989.

A-2 Book review of Reliability, *Availability, and Maintainability (RAM) Dictionary*, ed. Tracy P. Omdahl, ASQC Quality Press, 1988, appearing in *Quality and Reliability Engineering International*, Vol. %, No. 3, July-September, 1989, p.

A-3. Defense Systems Management College, *Integrated Logistics Support Guide*, Department of Defense, Ft. Belvoir, VA, May 1986.

A-4. Arnold, Wilbur V., *Designing Defense Systems: The Trade-Off Process*, Defense Systems Management College, Fort Belvoir, VA, 1986.

A-5. Thompson, Steven A., "Relating Life Cycle Costs to Weapon System Effectiveness: An Integrated Approach," *Proceedings of the IEEE 1978 National Aerospace and Electronics Conference*, NAEON 78, Dayton, OH, 16-18 May 1978, pp. 1083-4.

A-6 MIL-HDBK-759, *Human Factors Engineering Design for Army Material*, Department of Defense, 1975.

A-7 MIL-STD-1472C, *Human Engineering Design Criteria for Military Systems, Equipment, and Facilities*, 2 May 1981.

A-8 *Systems Engineering and Analysis*, Benjamin S. Blanchard and Wolter J. Fabrycky, Virginia Polytechnic Institute and State University, 1981.

A-9 *Reliability Design Handbook*, Reliability Analysis Center, Rome Air Development Center, Griffis Air Force Base (RADC-GAFB), Rome, NY, 1976.

A-10 *Engineering Design, Reliability, Maintainability and Testability*, James V. Jones, TAB Professional and Reference Books, 1988.

A-11. Van der Mooren, A.L., "Maintenance Aspects in Design of Mechanical Systems," *Proceedings of the Institution of Mechanical Engineers, International Conference, Engineering Design, Volume I*, 22-25 August 1989, Harrogate International Centre, pp. 1227-1238.

APPENDIX B

MAINTAINABILITY ANNOTATED BIBLIOGRAPHY

Abstract of Lessons Learned, Fifth Edition, Air Force Lessons Learned Program, Directorate of Systems Support, Air Force Acquisition Logistics Center (AFALC), Wright-Patterson AFB, OH, 1 March 1988.

> The AFALC was originally formed with a primary mission of bridging the gap between the acquisition and logistics communities to improve reliability and supportability of new weapons systems coming into the Air Force inventory while lowering the cost of ownership for those systems. One valuable method of meeting this goal is the compilation of past program management experiences in the form of lessons learned. The Deputy for Integrated Logistics, AFALC/LS, has been assigned the responsibility of implementing the Lessons Learned Program. The Directorate of Systems Support, AFALC/LSL, has the task of gathering, assigning, storing and disseminating lessons within the acquisition and logistics communities.
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> Basically, the data base contains two types of lessons learned: management and technical. Management Lessons address program decisions and actions in such areas as program control, budget/financial control, contracting techniques, support planning, configuration management, maintenance concepts and data management. Technical Lessons relate to systems, equipment and components, including hardware, software, support equipment, or the design factors that influence the performance of the system or equipment.

Acquisition Management, Repair Level Analysis (RLA) Procedures, AFLC/AFSC Pamphlet 800-4, Department of the Air Force, Headquarters Air Force Logistics Command, Wright-Patterson AFB, OH and Headquarters Air Force Systems Command, Andrews AFB, DC, 25 November 1983.

> This pamphlet tells how to formulate and implement repair level analysis (RLA), formerly optimum repair level analysis (ORLA) on new systems, equipment, and major modification programs. This is a guide for Air Force Logistics Command (AFLC) and Air Force Systems Command (AFSC) organizations to use in acquiring new systems and equipment. It gives contractors and prospective contractors an economic basis on which to recommend levels of repair or discard-at-failure for system components.
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> The intent of this pamphlet is to improve logistics cost effectiveness and the operational capability of future systems. It does this by ensuring the methods for developing valid maintenance plans become an integral part of engineering development.

Acquisition Management, USAF R&M 2000 Process, AFLC/AFSC Pamphlet 800-7, Department of the Air Force, Headquarters, U.S. Air Force, Washington, DC, 1 January 1989.

This pamphlet describes how to increase combat capability while saving resources through good reliability and maintainability (R&M) practices. The pamphlet describes Air Force goals for R&M and a set of guiding principles and practical building blocks which should be considered "preferred" practices for identifying operational R&M requirements; motivating defense contractors; and developing, producing, and maintaining Air Force systems. Successful program managers repeatedly cite these methods as the ones they use to meet or exceed customers' R&M *expectations* while satisfying other program objectives. The pamphlet is written in nontechnical language and is designed for a variety of audiences at all organizational levels, both in the Air Force and the defense industry. AFP 800-7 complements Air Force Regulation 800-2.

Adams, W.E., Lockheed-Georgia Company, "Avionic Flight Control Subsystem Design and Integration in the C-5 Airplane," *Aircraft Design Integration and Optimization*, Volume 1, Advisory Group for Aerospace Research and Development (AGARD) Conference Proceedings No. 147, NATO, 43rd Meeting of the Flight Mechanics Panel of AGARD held at Scuola di Guerra Aerea, Florence, Italy, 1-4 October 1973, published June 1974.

The preliminary design process had significant influence on the C-5 avionic flight control system development, production, and operational cost. The design decisions made during the preliminary design phase relative to the stability augmentation systems illustrate the extent of the impact on the design, test, manufacture, and installation of the avionic systems. These decisions lie mainly in the areas of mission success capability, airplane safety, reliability, survivability, and human factor characteristics and, for the illustrative stability augmentation systems, the aircraft's handling qualities. The design processes, including the subsystem integration with the airframe and with other functional subsystems, influenced the cost of the C-5 program. Experience gained from this program may lead to improvements in preliminary design decision making procedures.

Advanced Concepts for Avionics/Weapon System Design, Development and Integration, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 343, NATO, Copies of papers presented at the Avionics Panel 45th Symposium held at Ottawa, Canada, 18-22 April 1983.

In order to realize the performance in the development of modern military aircraft, full advantage is taken of the rapid advances in the computer and electronic technologies. Thus, as each new aircraft design depends increasingly on avionics, the overall system becomes more versatile, but also more complex.

Modern weapon systems are being structured with more interdependency among subsystems. However, potential maximum benefits of subsystem and weapon development integration have not yet been realized.

In order to realize the benefits of advanced integration concepts and maintain compatible timescales throughout the subsystems development and test phase, intelligent integrated design concepts and proper coordination of the development program are essential.

New design and development strategies should be considered in order to achieve the technical and performance benefits expected of highly advanced and integrated avionics/weapon systems in an economical and timely manner. The applicable design and development concepts being considered as appropriate for presentation and discussion in this meeting are as follows:

- Initiate design in terms of overall system to satisfy operational requirement
- Conduct parallel design and development activities in all relevant disciplines
- Retention of design and application flexibility and growth in subsystems by means of appropriate data processing and subsystem inter/intracommunications structure
- Planning of logistic support elements including reliability, maintainability and supportability as well as life cycle cost considerations
- Comprehensive integrated ground testing prior to airborne evaluation of the weapon systems
- Comprehensive integrated ground testing prior to airborne evaluation of the weapon systems

The objective of this meeting was to exchange information and ideas among the various disciplines involved in weapon system design to the benefit of integrated system developments for future defense programs. The meeting contributed to a mutual understanding of the tasks of all specialists involved in the realization of integrated weapon systems.

Air Force Lessons Learned Bulletin, Reliability and Maintainability, Directorate of Systems Support, Air Force Acquisition Logistics Center (AFALC), Wright-Patterson AFB, OH, 23 February 1989.

Reliability and maintainability are key factors that influence system design, system effectiveness, logistics support requirements and life cycle costs (LCC).

Reliability and maintainability are different, but complementary, engineering disciplines. Reliability is concerned with the ability of a system to operate for a specified period of time, in a specified manner, without failure or serious degradation. Maintainability is concerned with how quickly the system can be restored to working order once it has failed. Together, the R&M features of a system help determine the system's effectiveness in doing its assigned mission.

There are two clearly distinct kinds of reliability--mission reliability and logistics reliability. Mission reliability is the probability that a system will successfully complete its mission. Logistics reliability is the probability that a system will operate as planned under defined operational and support concepts, using specified logistics resources (spares and maintenance manpower). These two kinds of reliability often conflict. It is the job of the R&M manager specifically, and the program manager in general, to address and resolve this conflict within the constraints of the total program.

Maintainability is a part of systems engineering and program management, and represents a large part of total systems resources and costs. It must be

considered in terms of the system life-cycle with respect to program and system planning, system tradeoffs, and LCC.

The lessons learned contained in this bulletin are collected to help the R&M manager carry out an effective R&M program and to encourage dialogue between engineering operations and support personnel so that answers to questions and solutions to problems can be found.

Other bulletins containing information that could aid the R&M effort are Accessibility, Automatic Test Equipment, Corrosion, Fault Isolation and Failure Verification, Life Cycle Cost, Logistics Support Analysis, Maintenance Planning, Quality Assurance, Survivability, Test and Evaluation, and Training and Training Support. This bulletin should be used in concert with these other bulletins.

Air Force Lessons Learned Bulletin, Maintenance Planning, Directorate of Systems Support, Air Force Acquisition Logistics Center (AFALC), Wright-Patterson AFB, OH, 23 February 1989.

Maintenance Planning establishes the requirements for both on- and off-equipment maintenance, to be performed during the life of the system or equipment.

Maintenance planning defines the actions and support necessary to ensure that the system or equipment attains specified operational capability, sets the specific criteria for repair times, repair levels, testability, logistics reliability and maintainability characteristics, support equipment requirements, manpower skills, and facility requirements. Additionally, maintenance planning states the extent and use of interim contractor support (ICS).

This bulletin contains a collection of lessons learned, documented from existing programs. Contained are examples of both successful and less successful applications of the maintenance planning concept. Potential users may have constraints not considered in the appropriate action statement, however, the conditions or results presented in the lessons should be considered in decisions involving similar questions so that the same type of problems may be avoided.

1985 Joint AFSC/AFLC Reliability and Maintainability Workshop Proceedings, Volume II, Air Force Systems Command/Air Force Logistics Command, 13-15 November 1985, Wright-Patterson AFB, OH.

This workshop was designed to provide a forum for Air Force personnel to discuss how to successfully implement reliability and maintainability. The goal of the workshop was to increase the manager's awareness of the opportunities available for substantial R&M improvement. This volume contains presentations on R&M success stories, contractual procedures, how Air Force organizations are successfully implementing R&M, R&M tasks, and the use of proven R&M tools and techniques.

Anderson, R.T., *Reliability Design Handbook*, ITT Research Institute, under contract to Rome Air Development Center, Griffiss Air Force Base, NY, Catalog No. RDH-376, March 1976.

This Reliability Design Handbook is intended to serve as a tool for designers of military equipment and, in particular, for designers of equipment items that would typically make up avionics systems. The handbook provides guidelines for use by design engineers to assure the

achievement of a reliable end product. From the standpoint of design, it is consistent with, and extends, basic concepts and reliability improvement techniques described in MIL-HDBK-217B. Specifically, the handbook provides design information, factors, and parameters, and other engineering data affecting reliability. In addition, the handbook describes the approach to reliable design, includes theoretical and cost considerations and describes methods covering such considerations as part control, derating, environmental, resistance, redundancy and design evaluation.

Berger, Robert L., AFSC, Aeronautical Systems Division, "A Systems Approach--Minimizing Avionics Life Cycle Cost," Thirteenth Intersociety Conference on Environmental Systems, 11-13 July 1983, San Francisco, CA., 831107, SAE Technical Paper Series.

This paper introduces a new concept in air-airframe environmental control system (ECS) and avionics (airborne electronic equipment) integration which provides a method of optimizing system reliability while minimizing system life cycle cost (LCC). This concept is being introduced under a new program sponsored by the Aeronautical Systems Division at Wright-Patterson AFB for defining equipment thermal and reliability requirements and optimizing cooling capacity and its allocation to equipments. The proposed systems approach provides increased effectiveness in achieving reliability throughout the acquisition process. This is accomplished by putting product assurance in the hands of the design engineers rather than relying totally on the test or quality control engineer. The concept addresses specific tasks that need to be accomplished at both the system and subsystem levels to ensure the integrity of the total program. The concept is applicable to any electronic equipment, military or commercial.

New concepts include allocating cooling at the system level based on minimizing overall system LCC and requiring that the thermal design of electronic equipment be based on minimizing the LCC of the equipment rather than just meeting a reliability goal.

Bhagat, Wilbur, Wright-Patterson AFB, "R&M Through Avionics/Electronics Integrity Program," *IEEE*, 1989 Proceedings, Annual Reliability and Maintainability Symposium, Atlanta, GA, 24-26 January, pp 216-219.

This paper addresses the importance of designing reliability and maintainability (R&M) in the electronic equipment in the early stages of its development and describes a new approach called "Avionics/Electronics Integrity Program" (AVIP) which emphasizes early attention to design criteria and analysis, and dictates a process which strikes a balance between analysis and test. This paper outlines some of the problems and limitations that have been observed using the traditional reliability approach (MIL-STD-785 process) and discusses how the AVIP approach will overcome these problems and limitations. AVIP retains and incorporates the proven and useful elements of the traditional reliability approach, such as Failure Modes, Effects and Criticality Analysis (FMECA), Failure Reporting, Analysis and Corrective Action System (FRACAS), and Environmental Stress Screening (ESS). This paper is intended to provide the R&M, design and management communities with a basic understanding of, and an insight into, the process of achieving electronics R&M through the AVIP approach.

Blanchard, Benjamin S. and Wolter J. Fabrycky, Virginia Polytechnic Institute, *Systems Engineering and Analysis*, Prentice-Hall International Series in Industrial and Systems Engineering, W.J. Fabrycky and J.H. Mize, Editors, 1981.

Boehm, Manfred, "Maintainability, an ILS Effort to Manipulate LCC," *Design for Tactical Avionics Maintainability*, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 361, NATO, Copies of papers presented at the Avionics Panel 47th Symposium held at Quartier Reine Elisabeth, Brussels, Belgium, 7-10 May 1984.

> Maintainability is a word, which is in everybody's mind today, but which at the same time implies different understanding and selective interpretation. This is caused by the variety of individual personnel activities and responsibilities with their specific motives and objectives. There is a wide scale of interests from the sole operational motive to personal motives at the customer side as well as at the manufacturer side, everyone wanting to protect mainly their own interests.
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> In order to balance all these difference considerations there is only one solution--dialogue--a cooperative dialogue between all partners involved to follow the objective as to minimize the cost factor for the system/equipment utilization phase.
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> The dialogue has to be initialized already in the early system definition phase because the foundation of the maintainability with all its positive and negative consequences has already been performed in that early life cycle phase.
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> Failures in this phase may have catastrophical effects onto the LCC-factor of utilization. Therefore, special attention shall be given to the development phase with its relevant elements and considerations.
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> The divergence of interests and interdependences of maintainability and operational performance parameters will be demonstrated with the example of the development of a Nose Radar System concept for a military fighter aircraft.

Boothroyd, Geoffrey and Peter Dewhurst, *Product Design for Assembly*, Boothroyd Dewhurst, Inc., Wakefield, RI., January 1987.

> The Product Design for Assembly technique described in this handbook is concerned with reducing the cost of a product through simplification of its design. The best way to achieve this cost reduction is first to reduce the number of individual parts that must be assembled and then to ensure that the remaining parts are easy to manufacture and assemble. The analysis technique is systematic in its approach and is a formalized step-by-step process.
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> Assembly cost is largely determined at the design stage. The designer should be aware of the nature of assembly processes and should always have sound reasons for requiring separate parts (and hence higher assembly costs) rather than combining several parts into one manufactured item. The designer should always keep in mind that each combination of two parts into one will eliminate at least one operation in manual assembly or an entire section of an automatic assembly machine.
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> It is important to have a measure of how efficient the design is in terms of assembly. This handbook shows how to quantify this factor.

Buche, J. and I. Cohen, Grumman Aerospace Corp., "Translating Supportability Requirements into Design Reality," presented at the AIAA/AHS/ASEE Aircraft Systems, Design and Technology Meeting, Dayton OH, 20-22 Oct 86, *J. Aircraft*, Vol. 24, No. 8, pp. 490-494, A87-50333, Technical Information Services, American Institute of Aeronautics and Astronautics, New York, NY.

This paper explores some of the principal issues in the integration of supportability into the design process. Roles of the contractor's design, supportability, and management specialists and their government counterparts are discussed as they relate to logistics influence in design. Methods and processes by which weapon system logistics and readiness requirements are established, assessed, allocated to system elements, and translated into specific design features are described. Tradeoff consideration, an approach to effective tradeoff criteria, and the progress of supportability issues through the program phases are identified, with particular emphasis on the necessity for developing and maintaining an effective audit trail.

Carter, John, Marsland-Carter Company Limited, "Maintenance Management-Computerised Systems Come of Age," *Computer-Aided Engineering Journal*, December 1985, pp. 182185.

Maintenance management has always required the manipulation of large amounts of data, and the development of more cost-effective processing, storage and database systems has brought the use of computers to the fore in this area. This article considers the evolution of specialized equipment maintenance, the capabilities of today's computer-aided maintenance systems and the emerging expert systems technology.

Correale, Herman, "Supportability by Design Using CALS," *Proceedings of the 1987 IEEE Annual Reliability and Maintainability Symposium*, pp. 192-195, A87-46713, Technical Information Service, American Institute of Aeronautics and Astronautics, New York, NY.

This paper addresses current developments and unsolved issues related to the growing emphasis on Computer Aided Logistic Support (CALS) as an industry and government strategy for increasing supportability, reducing costs and increasing war fighting capabilities of weapon systems. It emphasizes the increasing involvement by all parties in achieving the stated Department of Defense (DoD) CALS goals, and pushing digital information technologies to new levels of application.

Czajkiewicz, Zbigniew J., Wichita State University, "Optimization of the Maintenance Process," *Simulation*, March 1985, pp. 137-141.

A comprehensive preventive maintenance program minimizes equipment breakdowns and cuts operating costs, which in turn improves productivity.

A mathematical definition of the maintenance process and criteria for its optimization is presented in two stages: (1) structural optimization of a maintenance process by selecting an appropriate repair strategy and (2) parametrical optimization consisting of choosing optimal (based on assumed criterion) times and scopes of repair actions. General classification of the repair strategies, their characteristics and results of simulation experiments are presented.

Definitions of Terms for Reliability and Maintainability, Military Standard, MIL-STD-721C, Department of Defense, 12 June 1981.

This Standard defines words and terms most commonly used that are associated with Reliability and Maintainability (R&M). It is intended to be used as a common base for R&M definitions and to reduce the possibility of conflicts, duplications, and incorrect interpretations either expressed or implied elsewhere in documentation. The definitions address the intent and policy of DoD Directive 5000.40. Statistical and mathematical terms that have gained wide acceptance are not defined in this Standard since they are included in other documents.

Denney, Robert O., Mike J. Partridge, and Roger B. Williams, Boeing Aerospace Co., "Integrated Testing and Maintenance Technologies," Final Technical Report for Period 25 September 1981 - 15 September 1983, AF Wright Aeronautical Laboratories, Wright-Patterson AFB, OH, AFWAL-TR-83-1183, December 1983, Defense Technical Information Center, Alexandria, VA.

Maintenance of weapon systems is becoming an increasingly important consideration in weapon system development because the cost of maintenance is a significant portion of the life cycle cost of the system. The objective of the Integrated Testing and Maintenance Technologies effort is to define requirements for an onboard test system for the avionic suite planned for tactical fighters in the 1990's. Problems with current onboard test systems were analyzed to determine where improvements could be made. In addition, the anticipated avionic architecture and mission of the 1990's were evaluated to determine the impact on maintenance capability. Requirements for the Integrated Testing and Maintenance System were developed and documented in a system specification. Identified improvements over current systems include better filtering of intermittent failure reports, better isolation of intermittent failures through the use of recorded data, more extensive use of system-level tests of mission operational data and a man-machine interface providing more information to the maintenance technician. In addition, artificial intelligence applications were evaluated to determine where they might be effectively applied to ITM. A design concept for a fault classification expert system was developed.

Design for Tactical Avionics Maintainability, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 361, NATO, Copies of papers presented at the Avionics Panel 47th Symposium held at Quartier Reine Elisabeth, Brussels, Belgium, 7-10 May 1984.

The inherent logical make-up of digital systems makes possible the opportunity for a large improvement in the maintainability cost of avionics. Limited success in the use of Built-in-Self-Test/Built-in-Test (BIST/BIT) for fault detection and location has discouraged users. The promised high percentage detection capability has resulted in an increased in-service delivered performance, but not has high as predicted, and false alarms have increased. Past and current digital systems have had BIST/BIT as an added-on feature when it should have been incorporated into the original design.

Testability must become a basic system design objective. However, only recently did adequate tools and advanced technology become available upon which to base imaginative new approaches to BIST/BIT. These new ideas are expected to produce accurate and efficient test programs and techniques.

With the rapid increase in the use of embedded computers in the avionics system and equipment, maintenance of the avionics software has not been designed with low life-cycle maintenance as an objective. Development concepts, methods and tools aimed at a well-structured, testable process will overcome past deficiencies.

The objective of this symposium was to bring forward for Avionics Panel review and discussion the development methods and techniques on both the hardware and software sides of the maintainability issue.

Dickman, Thomas J. and Major Thomas M. Roberts, The Analysis Sciences Corporation, "Modular Avionics System Architecture Decision Support System," *Proceedings of the IEEE National Aerospace and Electronics Conference*, Dayton, OH., 23-27 May 1988, Vol. 4 (A88-50926 22-01), New York, IEEE, pp. 1549-1552.

This study develops a methodology for evaluating modular avionics applications in terms of life cycle cost and system effectiveness. The methodology is to be used to compare alternative modular architecture strategies as well as conventional strategies for introducing avionics into new or existing weapon systems. The study is one of a series of tasks commissioned by ASD/AX as part of the pre-FSD investigation of modular avionics alternatives. The process described herein is intended to be a flexible means of evaluating postulated alternatives for Air Force wide implementation of modular avionics. The analysis is expected to be performed using data normally available during the conceptual phase of a development program. Avionics has had a relatively small impact on weapon system effectiveness but that impact is increasing. Functions performed by avionics have been limited to navigation, communications, and some portion of fire control. The role of avionics, however, has steadily increased with each new generation of aircraft. Today avionics is an integral part of fire control, flight control, engine control, and defensive countermeasures in addition to navigation and communication systems. Modular avionics alternatives offer potential improvements in capability by allowing common tasks to be performed by identical hardware and software elements. Commonality of avionics elements within weapon systems and among weapon systems may reduce both development cost and development risk. Reliable common avionics elements offer the potential of reducing the avionics support burden. The impact on the overall weapon system effectiveness has not yet been determined.

Fleming, Randall, Jill V. Josselyn (Systems Control Technology, Inc.), and Paul Boyle (Northrop Aircraft Division), "Integrated Design of Modular Avionics for Performance and Supportability," *Proceedings of the IEEE National Aerospace and Electronics Conference*, Dayton, OH., 18-22 May 1987, Vol. 4 (A88-34026 130-01), New York, IEEE, Inc., pp. 1296-1303.

Modern weapon systems currently being developed are relying more and more upon higher levels of avionics system integration in order to meet projected weapon system requirements. Traditional driving factors in weapons system design relating to performance are being mitigated by cost and manpower constraints related to life cycle costs and logistic support. Current techniques for developing LCC and ILS requirements may seriously impact the performance of a weapon system if they are not accounted for early in the design process.

This paper presents a case study of a generic complex modular avionics system during system and subsystem design phases. The case study demonstrates setup and application of an integrated performance and supportability analysis methodology. Although the methodology was originally set up for supportability design and analysis only, the capability and structure for integration of performance issues developed as the result of evaluating the impact of weapons systems constraints on the system design and support issues. A quantitative system mission and functional-driver link between supportability requirements and specific design issues was established early-on. This enabled numerous design tradeoffs/improvements for supportability throughout the program. The methodology and analysis provided a program-directed focus breaking across traditional organizational and communications barriers in avionics design and analysis.

Gardner, Capt. Thurman D., "An Examination of Operational Availability in Life Cycle Cost Models," A Thesis, LSSR 57-83, Air Force Institute of Technology, September 1983, Wright-Patterson AFB, OH., Defense Technical Information Service, Alexandria, VA.

The research objective was to show weapon system availability as a critical factor that must be evaluated as part of the first Life Cycle Cost (LCC) estimate. A three-part approach was used to substantiate the objective. First, the acquisition directives were examined to determine if availability was an objective. Secondly, some common LCC models were analyzed for purposes of adapting applicable models to calculate availability. Lastly, the output of an adapted model was used in a tradeoff analysis of similar avionics packages to determine if the added availability information was useful. The results of the approach showed that the guidance provided a poor representation of availability. The guidance did show availability could replace readiness as a primary objective. Secondly, a LCC model could be adapted to calculate availability. A third finding was that the added factor of availability improved the Program Manager's (PM) design decision process. Lastly, the LCC management concept could provide stronger support for the DoD acquisition objectives by equally balancing availability instead of supportability with cost, schedule, and performance.

Glassman, Ned and Esperanza Rodriquez, Hughes Aircraft Co., "Less Reliability and Maintainability ... Not More ... Is Better (Effectively Applying R&M Influences to the Design Process)," *IEEE*, 1989 Proceedings, Annual Reliability and Maintainability Symposium, Atlanta, GA, 24-26 January, pp 210-215.

Ineffective communication is the basis for many organizational problems. The author's opinion is that the "ilities" difficulty to effectively influence the design community also results from the lack of effective communications due to arbitrarily established boundaries.

This paper offers a solution in work at Hughes Aircraft Company, which focuses on the problem of communication between the "ilities" and the design community. The solution, the Supportability Design Evaluation System (SDES), recognizes that the result of effective communication can be achieved by reducing the need to communicate.

This solution embeds reliability and maintainability analytical tools directly into the designer's CAD/CAE workstations. This provides the designer on-line capability to evaluate his design in-process and to capture "ilities" improvements before metal is cut, mind-sets are established, and while time is available to do so.

New technological solutions, such as the SDES, also requires new approaches to organizational structure, responsibilities, and procurement practices to be totally successful.

Only by understanding and isolating the root cause of the problem, offering solutions that address the problem outside the context of today's organizational culture and design process, and being ready to accept the likely changes, can industry effectively meet the challenge of competitiveness and more effective products. The "ilities" communities must join in a proactive effort to make this happen.

Good, Debra E., "An Analysis of the Feasibility of Using Design Stability as a Decision Parameter for Making Logistics Supportability Decisions," A Thesis, LSSR-84-83, Air Force Institute of Technology, September 1983, Wright-Patterson AFB, OH., Defense Technical Information Center, Alexandria, VA.

This research investigated the criteria and analysis techniques that are currently being used in the Air Force to evaluate design stability as it relates to decisions concerning the establishment of an organic logistics support capability versus the use of ICS. The analysis was conducted in two parts: (1) a time series analysis of engineering change proposals (ECPs) which impacted logistics elements, and (2) a series of interviews designed to assess the adequacy of available techniques for determining the point at which design stability is achieved. Results of the ECP trend analysis indicate that while time series analysis can be used to define a model for a given set of historical data, the models for two very similar systems, the F-15 and F-16 fire control and flight control avionics, are entirely different. Thus, one cannot use a model developed with historical data from one program to predict the ECP trend for a new program. Results of the interviews indicate there is no concensus as to how to define design stability. Recommendations include: (a) another study be performed to replicate the results of this effort, and (b) revision of AFR 800-21 be considered to reflect these results.

Greeley, Brendan M. Jr., "Air Force Delays Programs to Enforce Systems Reliability," *Aviation Week and Space Technology*, 9 December 1985, pp. 16-17.

Greene, David C. and E. Edward Lowery, "Supportability Control Factors," *Proceedings of the 1986 IEEE Annual Reliability and Maintainability Symposium*, Las Vegas, NV., 28-30 January 1988, pp. 133-138.

Supportability is difficult to define and describe since it deals with a large number of disciplines under varying circumstances. However, through the use of the conventional system effectiveness control indices (Availability, Dependability, and Capability), supportability factors can be monitored and combined to form the supportability measure. A case is illustrated to demonstrate how supportability can be measured, and calculations are given.

Supportability can be quantified through a build-up of factors that are associated with the system effectiveness measures of availability, dependability, and capability. The qualitative factors that impact the R&M can be identified, associated, and monitored as regarding their influence on the measures. Other ILS factors can likewise be managed to assure the desired outcome.

Supportability can be "designed-to" by virtue of control over the R&M characteristics of the system attained through logistics analysis. Control over other contributing program factors is possible through the proper management of the functions that are involved in producing logistics products and services.

Griffin, Col. Larry (Office of the Assistant Secretary of Defense, Production and Logistics, Washington, DC) Moderator, Edward Haug (University of Iowa), William Henry (Boeing Aerospace), Dennis Hoffman (Texas Instrument), Larry Linton (Litton Amecom), and Joe Meridith (Newport News Shipbuilding Co.), Panelists, "Panel on Computer-Aided Acquisition and Logistics Support (CALS)/RAMCAD," *IEEE*, 1989 Proceedings, Annual Reliability and Maintainability Symposium, Atlanta, GA, 24-26 January, pp 403-404.

Gulcher, Robert H., Rockwell International, "B-1B: Designing for Supportability," *Aerospace America*, June 1984, pp. 54-56, Technical Information Services, American Institute of Aeronautics and Astronautics.

Historically, design efforts focused mainly on flight performance. Features that would have improved supportability, such as test connectors, access doors, and component packaging, were often not included in an aircraft design because they would have detracted from performance by adding weight. Squeezing additional performance out of a design led to frequent failures that ultimately aggravated the supportability problem. Furthermore, maintainability engineers, who were traditionally responsible for identifying supportability requirements, worked outside the engineering design groups, thus limiting their effectiveness in establishing supportability requirements during design. Consequently, aircraft often depended heavily on ground support systems, increasing support costs and reducing both availability and flexibility.

Experience on the B-1B program suggests that supportability of future aircraft can be further improved by fully integrating supportability requirements into design from conceptual design through planning of ground operations and support. Such a total systems approach will ensure early identification of supportability requirements.

Once the supportability requirements are identified, various design technologies can be applied to meet them. A self-sealing hydraulic actuator for example, could be used on future aircraft. In some cases redundant seals have increased the interval between repairs of actuators. High-performance APUs would improve self-sufficiency for engine start, ground test, and servicing, and could also reduce aircraft weight and simplify power and cooling systems needed for ground maintenance. A third example would be materials and techniques for quick onboard structural repair without compromising aircraft hardness or increasing radar cross-section.

Gunning, David R., "Integrated Maintenance Information System," Preliminary Draft, Combat Logistics Branch, Logistics and Human Factors Division, Air Force Human Resources Laboratory, Wright-Patterson AFB, Ohio, 27 January 1984.

> The Air Force is currently developing several computer systems for base-level maintenance. Unless integration occurs, the Air Force of the future will have several computer systems and updating requirements on the flight line. Confusion will occur with possibly incompatible hardware, data requirements, and required technician training. The Integrated Maintenance Information System (IMIS) will integrate the existing and developing systems with the automated technical data system, adding diagnostic job aids to increase the ability of technicians to troubleshoot and perform a wider range of maintenance actions. The Integrated Maintenance Information System will develop an integrated approach to total weapon system maintenance. Technical data, training, diagnostics, management, scheduling, and historical data bases will be linked together, and a portable graphic display will be developed to carry and present the required information at the job site. Interfaces will be developed for aircraft computers and for existing and emerging data bases. The first complete application of this technology will be on the Advanced Tactical Fighter. The IMIS goal will be to develop one system, one data base, one user interface device, and one piece of output hardware that flight line technicians can use to do timely and accurate maintenance.

Hindes, D. Kent, Gary A. Walker, and David H. Wilson, "Phase III Study, Development of Maintenance Metrics to Forecast Resource Demands of Weapons Systems," Final Report, Boeing Aerospace Company, Product Support, Experience Analysis Center, Seattle, WA, February 1982.

> This report describes the methodology and results of a 15-month Phase III effort to "Develop Maintenance Metrics to Forecast Resource Demands of Weapons Systems." Increased concern with the rising cost to support weapon systems currently in operation, as well as those in development, has created the need for more accurate methods of projecting maintenance requirements. The objective of this subject research was to alleviate the above need by identifying, determining, and integrating those measurable weapon system parameters that are necessary and sufficient to predict and quantify the drivers of maintenance resource demands.

Irwin, J.F., Northrop Corp., "Operational Readiness and its Impact on Fighter Avionic System Design," *Advanced Concepts for Avionics/Weapon System Design, Development and Integration: Conference Proceedings of the 45th Avionics Panel Symposium*, Ottawa, Canada, 18-22 April 1983, AD-A138 600, pp. 3-1 -3-12, Defense Technical Information Center, Alexandria, VA.

> Operational Readiness (OR) is a widely used term that covers various aspects of availability, maintainability, reliability, and testability.
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> Just as the development of avionic systems require the establishment of system engineering, software design and interface management guidelines, the same requirement exists for the world of operational readiness. These OR guidelines include the following controllable elements:
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> - Design-for-Testability (DFT)
> - Operational Fault Tolerance

- System Diagnostic and Reconfiguration
- Post-Flight Data Extraction/Analysis, and
- Integrated Test and Maintenance

Design and Acquisition of systems and prime electronic equipment must account for early consideration of testability and automatic test design requirements. Testability factors influence all phases of design, integration, deployment and support of electronic equipment and will adversely impact weapon system availability and ultimate return on investment if improperly specified and implemented.

The major goals of fault tolerant systems are increased weapon systems availability, mission survivability, and an affordable life cycle cost. Widespread acceptance of operational readiness objectives will probably be predicated on the demonstrated life cycle cost of those initial aircraft containing fault tolerant systems.

New technologies, such as Very Large Scale Integrated (VLSI) and Very High Speed Integrated Circuits (VHSIC), will have a major impact on tomorrow's operational effectiveness, provided the OR concepts are clearly defined and enforced. Processing elements, virtual memory techniques, and wideband buses are readily available for the next generation fighter. The design of weapon system computers capable of tolerating random hardware failures, has become a relatively mature technology at an affordable cost. However, full advantage must be taken of advances in computer technologies to integrate a fault tolerant design. Today, adequate methods exist to insure a high degree of availability and mission success through simple Built-in-Test (BIT) and auto-reconfigurable designs. This paper provides a managerial and technical roadmap for accomplishing the desired operational readiness goals in the next generation fighter. The contribution of the various attributes (including testability, avionic architecture, fault tolerant designs, BIT, standardization and operational readiness control) is provided.

Jones, James V., "Engineering Design, Reliability: Maintainability and Testability," TAB Professional and Reference Books, Division of TAB BOOKS, Inc., Blue Ridge Summit, PA, 1988.

Lappin, Michael K., MCAIR, "Supportability Evaluation Prediction Process," *Proceedings of the 1988 IEEE Annual Reliability and Maintainability Symposium*, Los Angeles, CA., 26-28 January 1988, pp. 102-107.

This paper describes the research efforts conducted under IRAD Project Description 7-900, Supportability Evaluation Prediction Process. A methodology has been developed that allows identification of supportability design criteria (SDC) and quantification of total field logistics support requirements. Interface with design engineers via computer aided design (CAD) workstations is also described. Specific development efforts include: a maintenance discrepancy data base (MDDB), that is used to provide cause and effect relationships; impact of associated maintenance tasks; automated like and similar analysis capabilities; and use of the expended maintenance importance ratio (EMIR).

This methodology allows the development of predictive R&M values, based on design team evaluations, to be available during the pre-concept phase of

any design program. The method takes advantage of the design freedom available during the pre-concept phase, determines the correct support system, and helps guide the design process to reduce O&S costs. MCAIR has implemented this methodology and embedded a simulation analysis process to provide a measure of cost and availability for any proposed design. This stochastic process measures the potential improvements in R&M and determines the best fit of manpower, spares, and support equipment for a given support posture. This approach allows MCAIR the ability to provide a thorough supportability analysis for any given R&M parameters during the pre-concept phase, thereby ensuring a reduction in cost due to reducing eventual retrofits, and a more supportable weapon system.

Lauder, R.P.F., "A Practical Example of Reducing Life Cycle Costs and Increasing Availability," Design for Tactical Avionics Maintainability, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 361, NATO, Copies of papers presented at the Avionics Panel 47th Symposium held at Quartier Reine Elisabeth, Brussels, Belgium, 7-10 May 1984.

The principles underlying effective operational availability are explored and quantified. It is shown that although large sums of money are expended on producing reliable components, these are vitiated if the end equipment is not exposed to a reliability growth program (RGP), because only 10 percent of the calculated MTBF will be realized in practice. It is claimed that costs can be reduced by using common commercial components without loss of MTBF provided it is followed by RGP.

A practical example is given of the expensive and time consuming steps that have to be taken in rescuing a low MTBF radar and increasing its availability. The steps and the methodology leading to them are described and the results shown (there are five figures and two references).

Lerner, Eric J., "Avionics Unreliability Turns Fighters into Shop Queens," *Aerospace America*, August 1985, pp. 68-71.

Aerospace America obtained from the Air Force maintenance records for major avionics systems on a number of fighter aircraft--F-15, F-16, F-4, F-111, and A-7. The data showed that avionics are a major, and in some cases *the* major, contributor to the maintenance requirements of these aircraft. Maintaining the avionics is in fact a key limiting factor on their sortie rates, especially for the F-15.

Only a few avionics systems accounted for the largest share of this maintenance burden. Some of these systems, such as the fire-control radar for the F-15 and F-16, spend as much time in the shop as in flight. The F-15 fire control system, for example, required maintenance after about 6 hours of use, and each repair took an average of 15-20 manhours.

Loose, Capt. Donald R., USAF, "Design for Maintainability, What Government Standards Do and Don't Say," Air Force Human Resources Laboratory Technical Paper, AFHRL-TP 89-28, Wright-Patterson AFB, OH., January 1989.

This literature survey contains no new technical information but rather consolidates already existing Government guidance on Design For Maintainability (DFM). Unfortunately, DFM expertise is scattered among

references from several engineering and logistics disciplines. Application in the weapon system acquisition process, therefore, is equally fragmented.

Consolidating this information serves two goals. First, it will be easier to access and apply. Second, it will be easier to determine what parts of this expertise are still weak within Government. These areas should be the focus of the acquisition logistics research community.

Lyman, Jerry, "Reliability Gets Promotion," *Electronics Week*, 11 March 1985, pp. 61-67.

The Annual Reliability and Maintainability Symposium, which was held on January 1985, spotlighted the efforts of the military and its vendors to increase field-reliability performance. The papers that were presented at the conference dealt with some of the most advanced signal-processing and avionics systems reaching the three Services. Covered were the rarely discussed topic of maintenance-induced failures and integrated diagnostics, including built-in test equipment and artificial intelligence.

For the military, the bottom line in electronic equipment is performance in the field. What counts to the service personnel who maintain this equipment is actual MTBFs. Two case histories described at the symposium give a detailed look at two recent electronic systems--an IBM Corporation advanced signal processor and a General Electric Company flight-control computer--under actual field conditions. The results are presented in this paper.

Maintenance of Supplies and Equipment, DARCOM Guide to Logistic Support Analysis, DARCOM-P 750-16, Headquarters, U.S. Army Materiel Development and Readiness Command, June 1980.

This pamphlet is intended for use in developing logistic support analysis (LSA) programs and logistic support analysis records (LSAR) for materiel acquisition programs in the U.S. Army Materiel Development and Readiness Command (DARCOM). It is intended for use in conjunction with MIL-STD-1388-1 and MIL-STD-1388-2, Logistic Support Analysis, for both Government-conducted and contractor-conducted LSA and LSAR efforts.

Management Sciences, Inc., Predictor/Results/Fracas, R, M, and L Design Techniques, Albuquerque, NM, June 1984.

The use of computer aided design, and computer aided manufacturing (CAD/CAM) is developing at a rapid pace. The Government-Industry joint study group on computerized techniques are reviewing the analytical powers of CAD/CAM software with regard to reliability, maintainability, and logistics (R,M and L). PREDICTOR covers many of the aspects the group is interested in as the development of PREDICTOR/RESULTS/FRACAS has been user driven to meet the generic needs of managers and technicians. This synopsis is written to provide direct relationships to the tasks outlined in the study. Also included are discussions about IDEALS. IDEALS is the unification program that ties the other programs together.

Mascarenhas, Jose M.G.B., "ATE User's View on Design for Maintainability," Design for Tactical Avionics Maintainability, Advisory Group for Aerospace Research and Development, AGARD Conference Proceedings No. 361, NATO, Copies of papers

presented at the Avionics Panel 47th Symposium held at Quartier Reine Elisabeth, Brussels, Belgium, 7-10 May 1984.

This paper first describes the main features of the ATE that PoAF is using. Emphasis is put on the hardware and software capabilities and limitations.

The paper examines some of the techniques available for test program generation and validation. Finally, the paper presents the author's viewpoint on board design for maintainability (particularly with ATE).

Nelson, J.R., P. Konoske Dey, M.R. Fiorello, J.R. Gebman, G.K. Smith, and A. Sweetland, "A Weapon-System Life-Cycle Overview: The 4-7D Experience," The Rand Corporation, Santa Monica, CA, a report prepared for the U.S. Air Force, R-1452-PR, October 1974.

This study focuses primarily on a comparison of test-phase results with the subsequent operational experience of the A-7D attack aircraft to determine when component reliability and maintenance problems were revealed, what kinds of problems showed up in the various stages of the weapon-system life cycle, and the impact these problems had on operational availability and operating cost. It is found that earlier correction of critical problems should reduce operational and maintenance costs and increase the capability of the system enough to permit a net improvement in the overall capability life-cycle cost of the system. An extended, comprehensive Initial Operational Test and Evaluation would allow identification of additional reliability and maintenance problems. A better approach to development of avionics components and related software is needed. Finally, data systems should be improved as necessary and exploited more fully.

Oldfield, D. and L.T.J. Salmon, "A Future System Design Technique Based on Functional Decomposition, Supported by Quantifiable Design Aids, and Guidelines for Minimum Maintenance Costs," *Advanced Concepts for Avionics/Weapon System Design, Development and Integration: Conference Proceedings of the 45th Avionics Panel Symposium*, Ottawa, Canada, 18-22 April 1983, AD-A138 600, pp. 3-1 -3-12, Defense Technical Information Center, Alexandria, VA.

The increasing cost and complexity of modern fast-jet aircraft, coupled with the long development period which takes place while technology is changing rapidly, make it necessary to consider a new approach to system design. Such an approach should be based on a structured top-down procedure, in which the rather general requirement can be changed into a detailed documented design in a controlled manner.

One important aspect of design is cost, and in particular cost-effectiveness and life-cycle cost. At least some of the design aims can be based on cost-effectiveness reasoning, and it is necessary to have an appreciation of the background to this. Reliability-dependent maintenance costs can amount to much more than the original purchase price, and hence it is essential to be aware of the possible cost-drivers, and include maintenance aspects in the design approach from the beginning.

This paper describes some of the work carried out at the Royal Aircraft Establishment (RAE) on these aspects.

Palazzo, C.J. and M.M. Rosenfeld, Grumman Aerospace Corporation, "Avionics Built-In-Test Effectiveness and Life Cycle Cost," *AIAA Aircraft Design, Systems and Technology*

Meeting, 17-19 October 1983, Fort Worth, TX, AIAA-83-2448, Technical Information Service, American Institute of Aeronautics and Astronautics, New York, NY.

Results of an investigation into the effectiveness of built-in-test (BIT) on aircraft weapon systems and its impact on operational assessability and life cycle cost (LCC) are presented herein. BIT effectiveness was found to be high in current operational systems although errors in data collection and interpretation precluded highly accurate measurements. Low BIT effectiveness had a negligible effect on logistic support costs (LSC), particularly for avionic units with moderate to high reliabilities. It was concluded that a major reason for improving BIT effectiveness was to increase its ability to determine the status of mission essential subsystems (i.e., increase operational assessability).

Priest, John W., *Engineering Design for Producibility and Reliability*, Marcel Dekker, Inc., New York and Basel, 1988.

Focusing on the engineering methodologies and practices that can improve any product's producibility, reliability, and quality, this useful reference/text shows how these elements can be designed into an item during product development. For each practice the book explains why it is important, reviews its methodologies, and gives design techniques helpful for successful implementation.

Thompson, Steven A., "Relating Life Cycle Costs to Weapon System Effectiveness: An Integrated Approach," *Proceedings of the IEEE 1978 National Aerospace and Electronics Conference*, NAEON 78, Dayton, OH, 16-18 May 1978, pp. 1083-4.

Although cost-effectiveness analyses have received much emphasis within the Department of Defense for the past two decades, one seems to encounter a void when attempting to find examples of analyses accomplished at the weapon system level. This paper describes the problems involved in an analysis of this magnitude, some steps that can be taken to make it a more tractable task, and a proposed research project to develop a system effectiveness structure relating the reliability characteristics, maintainability features, life cycle cost estimates, and performance measures of the various subsystems of a weapon system to an overall system effectiveness measure.

Topics in Reliability and Maintainability and Statistics, Consolidated Lecture Notes, Tutorial Sessions, 1989 Annual Reliability and Maintainability Symposium.

These Tutorial Notes consist of expository material prepared by the instructors for the tutorial sessions. The notes for each session are reviewed each year to assure currency, accuracy, and applicability.

van der Mooren, A.L., Eindhoven University of Technology, Eindhoven, The Netherlands, "Maintenance Aspects in Design of Mechanical Systems," *Proceedings of the Institution of Mechanical Engineers*, International Conference, Engineering Design, Volume I, 22-25 August 1989, Harrogate International Centre, pp. 1227-1238.

Walker, R.K., Northrop Aircraft Division, "Built-In-Test (BIT) Utilization for Improved Supportability of the F-20 Aircraft," *Proceedings of the International Automatic Testing Conference*, Uniondale, NY., 22-24 October 1985 (A86-43876 21--61), New York, IEEE, pp. 446-449.

Complex avionics systems of the past have been accompanied by major support problems. The early integrated systems of the 1960's resulted in large and expensive test systems both at the organizational and intermediate

maintenance levels. The 1970's followed with built-in-test (BIT) to accomplish much of the organizational level fault isolation and more complex and expensive automatic test equipment at the intermediate level. The problems multiplied when the BIT created additional support problems because of the "Re-Test-OKs," "Can-not-Duplicates," and "False Alarms." Fortunately this trend is being reversed. The technology of the 1980's is embodied in the Fl-20 Tigershark. Its avionics equipment utilizes BIT to achieve the long sought low cost supportability in addition to outstanding performance.

Webster, L.R. and J.M. Mader, Harris Satellite Communications and Government Aerospace Systems Divisions, "VLSI Impact on RAMS Strategies in Avionics Design," *Proceedings of the 1986 IEEE Annual Reliability and Maintainability Symposium*, Las Vegas, NV., 28-30 January 1986, pp. 303-306.

This paper discusses the impact of Very Large Scale Integrated Circuits (VLSI) on the Reliability, Availability, Maintainability, and Supportability (RAMS) characteristics of avionics systems to be deployed in the 1990 time frame. A reliability sensitivity analysis of a 4.5 million gate system is presented with data from more than 25 major system redundancy configurations analyzed. The impact of these various redundancy architectures on chip, module, equipment and system RAMS characteristics is detailed.

Using this medium-sized digital equipment analysis as a model, we proceed to uncover the implications of dramatically increased use of custom VLSI in avionics (and other) systems. The purpose is to provide RAMS practitioners with some insight into the design and use implications of the "Super-chips" that will soon become commonplace.

Some of the conclusions are: (1) non-monolithic interconnections essentially determine system reliability, (2) increased chip complexity provides high leverage RAMS opportunities, (3) RAMS personnel must cause communication to happen between systems definition and VLSI implementation personnel if the full potential of VLSI is to be realized, and (4) there are tough design challenges in thermal, electrostatic discharge radiation protection and circuit/system architecture which must be met in the design, production, and support of systems using these devices.

APPENDIX C

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CONTENTS

Tables

Figures

COMPUTER SUPPORT FOR RELIABILITY AND MAINTAINABILITY MODELING

The University of Maryland Center for Computer-Aided Life Cycle Engineering (CALCE) system for electronics equipment design software consists of an artificial intelligence (AI) executive editor and controller coupled to a decision support shell that integrates various design and analysis tools while providing transparent data and design process management. The CALCE system supports decision making by the design team by providing a framework for conducting design trade-offs and comparing allocated values against design requirements and constraints.

This appendix is a type of user's manual for the Reliability Modeling and the Maintainability Modeling modules of the CALCE system used in the demonstration of the methodology given in this paper.

The Reliability Modeling module allows the creation and manipulation of a model to determine part and system reliability based on part failure information. The current system, assembly or circuit board being modeled is termed "active." It is the system currently loaded and sitting in memory--its name is displayed in the upper right hand corner of the computer screen. Parts (referred to here as elements) and their characteristics are entered individually into a parts list to form a configuration. Complex active and standby redundancies as well as P out of Q redundancies[1] can be modeled. From a given mission time, the system reliability of the configuration is calculated, and a block diagram illustrating the system configuration can be displayed. Systems with different mission times and maintenance visits can be combined and treated as one. Graphics support for conducting trade-offs include plots of reliability (series, redundant, and redundant with repair) versus mission time and the mean time between critical failures (MTBCF) versus the number of maintenance visits per year.

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1 A "P out of Q redundancy" means that there are Q elements in parallel, but only P need to be active at one time.

The Maintainability Modeling module can be used to create a detailed model of the maintenance required for the system being designed. The module includes two data base managers. The first can create, modify, and delete generic lists of elemental maintenance tasks. This data base includes a 50-character description of the task, the time it takes to perform the task, a 9-character task ID number, and a list of the standard element maintenance tasks defined by Rome Air Development Center (RADC). The second maintainability data base is a system-specific description of the maintenance tasks required to keep the system in operation. This data base includes a list of all of the different ways in which each subsystem can fail. Each of these failure modes includes a 50-character description as well as a percentage frequency (the percentage of the total subsystem failures that will be of this type of failure mode). For each failure mode there is a subdata base containing a list of the elemental maintenance tasks required for preparation, isolation, disassembly, interchange, reassembly, alignment, checkout, and start-up of the subsystem after the failure has occurred. Included in this data are the manpower requirements and the repetitions for each task. When all the data have been entered, the system will calculate the different maintainability figures of merit (FOMs) for the system as set out in Military Handbook 472.

A. RELIABILITY MODELING

The reliability tree is the environment from which all aspects of the reliability modeling system are accessed. The tree nodes are "Analysis," "Block Diagram," "Reports," and "Tools." Each node branches from the heading "Reliability" (see Figure C-1).

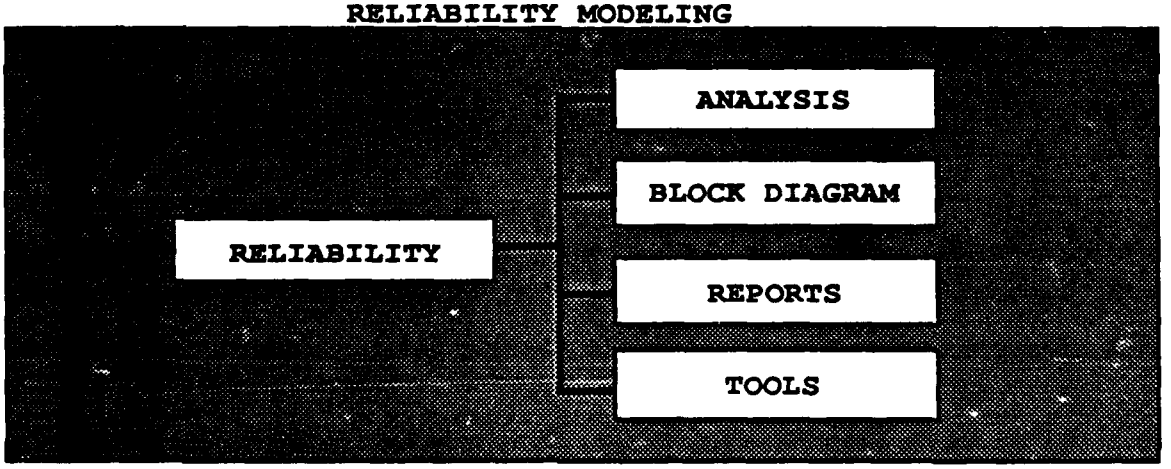

Figure C-1. Reliability Tree

The "Analysis" node allows for the creation and manipulation of models for determining component and system reliability. The "Block Diagram" node provides a graphic display of the model in block diagram form. The "Report" node generates a printed copy of the reliability data for the model. The "Tools" node provides easy access to independent tools used with Reliability Modeling, such as Pizzazz™ (a graphics package used for printing good quality screen images).

The arrow keys are used to move the cursor around the screen. When the cursor is on a node, the associated label in that node turns red. To enter a node, move the cursor onto the node and press <Enter>. A small menu that displays options will appear. To choose an option, use the up and down arrow keys to move the highlight bar to the option desired and press <Enter>. An explanation of each of the options follows (listed under its node). To exit a window and return to the tree, press <Esc>. To exit the tree and return to DOS, press <Esc>.

Table C-1. Reliability Tree Options

Node	Option	Function
Reliability	Notes	provides notes about the node
Analysis	Execute	begins the reliability modeling module
	Notes	provides notes about the node
Block Diagram	Display	begins the graphic display module
	Notes	provides notes about the node
Reports	Execute	begins the report generator
	Notes	provides notes about the node
Tools	Pizazz ON	activates the memory resident "Pizazz" screen capture utility
	Pizazz OFF	deactivates the "Pizazz" screen capture utility
	Notes	provides notes about the node

B. ANALYSIS NODE

The reliability modeling module is entered by selecting "Execute" as the Analysis option. When the reliability modeling module begins, the parts list is displayed with a list of options across the top of the screen (Figure C-2).

RELIABILITY MODELING SysRel w/R:0.860934 Active:ARSR4DBM

File Edit Setup Parameters Graphs XIT

Block ID	Part ID	Description	Repair Time (hrs)	Total Units	Required Units	Max-Mum Units
a1	SWP1	pulse comp.	2.0	1	1	1
a2	SWP2	doppler filter	2.0	1	1	1
a3	SWP3	PDI	2.0	1	1	1
a4	SWP4	CFAR	2.0	1	1	1
a5	SWP5	channel interface	2.0	1	1	1
a6	SWP6	AMSP channel	2.0	7	6	7
a7	SWP7	AMSP interface	2.0	4	3	4
a8	SWP8	beacon time monit.	2.0	2	1	2
a9	SWP9	beacon TTG	2.0	2	1	2
a10	SWP10	beacon code extr.	2.0	2	1	2
a11	BDP1	video quantizer	2.0	2	1	2
a12	BDP2	defruiter	2.0	2	1	2
a13	BDP3	bus/tx beacon	2.0	2	1	2
a14	BDP4	bus/tx tdy	2.0	2	1	2
a15	BDP5	global memory	2.0	2	1	2
a16	BDP6	global memory	2.0	2	1	2

Select a Data File

Figure C-2. Reliability Modeling--Parts List and Options

1. Parts List

Individual parts are referred to as LFEs (lower functional elements). A grouping of elements is called a CFE (complex functional element). LFEs and CFEs require block IDs, part IDs, and part descriptions. The LFEs and CFEs are listed separately in the parts list. An LFE may not be placed among CFEs.

Each element has a set of 13 associated attributes. Three of these attributes are used for part identification, block diagram placement designation (block ID), and part description and are always displayed across the top left of the screen as shown in Figure C-2. All but

one of the remaining ten attributes require numerical values. Four of these values are assigned by the user; the remaining five are computed from other attributes and may not be changed. The user selects which of the ten attributes are to be shown on the screen with the "Select" option, discussed in Section 2.a.

a. Distribution

The distribution specifies the mathematical model assumed for the failure rate of the elements. The failure density function is a general model for the distribution. The failure density function, f(t), is defined as

$$f(t) = (1/N)\ (dM/dt) = -dR/dt$$

where N is the number of elements, M is the number of elements that have failed, and R is the reliability of the element. The exponential distribution is designated by E. It assumes a constant failure rate, δ, given in failures per million hours (Fr/Mhr).

b. Total Number of Elements

A default value of one is assumed for each LFE. This attribute applies to parallel redundancies, specifying the total number of paths or elements in parallel.

c. Total Number of Required Elements

A default of one is assumed for each LFE. This attribute is used to denote P out of Q required elements in parallel. For example, if the total number of elements is three, and the number of required elements is two, then two out of three must be operable for system success.

d. Element Failure Rate

The element failure rate is the number of failures per million hours, obtained from part failure information.

e. Series Failure Rate

The failure rate for all of the elements in the CFE (or LFE if number of total elements is greater than one) in a series configuration is calculated by

$$\delta = \sum_{i=1}^{n} \delta(i)$$

f. Percent of Total Failure Rate

The percent of the total failure rate is the failure rate of the element per the total system failure rate.

g. Equivalent Failure Rate

The equivalent failure rate is the failure rate the configuration would have if it were only one element. This value is calculated from the equation

$$R_{CFE} = e^{-\delta' t}$$

Thus, the equivalent failure rate δ' is calculated as

$$\delta' = - (10^6/t) \ln R_{CFE}$$

h. Duty Cycle

The duty cycle is the ratio of the element's operating time to that of the system operating time. In calculating the reliability of an element with an exponential distribution, the argument of the exponent is multiplied by this ratio (see Section i).

i. Reliability

The reliability is the probability that a system will perform satisfactorily without repair for a given period of time when used under stated conditions. The formula for the reliability with an exponential distribution and a constant failure rate δ is

$$R(t) = e^{-\delta dt}$$

where d is the duty cycle and t is the mission time in hours.

2. Options

The reliability modeling module has 11 options for the creation and manipulation of models. Options are functions that perform specific tasks, such as adding or removing elements or changing element data. They are displayed across the top of the screen. Use the arrow keys to select options and press <Enter> to execute them, or type the highlighted letter of the chosen option. To exit an option and return to the main menu, press <Esc>.

a. Select

"Select" allows the operator to choose which of the ten attributes that require values are displayed on the screen. Although only four attributes can be seen on the screen simultaneously, more may be toggled on. From the list in "Select," the first four toggled on are displayed. The attributes toggle off and on with the <Enter> key. The attributes toggled on are highlighted on the "Select Attributes" screen. All of the attributes toggled on can be scrolled through in any of the options that allow scrolling ("View," "Make," "Change"). At least four attributes must always be toggled on.

b. Add

The model's parts list is generated in the function "Add." The procedure for adding elements to the parts lists is as follows. Upon entering "Add," a window will appear displaying a default block ID name for an LFE. For block ID, default names are a1, a2, a3, etc. To accept the default name press <Enter>, otherwise type another name. Block IDs can be no longer than four letters. Once entered, the window asks for a part ID and then a part description. For part ID and part description, no default name is given initially. The previous value for these names are repeated, however, in subsequent LFEs. The maximum length for part ID is six letters and for part description 20 letters. After these three names have been entered, press <Enter> to insert the LFE on the screen after the element pointed to by the cursor. The default position for LFEs is at the end of the LFE list.

c. Make

The function "Make" is used to develop the configuration of the model by building CFEs. Default block ID names are assigned to CFEs. Press <Enter> to accept the default name or enter another name and press <Enter> (the maximum length for block ID, part ID, and part description for CFEs are the same as that for LFEs). A window then appears so that the part ID may be defined. No default name for part ID is given initially. Type the part ID and press <Enter>. Now enter the part description in the window and press <Enter>. The CFE must then be defined to describe how the LFEs will be arranged in the CFE. A descriptor line appears at the bottom of the screen so that the CFE can be defin l. The syntax for defining CFEs is parentheses ( ) for series configurations, brackets [ ] for parallel redundancies, and curled brackets { } for standby redundancies. Only one space between elements' block IDs is required to distinguish them within a CFE. Pressing <F1>

provides a help screen for CFE syntax. Press <Enter> when the definition has been entered. Use the arrow keys to position the CFE in the parts list and press <Enter> to place the CFE on the screen after the element pointed to by the cursor. A CFE may be included in the definition of another CFE. However, a CFE may not be placed on the parts list before its constituents.

To denote the number of required operating elements when the elements are different (P out of Q in a parallel redundancy), put a colon after the closing brackets followed by the number of required elements. If the number of required elements is not specified, a default value of one will be assumed. Example arrangements are shown in Table C-2.

Table C-2. Examples of the Syntax for Placement of LFEs within CFEs

Syntax	Type
Define "m1": (n1 n2 n3)	a series arrangement of n1, n2, and n3 as CFE m1
Define "b2": [a5 a6]	a parallel arrangement of a5 and a6 as CFE b2
Define "b5": ([b3 b4] a12 a13)	b3 and b4 are parallel and are in series with a12 and a13, and the CFE name is b5
Define "c1": [(b1 c2) a7 a8]	arranges a7 and a8 in parallel with the series combination of b1 and c2, and the CFE name is c1; the total number of elements attribute is 3 and the required number of elements attribute is 2

When the elements in parallel are identical, the "Total Elements" attribute can be used to denote the number of elements in parallel and the "Number of Required Elements" attribute can be used to indicate the number that must operate. Thus, for identical parallel redundancies, the number of total and required elements are not specified in the definition of the CFE but are indicated using the attributes associated with the element. By implementing its attributes, an LFE can be placed in parallel with identical ones without having to make a CFE.

Table C-3 defines various configurations of CFEs. (They are illustrated in the Reliability Block Diagram shown in Figure C-8.) The syntax of the definition of CFE "c2" denotes that LFEs a9, a10, and a11 are different elements and that two out of three are required. In CFE "b1," however, the redundancy has been implemented using the attributes "Total Number of Elements" and "Required Number of Elements." The syntax

denote that each path is identical, so that CFE "b1" consists of two paths of LFEs a1, a2, and a3 and one of the two paths is required for system success.

Table C-3. Parallel Redundancies

Syntax	Type
Define "d3": [c1 c2 c3]:2	2 out of 3 elements are required for system success where c1, c2, and c3 are each different elements, and the CFE name is d3
Define "b1": (a1 a2 a3)	a series arrangement of a1, a2, and a3 as CFE b1; the total number of elements attribute is 2 and the required number of elements attribute is 1
Define "c2": [a9 a10 a11]:2	2 out of 3 elements are required for system success where a9, a10, and a11 are each different elements, and the CRE name is c2

To create standby arrangements, enclose the block IDs of the elements in the standby circuit { }, insert a space, and follow with the block IDs of the switch and monitor elements (which must be LFEs). Whether the average or worst case failure rates are to be used in calculations must be specified before a standby CFE can be added to the parts list. The syntax for defining a CFE containing a standby arrangement is given in Table C-4 and illustrated in Figure C-3.

Table C-4. Standby Arrangement

,Syntax	Type
Define "Y1": {x1 x2} x4 x5	where x 1 and x2 compose the standby circuit, x4 and x5 denote the switch and monitor, and the CFE name is "Y1."

Each element is displayed in one of three colors, which specifies the element's condition. Elements that are being used to define a CFE ("busy") are displayed in yellow. The element with the highest failure rate is displayed in red if it is not busy. All other elements are displayed in black.

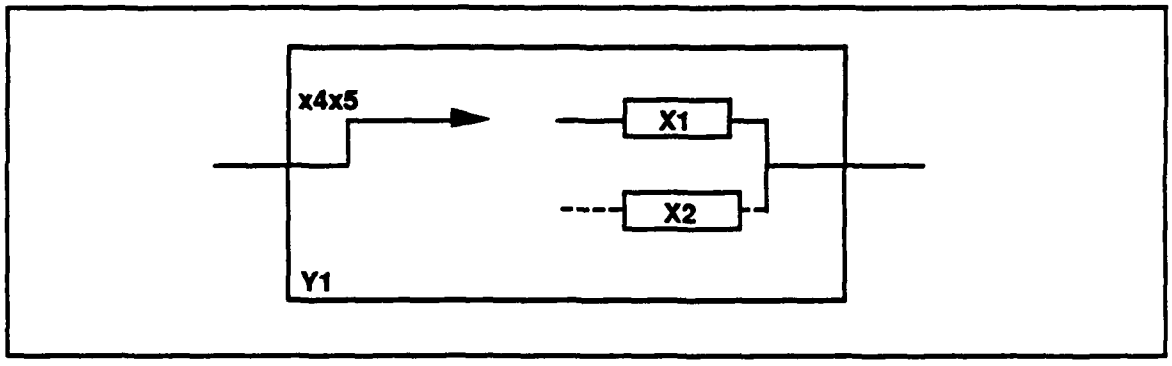

Figure C-3. Example CFE Containing a Standby Redundancy

d. Edit

The function option "Edit" allows the part identification attributes, block ID, part ID, and part description, to be edited. A pointer appears on the screen that allows scrolling through these three attributes. When the pointer is on a CFE, its definition is displayed at the top of the screen. Press <Enter> at the attribute to be edited. A window appears that allows the block ID, part ID, or description to be changed. An element's block ID cannot be edited if it is included in the definition of another CFE, nor can the definition of a CFE be changed if it is being used to define another CFE. To edit the definition of a CFE, press the space bar at any of the element's attributes listed above.

e. View

The "View" option allows the operators to scroll through all of the attributes toggled on in "Select."

f. Change

Press <Enter> and a pointer will appear on the screen that can scroll through all of the attributes toggled on in "Select." Position the pointer at the desired attribute with arrow keys and press <Enter>. A window appears that allows the value of the attribute to be changed (see Figure C-4). Enter the new value and press <Enter>. Use the "Change" option to change the default values assigned to the attributes in "Add."

CHANGE COMPONENT DATA SysRel w/R:0.860934 Active:ARSR4DBM

Block ID	Part ID	Description	Repair Time (hrs)	Total Units	Required Units	Max-Num Units
a1	SWP1	pulse comp.	2.0	1	1	1
a2	SWP2	doppler filter	2.0	1	1	1
a3	SWP3	PDI	2.0	1	1	1
a4	SWP4	CFAR	2.0	1	1	1
a5	SWP5	channel interface	2.0	1	1	1
a6	SWP6	AMSP channel	2.0	7	6	7
a7	SWP7	AMSP interface	2.0	4	3	4
a8	SWP8	beacon time monit.	2.0	2	1	2
a9	SWP9	beacon TTG	2.0	2	1	2
a10	SWP10	beacon code extr.	2.0	2	1	2
a11	BDP1	video quantizer	2.0	2	1	2
a12	BDP2	defruiter	2.0	2	1	2
a13	BDP3	bus/tx beacon	2.0	2	1	2

Allowable range 0.0 to 10000.0 [2.0]:
a1 Repair Time (hrs) ==> 2.0

<ENTER> Accept Current Value <ESC> Exit

Figure C-4. The Change Option

g. Remove

To remove a CFE or LFE from the parts list, press <Enter> and a pointer will appear on the screen. Position the pointer at the functional element to be removed and press <Enter>. When the pointer is on a CFE, its definition is displayed at the top of the screen. An element being used in a CFE cannot be removed unless the CFE is removed first.

h. Include

The "Include" option allows configurations with their own parameters to be added to other configurations as elements. Upon selecting this option, the operator is placed in the list of existing files. The configuration to be included is loaded from this list. The new included configuration will be treated as an LFE, requiring a block ID, part ID, and part description. The default part description is the name of the included configuration: however, it may be changed. To insert the configuration on the screen, position it with the

arrow keys and press <Enter>. Since an included configuration is treated as an LFE, it can only be placed in the LFE list.

i. Parameters

Parameters are quantities that apply to the whole configuration. Default values are assigned to parameters initially but can be changed. Some parameters are dependent, and some are calculated and cannot be changed. Press <Enter> at the highlighted parameter and a window will appear that allows the parameter value to be changed. Parameters that can be edited include mission time, hours and days between maintenance visits, and maintenance visits per year. Changing the number of maintenance visits per hour, day, or year causes the other two to be recalculated accordingly. The MTBCF, system reliability with repair, system reliability without repair, series failure rate, and series mean time between failures are parameters computed from the other parameters and may not be changed. See Figure C-5 for illustration. The equations used to compute these values are given in the following sections.

VIEW/CHANGE PARAMETERS SysRel w/R:0.860934 Active:ARSR4DBM

Block ID	Part ID	Description	Repair	Total	Required Units	Max-Num Units
		Service Life (years)		1.0		
		Mission Time (hours)		500		
a1	SWP1	Maintenance Interval Levels		3	1	1
a2	SWP2	Maintenance Interval T1 (hrs)		100.0	1	1
a3	SWP3	Maintenance Interval T2 (hrs)		400.0	1	1
a4	SWP4	Maintenance Interval T3 (hrs)		800.0	1	1
a5	SWP5	System Reliability w/Repair		0.8609341	1	1
a6	SWP6	System Reliability w/o Repair		0.8422870	6	7
a7	SWP7	Series Failure Rate (Fr/MHr)		1686.36	3	4
a8	SWP8	MTBCF (hours)		3339.7	1	2
a9	SWP9	MTBF (series) (hours)		593.0	1	2
a10	SWP10				1	2
a11	BDP1	video quantizer	2.0	2	1	2
a12	BDP2	defruiter	2.0	2	1	2
a13	BDP3	bus/tx beacon	2.0	2	1	2
a14	BDP4	bus/tx tdy	2.0	2	1	2
a15	BDP5	global memory	2.0	2	1	2
a16	BDP6	global memory	2.0	2	1	2

<ENTER> Select <ESC> Exit

Figure C-5. The View/Change Parameters Option

The system series failure rate is calculated in failures per million hours (Fr/Mhr)

$$\delta_s = \delta_1 + \delta_2 + ... + \delta_n$$

where δ_i is the element failure rate times the number of elements (i.e., series failure rate). The system series mean time between failure (MTBF) is then given by

$$10^6/\delta_s \text{ hr}$$

The MTBCF is calculated in hours by the following equation

$$\sum_{j=0}^{\infty} \int_{jT}^{T(j+1)} R_T(t)\, dt = \frac{\int_0^T R(\tau)\, d\tau}{1 - R_T(T)}$$

where $R_T(t)$ is the reliability function of a system in which maintenance is performed every T hours, and t is the mission time:

$$R_T(t) = [R_T(T)]^j R(\tau)$$

$$t = jT + \tau \quad j = 0,1,2, ...; \qquad 0 < \tau < T$$

The cost of a maintenance visit is calculated by

$$\sum_{n_i} (1\text{-}Ri(T))\ (\$/\text{manhour})\ ti$$

The cost of spares is calculated by

$$\sum_{n_i} (1\text{-}R_i(T))\ (cost_i)$$

where n is the number of each ith element in the system, t_i is the repair time required for the ith element, and $cost_i$ is the cost of the ith element.

The LCC is calculated by adding the acquisition and support costs. The proxy used for the acquisition cost is the total system cost, which is just the sum of the parts costs. The proxy for the support costs is calculated by multiplying the sum of the maintenance visit cost, the spares cost, and the travel cost by the number of maintenance visits per year. This yearly maintenance cost is discounted over the total mission time in years using the following equation, and the result is then added to the total system cost to obtain the LCC.

$$\sum_{i=1->n} (\text{yearly maintenance visit cost})/(1+\text{discount rate})_i$$

Sample Calculations of Parameters

Compare the parameter values that follow with those found in Figure C-6. The board displayed in Figure C-6 is the system described in the following paragraph.

Consider two identical components in an active parallel configuration with an element failure rate of 0.01 failures per hour, a mission time of 100 hours, and a time of T = 50 hours between maintenance visits. The reliability of the parallel system is

$$R(t) = 1 - [1 - e^{-\delta\tau}]2 = 2e^{-\delta\tau} - e^{-2\delta\tau} = 2e^{-t/100} - e^{-t/50}$$

The series failure rate is

$$\delta_s = \delta_1 + \delta_2 = 10{,}000 + 10{,}000 = 20{,}000 \text{ F/Mhr}$$

and the series MTBF = $10^6/\delta_s = 10^6/20{,}000 = 50$ hr

The MTBCF is calculated as

$$\text{MTBCF}(T=50) = \frac{\int_0^T R(\tau)\, d\tau}{1 - R(T)} = \frac{\int_0^T [2e^{-\tau/100} - e^{-\tau/50}]\, d\tau}{1 - (2e^{-T/100} - e^{-T/50})}$$

$$= \frac{150 + 50e^{-T/50} - 200e^{-T/100}}{1 - 2e^{-T/100} + e^{-T/50}} = 304.1 \text{ hours}$$

and the system reliability with repair is

$$R_T(t) = [R_T(T)]^j R(\tau)$$

$$= [2e^{-T/100} - e^{-T/50}]^j [2e^{-\tau/100} - e^{-\tau/50}]$$

$$= [2e^{-50/100} - e^{-50/50}]^2 [2e^{-0/100} - e^{-0/50}]$$

$$= 0.7143324$$

The equation describing the reliability with repair versus mission time curve for T = 50 hours is

$$R_T(t) = [2e^{-5} - e^{-1}]^j [2e^{-\tau/100} - e^{-\tau/50}]$$

where j is the maintenance visit counter; j = 1,2,3, ...; $0 < \tau < 50$ hours.

j. Graph

Two graphs can be displayed. The "Mission" option plots the reliability versus mission time and the "Visits" option plots the MTBCF versus the maintenance visits per year. The space bar is used to toggle between the model curves--the series configuration (red), the configuration with redundancies (green), and the configuration with redundancies and repair (blue). The model curve is generated from the equation for system reliability, and the series curve from the series failure rate. To move along the curve, the arrow keys are used. Press <Esc> to exit the graphs. See Figures C-6 and C-7.

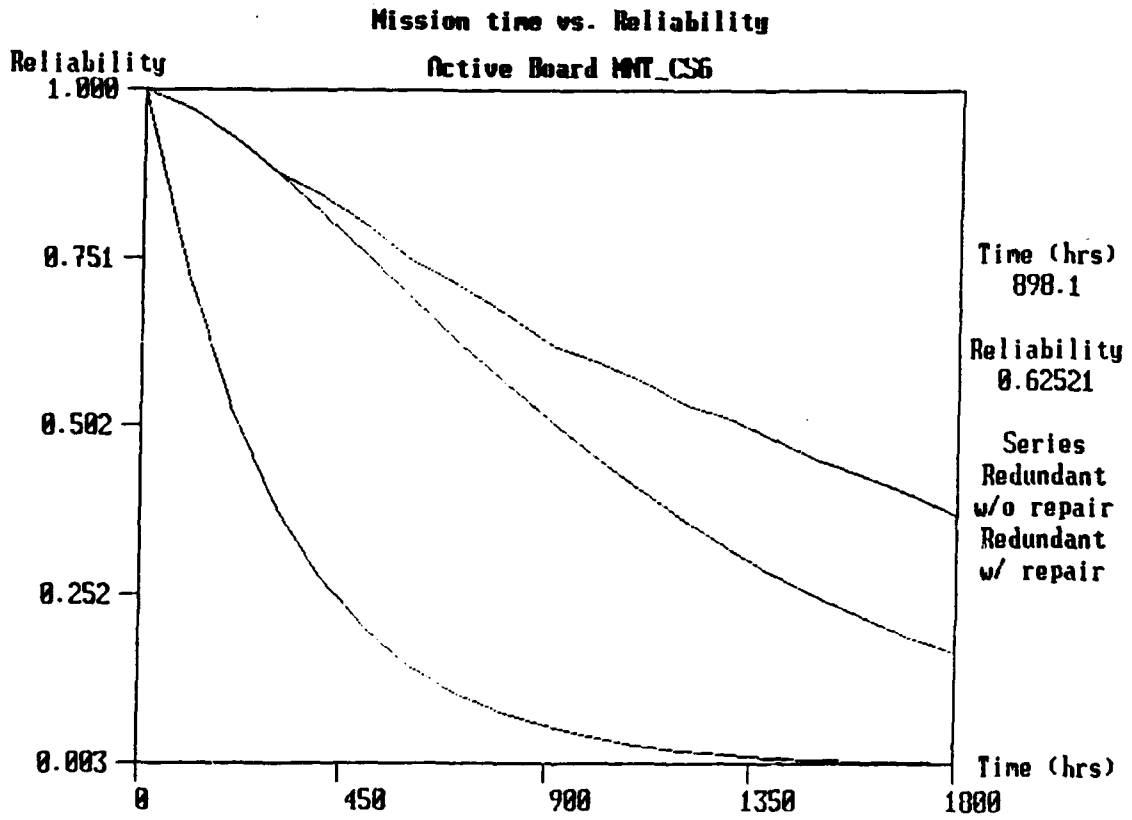

Figure C-6. Reliability Versus Mission Time

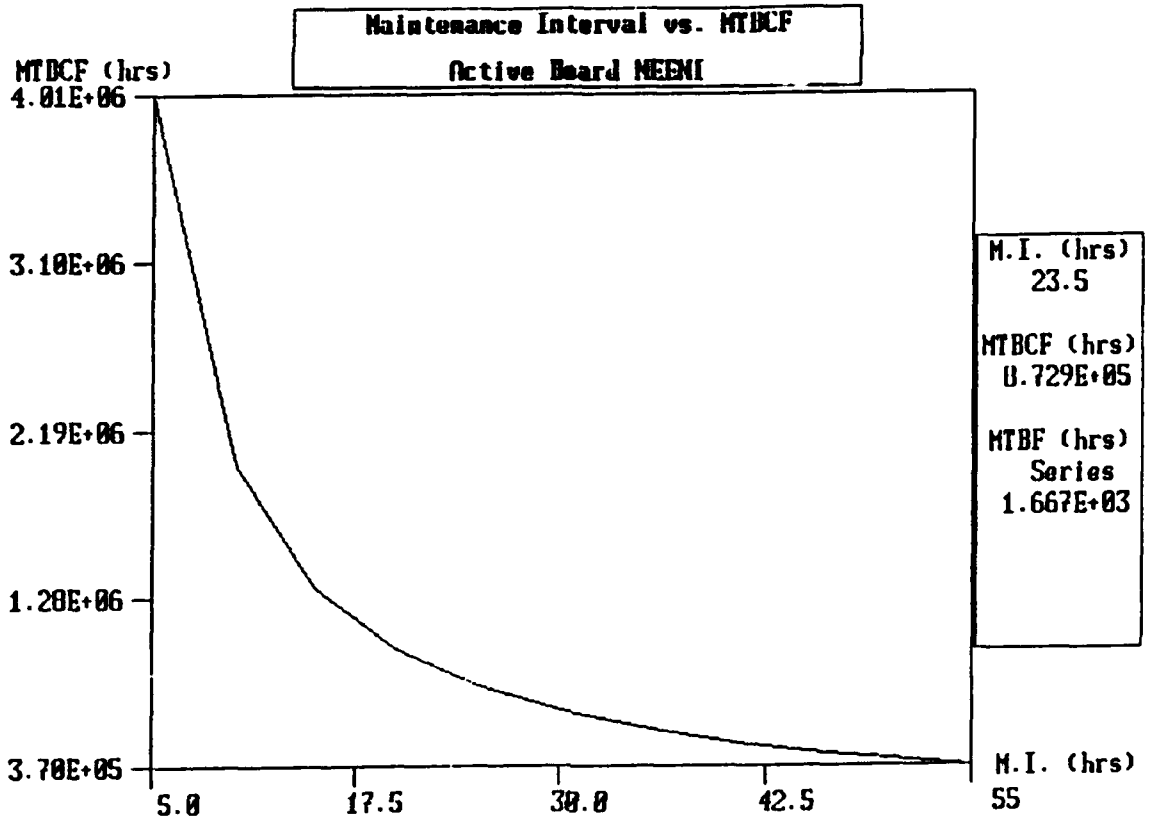

Figure C-7. Plot of Maintenance Visits Versus MTBCF

k. File

The "File" selection option allows loading of existing files, creating new files, removing files, and storing of files under "Save" or "Save As." To load an existing file, enter the "Load" option within "File" and a new screen will appear displaying the names of existing files. Use the arrow keys to select a file and press <Enter> to retrieve it. The active system remains active until another system is loaded by the "Load" option. Multiple copies of one set of system data or reports with different fields selected are therefore possible. To create a new file, enter the "New" option and a window will appear. Type the name of the new file (maximum of eight letters) and press <Enter>. Files may be stored using "Save" or stored under another name using "Save As." If a file is saved under another name, the file under the old name is stored and the file under its new name is made active. Before the program exits, the program asks whether the changes (if any) to the active file should be saved.

C. BLOCK DIAGRAM NODE

In "Block Diagram," the elements in the configuration graphics are identified by their part IDs. The shaded boxes designate CFEs. The LFEs contained in the shaded boxes illustrate the configuration of the CFE, and the CFEs part ID is displayed in the lower left corner of the box. The different types of redundancies are indicated on the block diagram by the location of the ratio of the required to total number of elements. The block diagram for the configuration built in Section B.2 is shown in Figure C-8. If the redundant elements are different, such as seen in CFE "c2," the ratio of required to total number of elements will be displayed in the upper left hand corner of the boxed CFE. If the redundant elements are identical, such as CFE "b1" and "c1," the ratio will be shown in the shaded boxed region above the CFE. CFEs are defined in the program using the LFEs' block IDs. In this example, the part IDs were given the same names as the corresponding block IDs to show component placement.

The redundancy of CFE "c1" is analogous to that of CFE "b1," except that the entire configuration composes one path. Thus, three of the configurations shown are in parallel, with two required for system success.

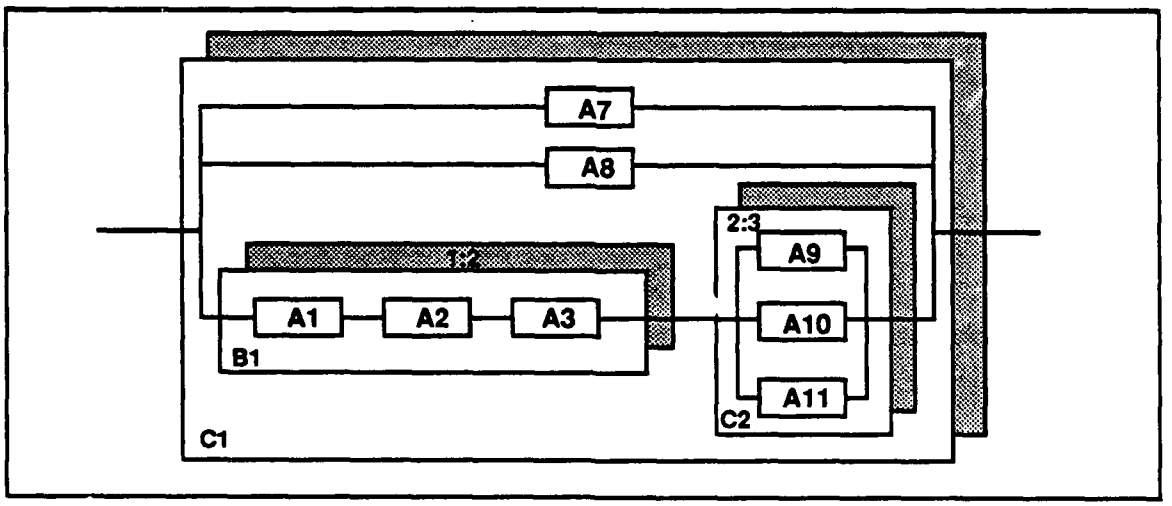

Figure C-8. Reliability Block Diagram

D. REPORTS NODE

The report generator ("Reports" on the reliability tree) is used to print out reports of the reliability data for a given configuration. Reports for more than one configuration can be printed in one session. When called from the tree, the report generator automatically loads the last system worked on. If another system is desired or data for more than one system is to be printed in the same session, use the "Load" option (a description follows).

The report consists of a cover page and a table of data. The cover page includes a title, date, configuration name, and the configuration parameters. The table consists of the Block ID, Part ID, Description, and the fields selected in the Select option. The table (every page of the table, if more than one page long) is headed by a title, date, configuration name, and the names of the selected fields.

The following paragraphs describe the four options in the main menu of the report generator.

1. Load

The "Load" option is used to select an active configuration for a report. Upon entering the "Load" option, a list of available configurations is given. To select one, move the highlight bar to the configuration desired and press <Enter>. The configuration data are loaded, and the main menu is redisplayed with the new active configuration name displayed in the upper right corner of the screen. To return to the main menu without loading a new configuration, press <Esc>.

2. Select

The "Select" option is used to specify the data fields that are to be included in the report for the active configuration. A minimum of four and a maximum of ten fields may be chosen. Choose a field by placing the highlight bar on the desired field and pressing <Enter>. The fields toggle between on and off, red indicating on and black indicating off. Press <Esc> when finished to return to the main menu.

3. Print

The "Print" option begins printing of the report. The prompt "Are you using a laser printer?" appears. The printer should be connected, turned on, set on-line, and positioned

at the top of the paper before answering this prompt. The printer can be set up anytime earlier, but must be done, at the latest, at this prompt.

4. Exit

The "exit" option exits the report generator and returns to the tree.

E. MAINTAINABILITY MODELING

The Maintainability Modeling Module is accessed through the CALCE Printed Wiring Board (PWB) Design Environment tree shown in Figure C-9. When this node is selected, the user may view all of the elements that make up the system or subsystem currently being analyzed (Figure C-10). The View Components option allows scrolling through all of the elements in the list. When an element is selected for a failure mode analysis, the Failure Mode menu automatically appears (Figure C-11).

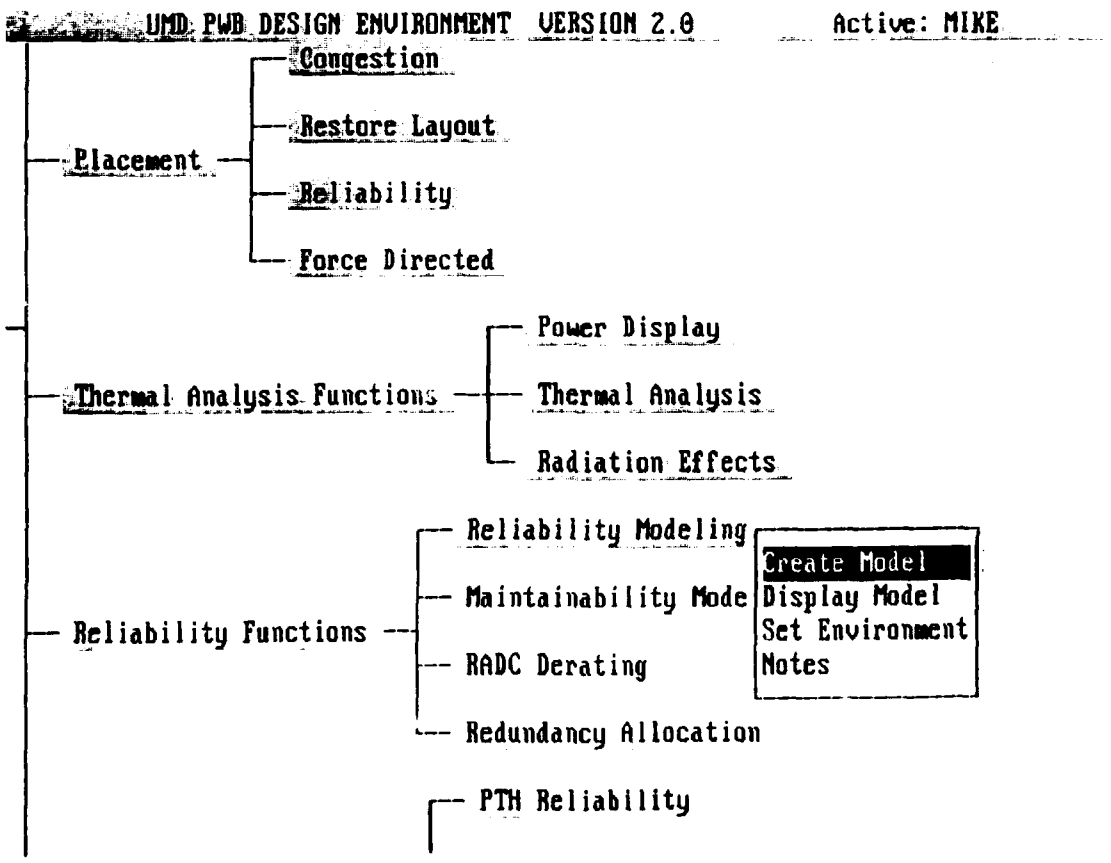

Figure C-9. The CALCE PWB Design Environment Tree

Maintainability Prediction Active ARSR-4A MTTR 3.43

View Components Failure Modes Elemental Tasks Analysis Xit

Mode ID	Comp. ID	Component Description	MTTR (hrs.)	Failure Rate (fail./E6 hr.)	Failure Analysis ?
ARSR-4A	01	PULSE COMP	0.00	14.77	YES
ARSR-4A	02	DOPPLER FILTER	8.42	17.23	YES
ARSR-4A	03	PDI	1.80	14.19	YES
ARSR-4A	04	CFAR	2.63	13.34	YES
ARSR-4A	05	CHANNEL INTERFACE	3.20	6.56	YES

View Component List

Figure C-10. The View Components Screen

Maintainability Prediction Active ARSR-4A MTTR 3.43

View Components Failure Modes Elemental Tasks Analysis Xit

View Failure Modes
Edit Failure Modes
Repair Method

Mode ID	Com ID	Component Description	MTTR (hrs.)	Failure Rate (fail./E6 hr.)	Failure Analysis ?
ARSR-4A	01		0.00	14.77	YES
ARSR-4A	02	DOPPLER FILTER	8.42	17.23	YES
ARSR-4A	03	PDI	1.80	14.19	YES
ARSR-4A	04	CFAR	2.63	13.34	YES
ARSR-4A	05	CHANNEL INTERFACE	3.20	6.56	YES

View Failure Modes

Figure C-11. The Failure Modes Menu

1. Failure Modes

When a Failure Modes option is selected for a component, the screen of failure modes appears (Figure C-12). From the Failure Modes menu, the user can edit the failure mode list for the selected component (Figure C-13). When a failure mode is selected, the Repair Method screen appears (Figure C-14).

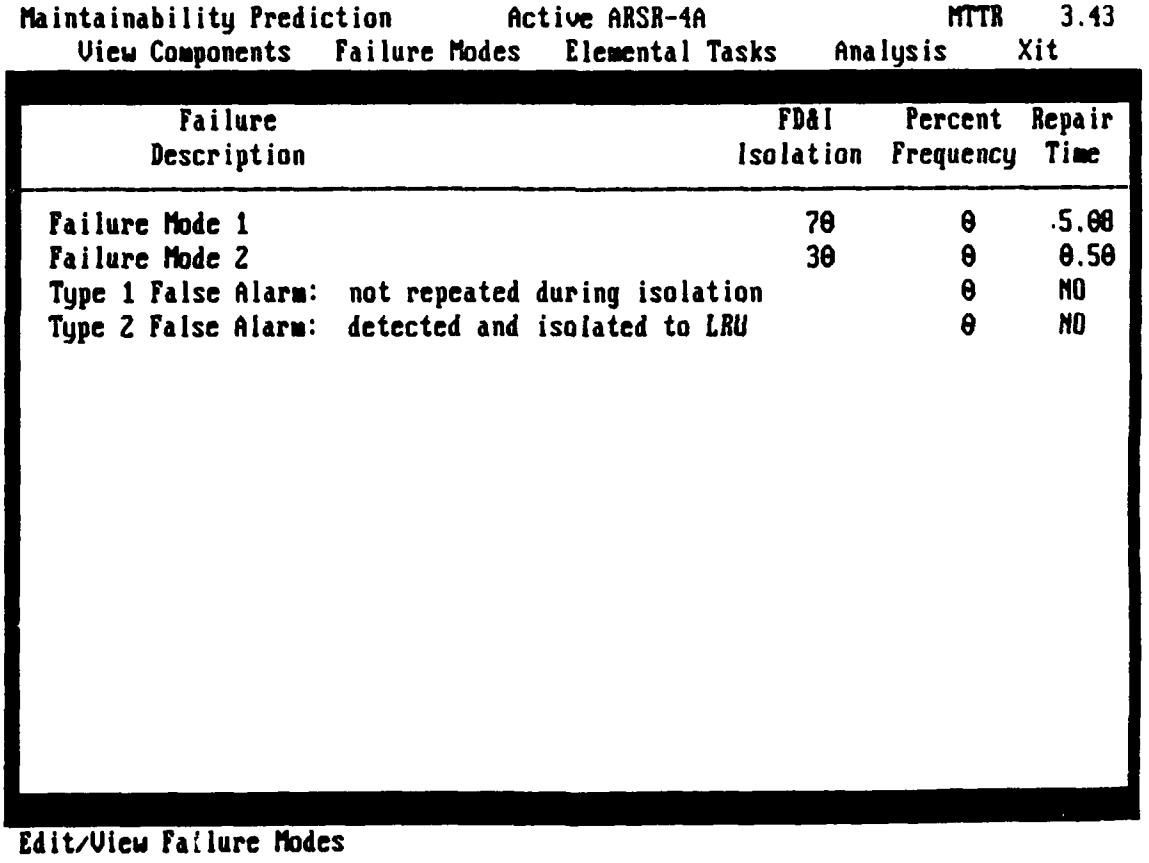

Figure C-12. The Failure Modes Screen

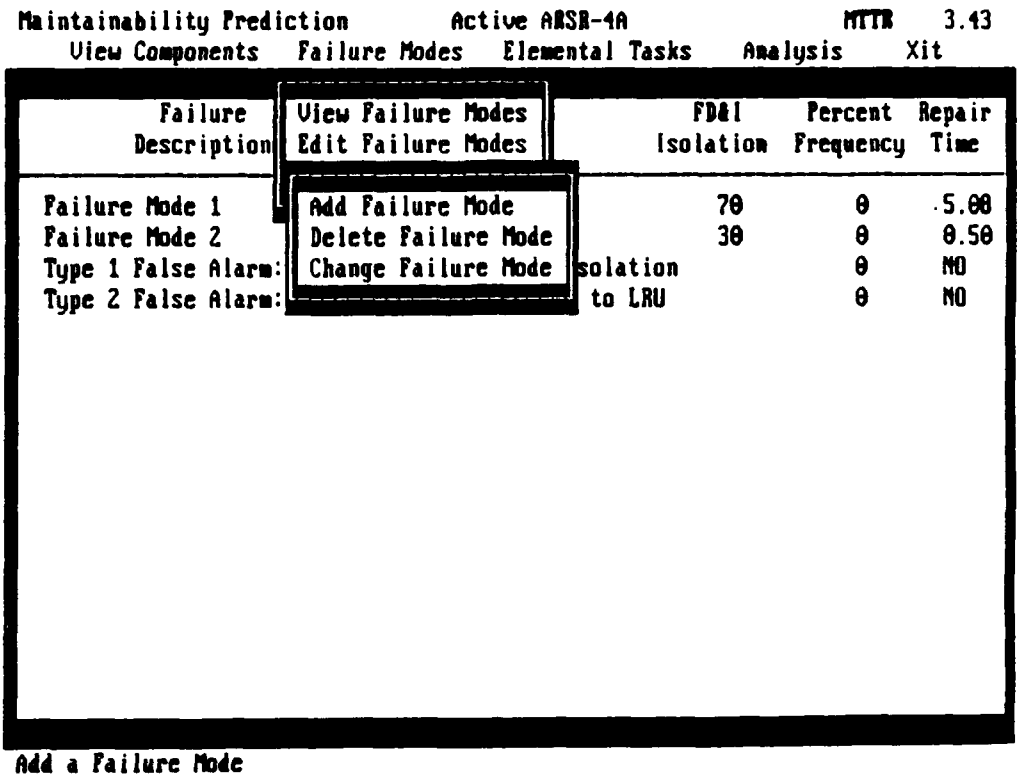

Figure C-13. The Edit Failure Modes Menu

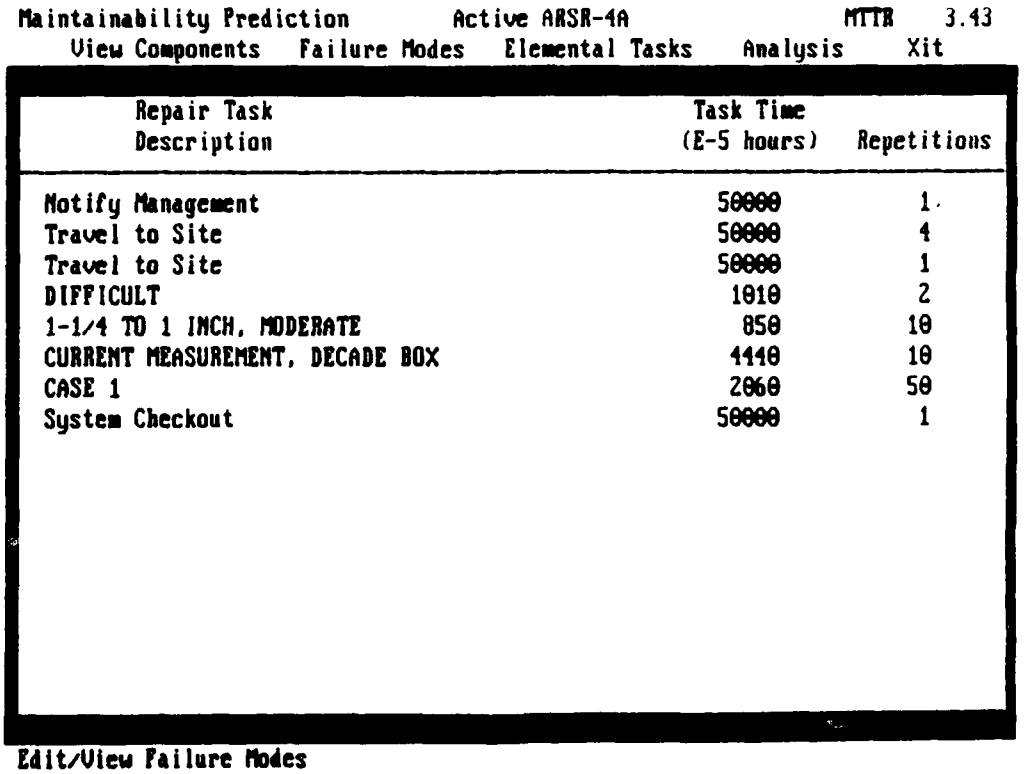

Figure C-14. The Repair Methods Screen

2. Repair Methods

From the Repair Methods menu (Figure C-15), a component analysis can be performed that verifies that the entered data are valid (i.e., ensures that the sum of the percentages is 100 and that repair methods exist for each failure mode), calculates the mean repair time, and updates the main reliability data base with the results. This menu is used to enter all of the maintenance steps required to return the system to operation after the specified failure has occurred. At least one elemental task should be entered for each of the eight major tasks (preparation, fault isolation, disassembly, interchange, reassembly, alignment, checkout, and start-up) outlined in Military Handbook 472, Procedure 5. When the correct task has been selected, the user is prompted for the manpower requirements and the number of repetitions necessary to perform the task for the current repair. If a task requires only one person but two people are required for the preceding and following tasks (making it possible for the second person to do something else useful during the performance of the first task), the manpower requirement for this task should be listed as two. Repair tasks can be deleted, modified, and viewed in the same way as failure modes. The repair tasks are selected from the file of Elemental Maintenance Tasks (Figure C-16).

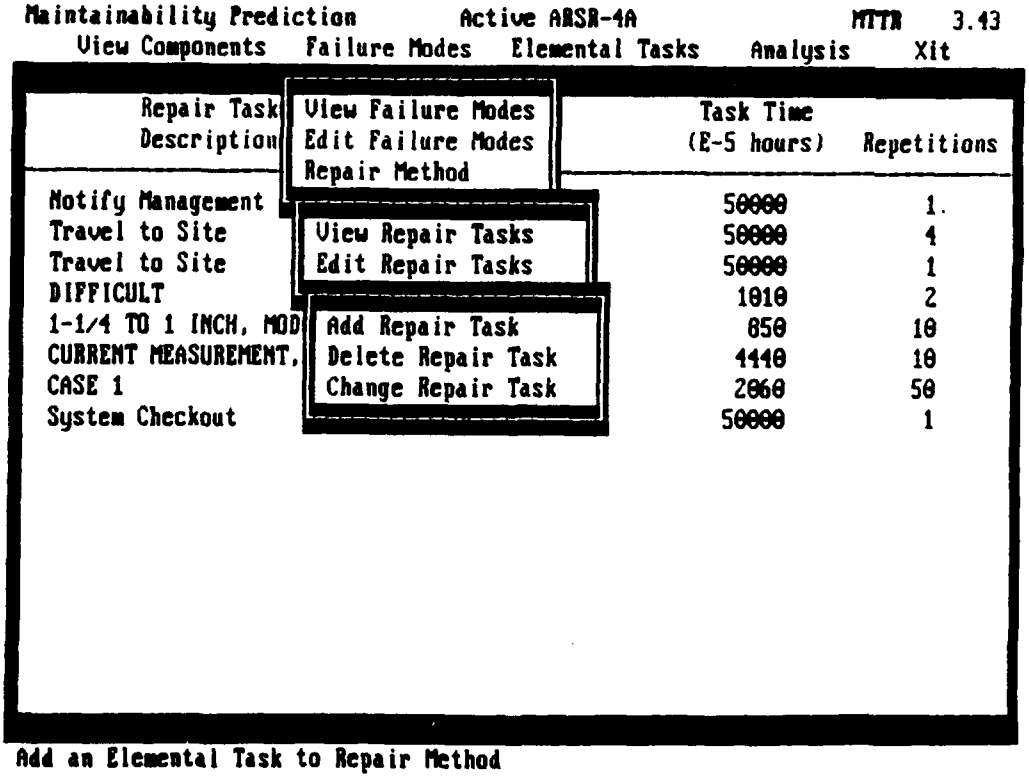

Figure C-15. The Repair Method Menu

Maintainability Prediction Active ARSR-4A MTTR 3.43

View Components Failure Modes Elemental Tasks Analysis Xit

Task ID Number	Task Description	Task Time (E-5 hours)
ECA-CM-Dx	ADJUST DEVICE	
ECA-CM-D1	CASE 1	1200
ECA-CM-Zx	ADJUST DEVICE	
ECA-CM-Z1	CASE 1	670
ECA-TA-Dx	CALIBRATE COAXIAL CABLE TESTER	
ECA-TA-D1	USED WITH 50-OHM CABLE	7950
ECA-TA-D2	USED WITH OTHER THAN 50-OHM CABLE	4790
ECL-FX-Dx	CLEANING FLUX, UP TO 3-INCH STROKE	
ECL-FX-D1	CASE 1	229
ECL-FX-Zx	CLEANING FLUX, UP TO 3-INCH STROKE	
ECL-FX-Z1	CASE 1	84
ECL-HC-Rx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-R1	CASE 1	471
ECL-HC-Yx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-Y1	CASE 1	308
ECL-SE-Dx	CLEAN SOLDERING IRON	
ECL-SE-D1	CASE 1	38

Edit/View Lists of Elemental Maintenance Tasks

Figure C-16. The Elemental Maintenance Tasks Screen

3. Elemental Tasks

The Elemental Tasks menu is used to edit the generic lists of elemental maintenance tasks (Figure C-17). From this menu the user adds, deletes, modifies, and views the tasks in the currently active file. The user may also activate different elemental task files or create new files.

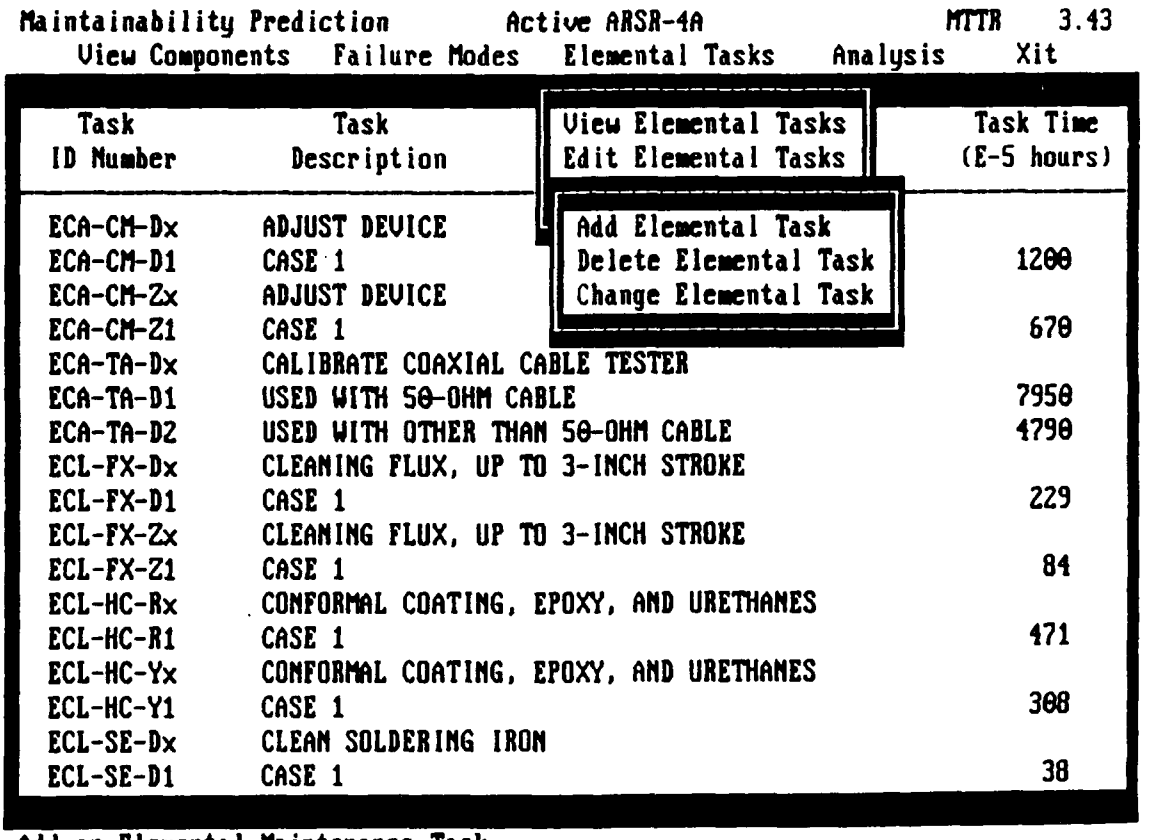

Figure C-17. The Edit Elemental Maintenance Tasks Menu

4. Analysis

At any time, a system or component maintainability analysis can be done using the Analysis option (Figure C-18). The system analysis for the ARSR-4A is shown on the screen in Figure C-19.

Maintainability Prediction Active ARSR-4A MTTR 3.43
View Components Failure Modes Elemental Tasks Analysis Xit

Task ID Number	Task Description	System Analysis Component Analysis
ECA-CM-Dx	ADJUST DEVICE	
ECA-CM-D1	CASE 1	1200
ECA-CM-Zx	ADJUST DEVICE	
ECA-CM-Z1	CASE 1	670
ECA-TA-Dx	CALIBRATE COAXIAL CABLE TESTER	
ECA-TA-D1	USED WITH 50-OHM CABLE	7950
ECA-TA-D2	USED WITH OTHER THAN 50-OHM CABLE	4790
ECL-FX-Dx	CLEANING FLUX, UP TO 3-INCH STROKE	
ECL-FX-D1	CASE 1	229
ECL-FX-Zx	CLEANING FLUX, UP TO 3-INCH STROKE	
ECL-FX-Z1	CASE 1	84
ECL-HC-Rx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-R1	CASE 1	471
ECL-HC-Yx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-Y1	CASE 1	300
ECL-SE-Dx	CLEAN SOLDERING IRON	
ECL-SE-D1	CASE 1	38

Calculate System Maintainability

Figure C-18. The Analysis Option

Analyze System Maintainability Active ARSR-4A

Task ID Number	Task	Task Time (E-5 hours)
ECA-CM-Dx		
ECA-CM-D1		1200
ECA-CM-Zx		
ECA-CM-Z1		670
ECA-TA-Dx		
ECA-TA-D1		7950
ECA-TA-D2		4790
ECL-FX-Dx		
ECL-FX-D1		229
ECL-FX-Zx		
ECL-FX-Z1		84
ECL-HC-Rx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-R1	CASE 1	471
ECL-HC-Yx	CONFORMAL COATING, EPOXY, AND URETHANES	
ECL-HC-Y1	CASE 1	308
ECL-SE-Dx	CLEAN SOLDERING IRON	
ECL-SE-D1	CASE 1	38

ARSR-4A

MTTR	3.430093E+0000
MMH/Repair	3.430093E+0000
MMH/MA	3.430093E+0000
MMH/OH	2.267017E-0004

<Esc> Menu

Figure C-19. A System Maintainability Analysis

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