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THE OATMEAL MODEL-OPTIMUM ALLOCATION OF TEST EQUIPMENT/MANPOWER EVALUATED AGAINST LOGISTICS

INVENTORY
RESEARCH
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February 1983

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

Currently, sophisticated multi-echelon models compute stockage quantities for spares and repair parts which will minimize total inventory investment while achieving a target level of operational availability. The maintenance policies to be followed are input to the stockage models.

The "Optimum Allocation of Test Equipment/Manpower Evaluated Against Logistics" (OATMEAL) model will determine optimum maintenance as well as stockage policies. Specifically, it will determine at which echelon each

ABSTRACT (CONT)

maintenance function will be performed, including an option for component throwaway. Test equipment requirements to handle workload at each echelon are simultaneously optimized.

The costs minimized include those which depend on the range, number, and placement of test equipments, those which depend on whether repair is done and where it is performed, and those which depend on the range and dollar value of repair parts and assemblies stocked at each echelon. The model calculates inventory levels and maintenance policies which will achieve the operational availability target input by the user. It will not choose maintenance policies that preclude achievement of the target.

Real life test cases are included which investigate the efficacy of the MIP (Mixed Integer Program) module of the model.

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Mike O'Donnel was the interface between model developers and real world requirements. OATMEAL is in a sense a model of his interpretation of the world, and it was his assessment of the relative priorities of introducing real world complexities which guided the level of detail included in the current version of OATMEAL.

Charles Plumeri assisted in solving various problems which arose as the modelling proceeded. He wrote a preprocessor, the current user's guide, and helped in debugging. He designed the user oriented output format.

Meyer Kotkin took part in the early discussions on model formulation at which the basic objective of OATMEAL was determined, and use of the Lagrangian approach agreed on.

Jerry Nielson contributed significantly to the readability of this report.

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CHAPTER I

OVERVIEW

1.1 Objective

Before deploying a new weapon system, the US Army must determine how to support the system in the most cost effective manner. Currently, sophisticated multi-echelon models compute stockage quantities for spares and repair parts which minimize total inventory investment while achieving a target level of operational availability. The maintenance policies to be followed are input to the stockage models.

The "Optimum Allocation of Test Equipment/Manpower Evaluated Against Logistics" (OATMEAL) model determines optimum maintenance as well as stockage policies. Specifically, it determines at which echelon each maintenance function should be performed, or whether the maintenance function should be eliminated; i.e., it does repair vs throw-away analysis as well as level of repair analysis.

The costs minimized include those which depend on the range, number and placement of test equipments, those which depend on whether repair is done and where it is performed, and those which depend on the range and dollar value of repair parts and assemblies stocked at each echelon. The model calculates inventory levels and maintenance policies which will achieve the operational availability target input by the user. It will not choose maintenance policies that preclude achievement of the target.

The objective is to achieve the target operational availability at minimum life cycle cost.

1.2 Conceptualization of Maintenance

The model looks at three levels of indenture within a weapon system: components, modules, and piece parts. The indenture breakdown of a home audio system is depicted in Figure 1. A failure mode is defined as a system failure due to a specific module in a specific component. All failure rates are input by failure mode, and maintenance allocation decisions are also made by failure mode. OATMEAL considers four echelons of maintenance: (1) organizational, (2) direct support (DS), (3) general support (GS), and (4) depot.

Consider maintenance on the audio system shown in Figure 1. In every case of turntable failure, the audio system is repaired at ORG. If the arm mechanism fails, the ORG replaces the turntable and returns the unserviceable turntable to the DSU.

At the DSU a new arm mechanism is put in, and the old arm mechanism is thrown away. If the motor fails, the unserviceable turntable will be evacuated all the way to GSU for repair. After the motor is replaced at GSU, the unserviceable motor is shipped to depot for repair. If the needle fails, all work is done at ORG, and the needle is thrown away.

The user may have originally designated the needle as a consumable, but the arm mechanism as potentially repairable, while the model concluded it was not cost effective to repair the arm.

It sometimes happens that the same module appears in two (or more) different components. Failure rates would be input separately for each module application, but the commonality would be recognized in computing stockage and logistical costs.

Since detailed part data is not generally available in early development, the pieceparts are considered in an aggregate manner. It is also possible to represent a group of modules, or even components by an average module or component, specifying how many distinct modules or components this average represents.

1.3 Test Equipment and Repair Skills

The need to use test equipment which can be quite expensive makes the level of repair analysis mathematically challenging. A given repair action may require more than one piece of equipment, and many different actions may have a requirement for the same piece of equipment. It is assumed that any piece of equipment required for fault diagnosis will also be required for repair, so that diagnosis/repair can be considered one procedure. This is reasonable because usually a repair is not considered complete unless the equipment used for diagnosis has performed a functional check to verify the success of the repair.

Test equipment is labelled as either common or peculiar at each echelon. If peculiar, only integer quantities can be placed at a repair facility. The whole cost of the equipment must be considered, even though the equipment is used at the facility only a fraction of the time. If the test equipment is common, it is assumed that only use must be paid for; if the end item needs 1/4 of the throughput of a common piece of test equipment at the facility, it bears 1/4 of the total cost for the equipment.

Test equipment may be needed for three different types of repair actions:

a. Repair weapon system when it fails due to the failure of a specific component.

b. Repair a component when it fails due to the failure of a specific module.

c. Repair a module whenever it fails.

Repair Skills. Cost of repair including labor costs is input to the model. However, sometimes repair requires special skills which would be new to an echelon. The user may identify special repair skills, so that the training costs and higher salaries are properly calculated. If a special skill is needed at DSU, but the skill will be required for only 1/4 of a man year per year, full training costs for one person per DSU must still be incurred. The model accounts for this just as it properly accounts for peculiar test equipment. In both cases there is an incentive to allocate maintenance so that skills and equipments are not needed at echelons where they will be grossly underutilized.

1.4 Inputs and Outputs

Input consists of the type of data necessary to run a supply model such as SESAME [10], plus additional cost and maintenance related data. The user can also provide inputs which exclude certain types of solutions as not feasible or realistic; for example, he can specify that a certain test equipment cannot be placed below the GSU. The maintenance data consists primarily of test equipment and special skill requirements for each maintenance action.

There can be up to four supply and maintenance echelons allowed. It is assumed supply and maintenance functions are colocated, but an intermediate echelon can be specified to have only a maintenance function.

Replacement task distributions and maintenance task distributions [11] are outputs of OATMEAL whereas they would be input to supply models. An item's replacement task distribution gives the percent of removals which occur at each echelon, while the maintenance task distribution specifies the percent of removed items which can be repaired at each echelon.

Other outputs of OATMEAL are the numbers and locations of test equipment and special personnel, and the stockage quantities associated with the maintenance policy chosen.

1.5 Solution Approach

The heart of OATMEAL is a mixed integer program (MIP) mode . Consider the approach to solution to consist of four stages - preprocessing, formulation, optimization, and evaluation. The solution flow is depicted in Figure 2.

Preprocessor. This program [8] accepts input from the user in a format designed to be as convenient as possible. Default values for inputs are provided whenever it makes sense to do so, and there are edit checks. The output is a parsimonious set of parameter and variable values necessary to describe the problem mathematically.

Formulator. This program formulates the problem as a MIP model in the specific format for the commercial software package being used (see below). However, to do this, it must first generate stockage (and cost implication thereof) for all candidate maintenance policies. The Formulator uses the SESAME multiechelon stockage model [5] as a subroutine to calculate optimally quantities of components and modules for a particular maintenance policy vector. By policy vector we mean an assignment, for each failure mode, of where to replace and where to repair the respective components and modules. The associated stockage costs will then be accessible to the MIP cost function formulation.

Optimizer: The "MIP" refers to the commercial software package which accomplishes the optimization. Packages for accomplishing MIP are available, each of which required many man years to develop. The specific package now being used is APEX III, [1], developed by Control Data Corporation, but others, such as IBM's MPSX, can be substituted with little change.

MIP "optimizes" - finds the maintenance policy vector which minimizes costs, including stockage costs and backorder penalty costs - by using an efficient heuristic search so that all the myriad combinations do not have to be evaluated.

Evaluator. As the name implies, this program evaluates; it accepts as input all the data about the problem being run and also a maintenance policy vector (the replace-repair actions by failure mode) to be assessed in terms of cost and performance. This policy vector may have come from the optimizer or been proposed by the user (note alternative policy block in Figure 2). The evaluator uses SESAME subroutine to determine for each component and module the optimum stockage quantities. The evaluator will determine the operational availability performance based on the computed stockage quantities and the selected maintenance policy vector; it also will compute all relevant costs (see Chapter 2 for cost elements and expressions). Finally the evaluator will convert the failure mode policy vector to component and module replacement task distributions and maintenance task distributions (Section A.8.4).

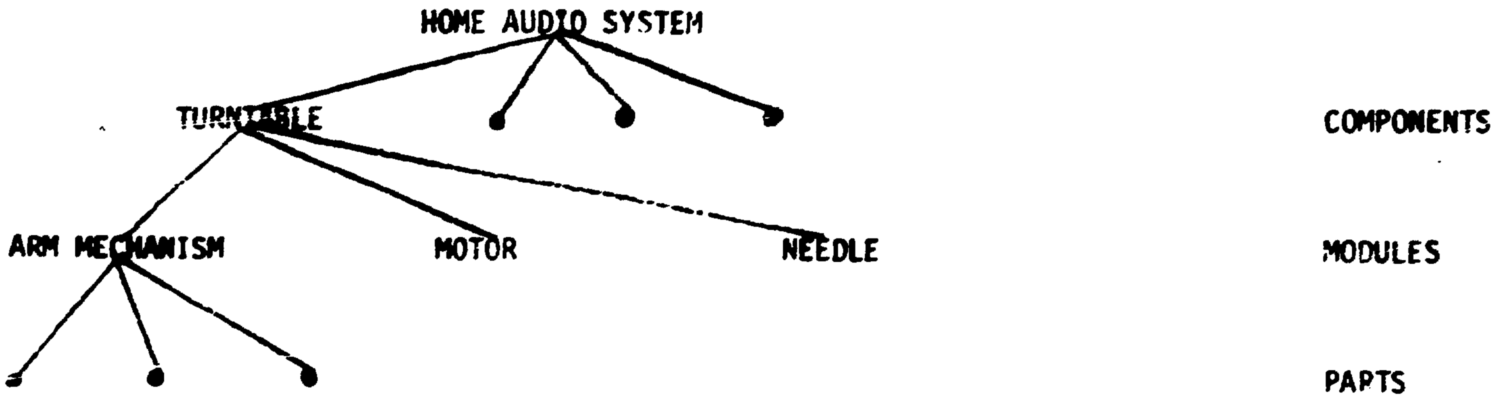
OATMEAL, by incorporating SESAME model subroutines, simultaneously optimizes maintenance and supply. If SESAME or a comparable stockage optimizer is not included in a repair level analysis model, estimates of the impact of different maintenance policies on stockage costs cannot be correctly estimated. Therefore, this may result in the choice of maintenance policies which are not as cost effective as expected. This phenomenon will be most pronounced when the maintenance policies have an adverse impact on operational availability, requiring a very large investment in inventory to compensate.

1.6 Documentation of OATMEAL.

The User's Guide [8] explains in detail the input required from the users, default parameters, the interpretation of output, and different approaches to using the OATMEAL model for maximum benefit. It also documents the transformations made by the pre-processor to develop the inputs required by the MIP formulator.

This report is intended for a range of readers with different objectives. This Chapter, Chapter II and Sections 3.1-3.3 of Chapter III do not require a sophisticated mathematical background, and are intended to give analytically inclined readers a good understanding of the capabilities of the model. Chapter II describes how the model evaluates costs and operational availability. Chapter III discusses the elements of the optimization process, i.e. the MIP formulation, selection of a backorder penalty parameter, and evaluation of the cost-availability performance for maintenance policy vectors.

MAINTENANCE CONCEPTS



MAINTENANCE POLICIES FOR GIVEN FAILURE MODES:

	END ITEM REPAIR (REPLACE COMPONENT)	COMPONENT REPAIR (REPLACE MODULE)	MODULE REPAIR (REPLACE PART)
ARM:	ORG	DSU	THROW AWAY
MOTOR:	ORG	GSU	DEPOT
NEEDLE:	ORG	ORG	THROW AWAY

FIGURE 1

OATMEAL FLOW

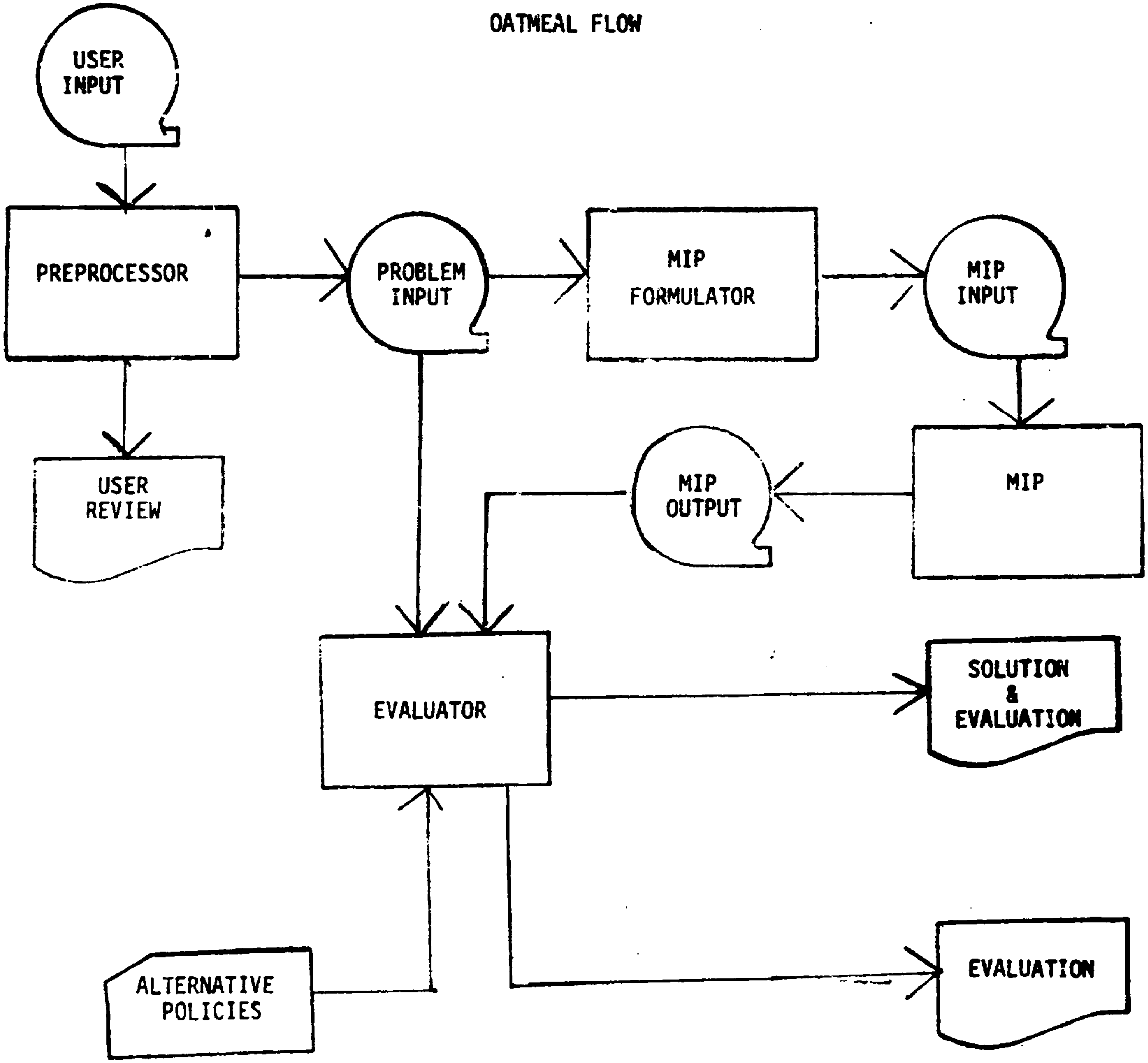


FIGURE 2

MIP - MIXED INTEGER PROGRAM

CHAPTER II

EVALUATION OF COST AND AVAILABILITY

2.1 Introduction

This chapter will give the reader the scope of the costs considered, the actual cost equations, and an idea of how performance is evaluated through end item availability. A more mathematical treatment of the functional details of OATMEAL is left to Chapter III.

2.2 Use of Present Value

Because OATMEAL's objective is to minimize life cycle costs, the costs considered are a mixture of one-time costs and recurring annual costs. To make these two types of costs commensurable, the present value approach as recommended in DoDI 7041.2 [12] is used.

As an example, given that:

a. 100 requisitions are processed per year.

b. Cost per requisition processed is $10.

c. Expected lifetime for the system is 11 years.

d. Discount rate for present value analysis is 10%.

Then, assuming costs are incurred at midyear,

$$\text{Requisition Costs (Present Value)} = \sum_{t=1}^{11} (\$10) \times (100) \times \left(\frac{1}{1.10}\right)^{t-1/2}$$

This may be rewritten as:

$$\text{Requisition Costs (Present Value)} = (\$10) \times (100) \times \sum_{t=1}^{11} \left(\frac{1}{1.10}\right)^{t-1/2}$$

$$= \text{Annual Requisition Costs} \times \text{PVFAC}$$

where PVFAC = present value adjustment factor. Note that PVFAC depends only on the expected life of the system and the discount rate, and can be used to convert other annual costs to the present value of expected lifetime costs. While PVFAC may be calculated as shown, it is input to OATMEAL from the pre-processor, which takes the correct value from official DoD tables.

2.3 Full Deployment Assumptions

Full deployment is assumed in year 1. This means cost estimates produced are not true life cycle costs, but are useful for ranking policy alternatives. This approach was taken to simplify data requirements and processing with the expectation that this would not unduly bias choice of one alternative over another. It does tend to exaggerate the impact of costs which will phase in over time, so some refinements may ultimately be necessary, e.g., a factor applied to PVFAC. Note that not only do annual costs such as requisition processing build up to full deployment levels, but even "onetime" costs such as purchase price for test equipment, are not really all incurred at one time; test equipment, for example, need only be deployed as the weapon system is introduced over time to additional fighting units.

2.4 Logistical Support Cost Components

Costs are computed for each individual component and module using the equations described. The variables underlined in the equations are passed directly from the preprocessor. The other variables are computed or modified by OATMEAL and depend on the maintenance policies chosen.

2.4.1 Throw Out Costs

Throw out costs represent the annual value of the components and modules which wash out and must therefore be replaced by new procurement. As with all the other annual costs, PVFAC is used to convert the estimate of annual costs to the present value of expected lifetime throw away costs. It is assumed that the administrative costs of making procurements will not significantly vary among alternative maintenance policies and need not be considered.

Mathematically, the equation for throw out costs for any given component or module is:

$$\text{THROW OUT COST} = \underline{\text{PVFAC}} \times (\text{Annual Removals}) \times (\%\ \text{Washout}) \times (\underline{\text{Unit Price}})$$

Annual removals reflect failure rates plus "false" removals. A "false" removal occurs when a component or module which is perfectly good is removed due to an error or ambiguity in diagnosis. Currently, the model user inputs a failure rate for each failure mode, but a single false removal rate which applies to all items. If the false removal rate is 10 percent and a component or module is expected to fail 100 times a year, total removals are estimated as (100 + 100 x 10%) or 110.

Maintenance policies impact removal rates in that if a component is thrown out rather than repaired, this will eliminate demand for modules used to repair that component. Throw out costs are computed for the component, since each component thrown out must be replaced by procurement, but no throw out costs are computed for its modules.

An inherent washout rate is input for each component and module, reflecting the percent of removals which cannot be fixed regardless of the maintenance policies chosen. If a throw out policy is selected by the model, or input for evaluation, the washout rate becomes 100 percent.

2.4.2 Repair Costs: Common Labor and Manuals

Repair costs include labor, parts, and the need to develop repair manuals. Two types of labor are considered, common and special skills. The reason for treating special skills separately is that just as peculiar test equipment, they may not be fully utilized; e.g., if repair requiring a special skill is done at ORG, the full cost of putting the specially trained person at ORG is incurred even though he may need to use his special skill only a small portion of the time. Special skills costs are discussed further in Section 2.5 while parts costs are discussed in Section 2.4.8.

While special skill requirements are treated in detail, common labor costs are treated somewhat approximately in order to simplify the data requirements of the model. The user inputs the average hours of labor to repair each component and each module. He does not enter the hours to repair the end item itself, or relate the number of hours to repair a component to the failure mode. Thus, common labor repair costs are computed per component or per module repair action.

Because of differences in pay scales and working hours by echelon, the same job will incur a different cost depending on the echelon at which it is done. The pre-processor takes all this information into account and inputs to OATMEAL the cost per repair action by echelon. The number of repair actions per echelon is then computed by the EVALUATOR from the annual removals and the maintenance task distribution.

MTD_k is defined as the percent of all removals (no matter where removed) repaired at echelon k, where k takes on the values 1, 2, 3 and 4 to refer respectively to the ORG, DSU, GSU and depot repair echelons (e.g. MTD_3 is percent of all removals repaired at GSU). The sum of $MTD_1 + MTD_2 + MTD_3 + MTD_4$ plus the washout rate will always equal 100 percent.

Repair Cost_k is defined as the cost per repair action if done at echelon k. Mathematically, for each component and module

$$\text{COMMON LABOR COSTS} = \underline{(\text{PVFAC})} \times (\text{Annual Removals}) \times \sum_k (\text{MTD}_k) \times \underline{(\text{Repair Cost}_k)}$$

Preparation of manuals is viewed as a composite of documenting each component and each module repair action. The pre-processor estimates these costs based on the number of pages required to document each type of repair action as input by the user. The EVALUATOR adds manual preparation cost to component and module repair cost unless the policy is to do no repair (throwaway) of the component or module.

2.4.3 Transportation Costs

Transportation cost evaluations are straightforward once we clarify the distinctions between demands, removals, and retrograde. We do this with an example chosen for its pedogogical value rather than its realism. Suppose we have a simple supply system consisting of organizations, direct support units, and a depot. For a particular module (denoted PMOD) there are:

30 ORG echelon PMOD removals per year
10 ORG echelon PMOD repairs per year
3 ORG echelon PMOD washouts per year
50 DSU echelon PMOD removals per year
40 DSU echelon PMOD repairs per year
5 DSU echelon PMOD washouts per year

The ORGs will demand 20 PMODs a year from the DSUs (30 removals minus 10 repairs). The DSU's need to supply these 20 and replace the 50 PMODs removed at DSU. Since the DSUs are able to repair 40 a year, their net shortfall is (50 + 20 - 40) or 30. Thus at DSU level there are 50 removals a year and 30 demands on the depot.

The ORGs are retrograding (30 - 10 - 3) or 17 PMODs to the DSUs for repair. The DSUs see these 17 unserviceable PMOD's plus 50 removals at DSU, and then repair 40 and washout 5. So DSU retrograde to the depot is (17 + 50 - 40 - 5) or 22. Currently, two assumptions are made which relate to transportation costs. It is assumed only repairable items are retrograded. Thus, in our example we assumed the ORGs were knowledgeable enough to identify three PMODs as washout and not ship them to the DSU with the 17 PMODs retrograded. It is also assumed retrograde cost rates are equal to forward transportation rates. For more details on retrograde calculations see Appendix A Section A.8.3.

The reader can see, from the example given, that the maintenance policies, by affecting where repair is done, affect both demand and retrograde. Let Annual Demand_k denote the total demands placed by echelon k sites on their suppliers and Transport Rate_k denote the cost per pound of moving material from supplier to echelon k. Analogously, Annual Retrograde_k and Retro Rate_k refer to movement from echelon k to the maintenance units providing support. Then,

TRANSPORTATION COST =

$$\underline{\text{PVFAC}} \times \underline{(\text{Item Weight})} \times \sum_k (\text{Annual Demand}_k) \times \underline{\text{Transport Rate}_k})$$

$$+ \underline{\text{PVFAC}} \times \underline{(\text{Item Weight})} \times \sum_k (\text{Annual Retrograde}_k) \times (\underline{\text{Retro Rate}_k})$$

2.4.4 Requisition Costs

Annual Requisitions_k is defined as the number of requisitions for a given component or module placed annually by echelon k sites on their suppliers. One-for-one ordering is assumed for the most part, i.e. each item demanded results in an additional requisition. However, this is qualified to the extent that it is assumed no single site will requisition the same item more than 12 times a year. Thus, for low demand items, number of requisitions equals number of demands, but not for high demand items, for which Annual Requisitions_k may not exceed 12.

Mathematically,

$$\text{REQUISITION COSTS} = \underline{\text{PVFAC}} \times \sum_k (\text{Annual Requisitions}_k) \times (\underline{\text{Requisition Cost Parameter}})$$

2.4.5 Stockage Costs

Stockage costs include the one-time costs of buying stock to fill the pipeline, and an annual holding cost to cover stockage and losses or pilferage of inventory. One issue is: what is the impact on cost of engineering redesign whereby better performing components or modules replace those previously used? Will the new item simply be bought when it is time to replenish washouts of the old item, or will all stocks of the old item be excessed at time of engineering redesign, increasing cost? A second issue is: Can pipelines be drawn down gradually so that if, for example, phase out begins in 1994, procurements to replace washouts after 1994 are avoided by using stocks in the pipeline, saving money?

To simplify data requirements the issues raised are avoided by not including either excess costs, or savings from pipeline reductions. Letting HCFAC be the annual cost of storage and pilferage, as a percent of unit price:

STOCKAGE COST = (Quantity Stocked) x (Unit Price) +
PVFAC x (Quantity Stocked) x (Unit Price) x HCFAC

2.4.6 Bin Costs

Bin costs are those management and holding costs which vary as a function of the range of items stocked rather than the dollar value or quantities stocked. The bin cost parameter is the cost per NSN per stockage location per year so that for each component or module:

BIN COST = PVFAC x (Number of Stocking Locations) x (Bin Cost Parameter)

Bin costs and stockage costs are the two cost components that depend on the answers found by the SESAME subroutines of OATMEAL as to how much and where to stock components and modules.

2.4.7 Catalog Costs

Each module and component is coded as to whether it is a new item or not. If it is new, a one time catalog introduction cost is incurred; additionally a recurring maintenance cost is assessed.

Therefore,

CATALOG COSTS = (Total New Items) x (Item Introduction Cost) +
PVFAC x (Total New Items) x (Item Maintenance Cost)

2.4.8 Parts Costs

For each module an average part is created to represent all parts used in fixing the module. The unit price to be used for the average part is calculated by the pre-processor based on the average value of parts used per repair action. Demand is estimated as the total demand for the module, less module washouts divided by the number of parts the average represents.* The echelons at which demand arises are inferred from the echelons at which the module is repaired.

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* The number of parts is actually based on new parts only. This means demand for old parts is attributed to new parts so that added stockage costs for old parts are reflected as added cost for new parts.

Once the average part is described, SESAME subroutines are used to calculate stockage and all logistics costs are calculated including throwaway (washout is always 100 percent), requisitioning cost, stockage cost and bin cost. These costs are multiplied by the number of parts the average represents. The number of new parts introduced contributes to cataloging costs.

2.4.9 Backorder Costs

Component backorders degrade operational availability, while module backorders increase the number of components in the repair pipeline. Ideally, these increased pipelines would be accounted for in computing component stockage. Neither SESAME nor the OATMEAL model currently does this. Therefore, the backorders themselves are costed out. If module backorders will increase the number of components in the pipeline by n, and each component costs UP, module backorders are costed out as (n) x (UP).*

By analogous reasoning, parts backorders are costed out in terms of the increase in the expected number of modules in the repair pipeline.

2.5 Test Equipment and Special Manpower Costs

For each type of test equipment and each different kind of specially trained repairman, the EVALUATOR calculates the total requirement and multiplies by the cost per equipment or per repairman which is input. The pre-processor bases test equipment cost on purchase price, installation cost, and an annual maintenance cost expressed as a percent of purchase price. It also checks to see if the test equipment life is less than the weapon system's life, in which case it includes a cost to reflect the need to eventually replace the test equipment. The pre-processor bases repairman costs on salary and training cost; annual training cost is the cost of training divided by the average length of time a repairman stays in his position. Repairman cost may vary by echelon.

OATMEAL calculates workload on equipment or special repairmen in detail. Workload factors are input to the EVALUATOR by failure mode for end item and component repair; i.e. workload to repair the end item may depend on which component failed, and workload to fix the component may depend on which module failed. Module repair workloads do not depend on which component the module came from, nor does the user, in developing input to the pre-processor, necessarily

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*Actually, to be consistent with calculation of stockage cost, we use (n) x (UP) + (PVFAC) x (n) x (UP) x (HCFAC).

have to use the capability to make component and end item repair workloads depend on failure mode.

Equipment and repairmen requirements are calculated by site, reflecting the workload factors, equipments supported by the site, and the maintenance policies. If the equipment or repairman will be at the site just to support the single weapon system, i.e. it is peculiar to the weapon system, requirements are rounded up: 2.2 becomes 3 and so on.

2.6 Evaluation of Operational Availability

Operational availability is estimated as:

$$OA = \frac{MCTBF}{MCTBF + MTR + MTT + MLDT}$$

where

OA - operational availability of the weapon system

MCTBF - mean calendar time between failures

MTR - mean time to repair the weapon system if all resources are available

MTT - mean transportation time

MLDT - mean logistics down time

MCTBF and MTR are inputs and relate to the performance of the weapon system independent of what support it receives.

MTT is a function of the repair level decisions. If the system is always repaired at user level with user personnel and equipment, MTT equals 0. Otherwise, MTT covers the time for the upper echelon personnel to get to the user, or for the system to be moved to the repair site and back.

MLDT is the mean time to get an essential component from the supply system when needed for weapon system repair. It depends on the repair level analysis in that for any given set of maintenance policies, there is an associated set of stockage levels, and the MLDT is a function of these supply levels and the maintenance policies. The SESAME stockage model calculates MLDT.

CHAPTER III

OPTIMIZATION

3.1 Introduction

This chapter discusses the mathematics and procedures for problem formulation and optimization.

One difficulty encountered relates to the need to use SESAME in problem formulation. To compute stockage, SESAME must first find the value of a Lagrangian (called CURPAR in the SESAME literature) by which stockage is related to the operational availability target. Unfortunately, SESAME cannot find the Lagrangian without first knowing what maintenance allocation decisions will be made.

Thus, there is circularity: optimimum maintenance allocation decisions depend on stockage costs, while the computation of stockage quantities require that CURPAR be known, and CURPAR depends on what the maintenance allocation decisions are. In Sections 3.5 and 3.6 we describe the circularity and how we circumvent it in detail. Until then the reader is asked to accept that SESAME can compute stockage in the problem formulation stage.

3.2 Problem Formulation Procedures

As stated in Chapter I, OATMEAL considers three levels of indenture and four echelons of maintenance (plus throw-away). This structure would generate 5^3 possible maintenance policies for each failure mode. However, OATMEAL requires that a module be repaired at the same or higher echelon as the component, and the component repaired at the same or higher echelon as the end item. Further, end item repair is limited to ORG or DS, resulting in 25 possible maintenance task allocations for each failure mode. These policies can be expressed as a triplet in which the first variable states the echelon for end item repair, the second, component repair, and the third, module repair (see Table 3.1). In particular cases, some of the 25 may be excluded by the user. Although the optimization examines 25 maintenance policies for each failure mode, the formulator does not. Instead, the costs for these policies are built up from the costs found for components and modules considered individually. Thus, in computing stockage, the formulator applies SESAME to each of nine alternatives for each component and to each of 15 alternatives for each module.

COMPONENT ALTERNATIVES

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
REPLACE	ORG	ORG	ORG	ORG	ORG	DSU	DSU	DSU	DSU
REPAIR	ORG	DSU	GSU	Depot	Throw Away	DSU	GSU	Depot	Throw Away

TABLE 3.1. POLICY NUMBER TABLE

1 = ORG 2 = DSU 3 = GSU 4 = DEPOT 5 = Throwaway

Policy Number	End Item Repair	Component Repair	Module Repair
1	1	1	1
2	1	1	2
3	1	1	3
4	1	1	4
5	1	1	5
6	1	2	2
7	1	2	3
8	1	2	4
9	1	2	5
10	1	3	3
11	1	3	4
12	1	3	5
13	1	4	4
14	1	4	5
15	1	5	5
16	2	2	2
17	2	2	3
18	2	2	4
19	2	2	5
20	2	3	3
21	2	3	4
22	2	3	5
23	2	4	4
24	2	4	5
25	2	5	5

The following example shows how the formulator derives failure mode costs from costs for individual components and modules.

EXAMPLE

Logistics Costs for Component 1

For ORG Removal/DSU Repair	$100
For ORG Removal/Depot Repair	$140

Logistics Costs for Module 1

For DSU Removal/Throwaway	$ 50
For Depot Removal/Throwaway	$ 30

Failure Mode 1

Defined as Failure of Module 1 Causing Failure of Component 1

Accounts for 40% of Component 1 Failures

Accounts for 80% of Module 1 Failure (this implies module 1 is in some other component besides component 1)

Logistics Cost for Failure Mode 1

Policy	Cost
ORG Removal/DSU Repair/Module Throwaway	(40%)($100) + (80%)($50)
ORG Removal/Depot Repair/Module Throwaway	(40%)($140) + (80%)($30)

3.3 Why Mixed Integer Programming Is Needed

The procedure just outlined develops the logistical cost impact of each maintenance alternative for each failure mode. The least cost set of alternatives is readily identified. If this set is implemented, however, test equipment (and special repair skills) costs could be excessive because no effort has been made to place all maintenance functions which use the same equipment at as few sites as possible. Conversely, if policies are selected simply to minimize test equipment costs, logistical costs may become excessive. If each piece of equipment were used for just one failure mode, we could include test equipment costs in with logistical costs in choosing the policy alternative for that mode. When test equipment has many uses, however, we can no longer select the policy for one failure mode independently of the policies we choose for other failure modes.

A successful approach to doing repair level analysis with shared test equipment has been developed and implemented by the US Air Force building on work by MITRE Corporation [9,7]. This work does not incorporate subroutines which compute optimum stockage, nor does it choose policies subject to a constraint on operational availability, both being features which could be added. Other restrictions were of concern. The Air Force approach appears to be limited to examining no more than two echelons at one time. Also, it does not relate the maintenance decisions to the quantity of a test equipment required, just the location.

The relationship between maintenance policies and quantity is not always important. In some cases, there is never a need to place more than one each of a test equipment type at any site. In other cases, however, maintenance policies for different failure modes must be coordinated not only to reduce the number of locations for test equipment, but the quantity per location; e.g., it may be possible, if policies are properly selected, to get by with three at depot, and one each at ten DSU's, rather than one at depot and two each at the ten DSU's. To help reduce quantity, OATMEAL may occasionally select two policy alternatives for one failure mode, perhaps depot repair to handle overflow from GSU repair.

The Air Force approach is based on the mathematical technique of network theory analysis. Network theory is a special case of mixed integer programming (MIP) in that any problem which can be solved by network theory analysis can be solved by MIP. This certainly does not work in reverse, not all MIP problems can be solved by network theory. The use of MIP, as described in the next section, is therefore a more general approach, but will not be as efficient for problems where network theory is suitable.

Interestingly, it is not oversimplifying too much to describe most MIP algorithms as a synthesis of linear programming and a technique called branch and bound. Special cases of the repair level analysis problem can be solved by branch and bound without linear programming [6].

3.4 Mathematics of Problem Formulation

The MIP objective is to minimize the sum of those equipment and logistic costs described in Chapter II. The decision variables specify where repair is to be done and the quantity and placement of test equipment. The MIP constraints insure that all necessary repair work is accounted for and that the equipment decisions are consistent with the repair decisions in that the equipment provided will handle the workload placed on test equipment at each echelon by the repair decisions.

Satisfying a system availability performance goal is not explicit in the objective functions or constraints, but does impact on the policies chosen. How this is accomplished is explained in Sections 3.5 and 3.6.

First, let's discuss the constraint and objective function equations of the

MIP in more detail. Notation and the entire formulation are summarized in Section 3.3. We will be referring to the equations of Section 3.3, one equation at a time, beginning with the constraints and then examining the objective function.

Every time a failure mode incident "ij" occurs (module j in component i fails so the end item is repaired), maintenance actions are generated and some maintenance policy must react to them. For example, the end item would be repaired at echelon P by replacing component i; the component would be repaired at echelon R by replacing module j; and the module would be repaired at level r. A decision to be made by the MIP is what percentage Y_{ij} of such failure incidents should be handled by policy (P,R,r), and the constraint (for each failure mode) is that the percentages sum to 1 over all feasible policies. Echelons are numbered as follows:

Echelon	ORG	DSU	GSU	Depot	Throwaway
Number	1	2	3	4	5

Currently, P must be either 1 or 2 (end item repair at ORG or DSU); R must equal or exceed P (component cannot be repaired at lower echelon than end item); r must equal or exceed R (repair module at or above where it is replaced). In Section 3.5, the constraint on percentages is denoted the "Accountability" constraint, all work is accounted for.

The next set of constraints relate to workload on test equipments. Workload is input to OATMEAL as the variables $N_i(e)$, $n_j(e)$, $N_{ij}(e)$, depending on the function. $N_i(e)$ defines workload for equipment e attributable to repair of the end item using component i, so that any failure mode involving component i places a workload of $N_i(e)$ on test equipment e. $n_j(e)$ defines workload attributable to the repair of module j, while $N_{ij}(e)$ defines workload attributable to repair of component i when module j fails. Workload is defined as the fraction of equipment availability required per end item per year: if equipment e is up 2000 hours a year, if repair of the end item when component i fails requires 2 hours use, and if the component i failure rate is 0.5 times per year per end item, then $N_i(e)$ equals (2.0 x 0.5)/2000 or .0005.

There is a workload constraint for each equipment, e, for each echelon k. If $N_i(e)$ is non-zero, any failure mode involving component i with end item replacement at echelon k contributes to the workload; put differently, if Y_{ij} (k,R,r) is non-zero for some values of R and r, and $N_i(e)$ is non-zero, there is a contribution of $[Y_{ij}(k,R,r)]$ x $[N_i(e)]$ x [equipment density per echelon k site] to the workload constraint for equipment e at echelon k. Similarly, if $n_j(e)$ and $Y_{ij}(P,R,k)$ are non-zero for any values of P and R there is a contribution to workload at echelon k as there is if $N_{ij}(e)$ and Y_{ij} (P,k,r) are non-zero.

The sum of all 3 types of requirements attributable to $N_i(e)$, $N_{ij}(e)$, $n_j(e)$ must be less than or equal to $t_{e,k}$, the number of test equipment e at echelon k in order to insure (in a steady state sense) that the repair functions can be performed. These $t_{e,k}$ variables are pseudo-decision variables in that they are almost entirely dependent upon the Y_{ij} decisions; in the cases where the number of test equipment e at an echelon k must be an integer value (TE is peculiar to this end item) there is interdependency in that the MIP procedure may modify the Y_{ij} decisions to minimize integers $t_{e,k}$.

The objective function is to minimize costs associated with the Y_{ij}, $t_{e,k}$ decisions. The $t_{e,k}$ values are multiplied by the equipment cost C_e and the number of repair sites at echelon k. Associated with the $Y_{ij}(P,R,r)$ decisions are the logistics costs for the failure mode "ij" and policy (P,R,r). Section 3.1 discussed computation of logistics costs by failure mode in detail. Summarized mathematically, the component and module logistics costs, $C_i(P,R)$ and $M_j(P,r)$ respectively, are prorated by fractions $FC_i(j)$ and $FM_j(i)$ which denote, respectively, fraction of component i removals accounted for by failure mode "ij" and fraction of module j removals accounted for by failure mode "ij."

Size of MIP. There are twenty-five possible combinations of values for (P,R,r): (1,1,1), (1,1,2), (1,1,3), (1,1,4), (1,1,5), (1,2,2), (1,2,3), (1,2,4), (1,2,5), (1,3,3), (1,3,4), (1,3,5), (1,4,4), (1,4,5), (1,5,-), (2,2,2).....(2,5,-).

Let

NAPP - number of failure modes, sometimes referred to as applications.

NEQECH - number of equipment/echelon combinations, so that if there are 10 equipment types, each of which can be placed at any of 3 echelons, NEQECH = 30.

Then:

Numer of Accountability Contraints = NAPP
Number of Workload Constraints = NEQECH
Number of Continuous Variables, $Y_{ij}(P,R,r)$ = 25 x NAPP
Number of possibly integer variables $t_{e,k}$ = NEQECH.

3.5 Mathematical Formalism of ORLA Model

Inputs to ORLA

$C_i(P,R)$ - total repair and logistics costs associated with component i when used at level P (to fix the end item) and repaired at level R.

$M_j(R,r)$ - total repair and logistics costs associated with module j when used at level R (to fix a component) and repaired at level r.

$DENS_k$ - density of equipment supported by an echelon k supply/repair facility.

$n_j(e)$ - fraction of 1 year's working hours of equipment e required to repair module j for all failures of module. (Per end item).

$N_{ij}(e)$ - fraction of 1 year's working hours of equipment e required to repair component i when module j fails for all failures of that mode. (Per end item).

$N_i(e)$ - fraction of 1 year's working hours of equipment e required for repair of the end item for all failures of component i. (Per end item).

U_k - number of echelon k supply/repair facilities.

C_e - cost of equipment or mos type e.

$FC_i(j)$ - percent of component i failures due to module j.

$FM_j(i)$ - percent of module j failures which occur in its application to component i.

Decision Variables

$t_{e,k}$ - number of equipment e at echelon k (defined as integer for peculiar test equipment/repair skills).

$Y_{ij}(P,R.r)$ - A failure mode is designated by the component (i) and module (j) involved. This variable gives the percent of failures for that mode for which the policy is to repair the end item at echelon P, repair the component at echelon R and repair the module at echelon r. If P is 5, this means component is thrown out. If R is 5 it means the module is thrown out.

Minimize

$$\sum_{e} C_e \sum_{k} U_k \, t_{e,k} +$$

$$\sum_{i} \sum_{j} \sum_{P=1}^{4^*} \sum_{R=P}^{5} \sum_{r=R}^{5} Y_{ij}(P,R,r) \cdot \Big\{ [FC_i(j)] C_i(P,R) +$$

$$[FM_j(i)](M_j(R,r)) \Big\}$$

Subject to:

$$\sum_{P=1}^{4} \sum_{R=P}^{5} \sum_{r=R}^{5} Y_{ij}(P,R,r) = 1 \qquad : \text{"Accountability"}$$

$$\left.\begin{array}{l} DENS_k \sum_{i} \sum_{j} N_{ij}(e) \sum_{P=1}^{k} \sum_{r=k}^{5} Y_{ij}(P,k,r) \\ + DENS_k \sum_{i} \sum_{j} N_i(e) \sum_{R=k}^{5} \sum_{r=R}^{5} Y_{ij}(k,R,r) \\ + DENS_k \sum_{i} \sum_{j} n_j(e) \sum_{P=1}^{k} \sum_{R=P}^{k} Y_{ij}(P,R,k) \end{array}\right\} : \text{"Availability"}$$

$$- t_{ek} \leq 0$$

All Variables ≥ 0

$t_{e,k}$ integer if the equipment is peculiar

Y_{ij} is ≤ 1.

---

*Equations are written for the more general case where end item repair above DSU is allowed (at echelons 3,4).

3.6 MIP Approximation

As mentioned in Section 3.1, the method of computing logistics costs by failure mode using proration is only approximately correct. For example, suppose a component has two failure modes, and that the MIP selects a policy of DSU repair when failure mode 1 occurs and depot repair when failure mode 2 occurs. Let the facts be:

Logistics Costs for component
for 100% DSU repair - $100
for 100% depot repair - $140.

Percent of component failures due to each failure mode
failures due to mode 1 - 60%
failures due to mode 2 - 40%

The total logistics costs for the component as computed in the MIP objective function would be 60% ($100) + 40% ($140).

A more accurate assessment of costs would be obtained by running SESAME with a Maintenance Task Distribution showing 60% DSU repair and 40% depot repair. In fact this would be done in the EVALUATOR. This cannot be done in the MIP FORMULATOR which develops the objective function, because it is only after the MIP is solved that we know what will be done for each failure mode and therefore what the Maintenance Task Distribution should be.

3.7 Relation of Supply Lagrangian to Maintenance Policy

For a given maintenance policy vector (a designation for every component and module in the system of where to replace and repair), a definite relation exists between the SESAME Lagrangian value and the availability achieved (higher value, higher availability); and this relation is developed thru the SESAME multi-echelon stockage decisions. However, before the policy vector is fixed (by the OATMEAL optimization procedure) the relation between a chosen Lagrangian value and an achievable system availability is not necessarily a one to one mapping.

For example a maintenance policy vector P(1) is initially chosen; a Lagrangian value $\lambda_T(1)$ is found that compels enough stockage so that the target availability A_T is achieved. For that $\lambda_T(1)$, the MIP finds a maintenance policy P(2) that minimizes stockage backorder and maintenance costs but achieves an availability A_{P2}. In order to now meet A_T with policy vector P(2) the Lagrangian may have to be raised or lowered to $\lambda_T(2)$. However, now the policy P(2) may no longer be optimal for $\lambda_T(2)$. More about this is detailed in Appendix A.1.

To avoid this potential for looping a method for intelligently choosing an initial Lagrangian is needed, but let's first review the whole Lagrangian concept.

3.8 Initial Lagrangian Selection and Treatment of Operational Availability Constraint

Using the formula for operational availability (OA) in Section 2.6, a constraint on OA may be stated as:

$$\frac{\text{MCTBF}}{\text{MCTBF} + \text{MTR} + \text{MTT} + \text{MLDT}} \geq \text{TARGET}$$

By algebraic manipulation, this is equivalent to:

$$\frac{\text{MCTBF} - (\text{MCTBF})(\text{TARGET})}{\text{TARGET}} \geq \text{MTR} + \text{MTT} + \text{MLDT}$$

The repair level analysis objective may then be stated as:

Minimize Cost

Subject To: $\text{MTR} + \text{MTT} + \text{MLDT} \leq \dfrac{\text{MCTBF} - (\text{MCTBF})(\text{TARGET})}{\text{TARGET}}$

Under the Generalized Lagrangian method, this problem is transformed to an unconstrained optimization with a Lagrangian parameter "λ":

Minimize Cost + (λ) (MTR + MTT + MLDT)

A solution to this problem will have associated with it both a cost, and an achieved OA. Everett's Theorem [2] guarantees that no other solution with equal or higher operational availability can cost less.

Thus, one approach to accommodating the OA constraint is depicted in Figure 3.1: we choose a Lagrangian, solve the transformed problem and adjust the Lagrangian until we find a solution with OA close to our target.

Recall that one set of variables in the MIP objective function are the $C_i(P,R)$. To solve the Lagrangian form of the problem, the end item delay associated with replacing component i at level P and fixing it at level R is multiplied by λ and added to $C_i(P,R)$. Delay will be caused either by component backorders - this value and its impact on MLDT is computed by the SESAME subroutines used in getting the $C_i(P,R)$ - or because P is above ORG, adding to MTT (cf Section 2.6).

The difficulty with the approach as outlined is that it can be time consuming since the whole problem, using MIP, must be resolved each time a new value of λ is tried.

For many applications the user is willing to accept some degree of non-optimality in order to have a tool which is easy to use. We will therefore consider how to avoid looping and still obtain a good answer.

What we would like to do is find a good initial value for "λ". Then once the MIP is run, any discrepancy between achieved and target OA is addressed by modifying stockage policies, while retaining the maintenance policies found in the MIP. The Evaluator is programmed to do this; given the set of maintenance policies found by the MIP, it will always compute stockage based on the target OA; it does not simply reproduce the stockage quantities incorporated in the $C_i(R,P)$ during the MIP formulation.

We would like to determine as accurately as possible, before running the MIP, the relationship between the Lagrangian value used and the resulting OA property of the MIP solution. This relationship depends on where each component is replaced and repaired in the MIP solution.

Most critical is where the component is replaced. This completely determines the contribution of that component to MTT. (Section 2.6). The repair echelon helps determine the contribution of that component to MLDT, but it is not critical to the value of MLDT which will emerge. If a component is repaired at depot rather than DSU, more stockage may be required to cover a longer pipeline, but the contribution to MLDT need not change much. In fact the fill rate for a component at user level in the optimal solution depends "essentially" only on the Lagrangian value, not on where the component is repaired. This is discussed in [3] where sufficient background is given to explain the impact of "essentially."

These observations were incorporated into the method for choosing the initial "λ". A search routine for λ is built into the MIP formulation; it is comparable to the search routine incorporated into the full SESAME supply model which is also designed to find the λ which will give the target OA. The difference is that in SESAME we know in advance the replace and repair echelons for each component. In the MIP formulator we guess that the repair echelon will be the GSU since this is not critical, and determine the replace echelon as part of the search.

The whole process is depicted in Figure 3.2. For each trial λ, stockage is computed using the appropriate subroutines from SESAME, and the resulting contribution of that component to MLDT and MTT is determined by these subroutines. Once all items have been processed the OA can be computed and λ adjusted as necessary. In the MIP formulator each item is processed twice, once assuming the component is replaced at ORG, and once assuming it is replaced at DSU.

How do we know which set of answers to use, those based on the ORG replacement assumption or those based on the the DSU assumption? For each component this is based on the replacement assumption which leads to least cost for that component. Cost is based both on logistical cost, and on a proportional share of potential test equipment cost. For example, in assessing cost given ORG replacememt, we assume all test equipment needed for end item repair is at ORG and allocate cost to the component based on the test equipment throughout it requires as a fraction of total requirements for that test equipment for end item repair.

To summarize, initial λ selection is based on a search routine in the MIP formulator, akin to the search for "λ" in the SESAME supply model. In this search we try to predict the replacement level for each component which will be chosen by the MIP. We will not always be right because our way of handling test equipment costs in the search is not comparable to the way the MIP does it.

Experience with test cases on the λ-search procedure is discussed in Appendix A.2. Appendix A.3 discusses computer costs, and how to proceed in those cases where the user wishes to devote the effort to getting the ideal value for λ as depicted in Figure 3.1.

TREATMENT OF OA CONSTRAINT

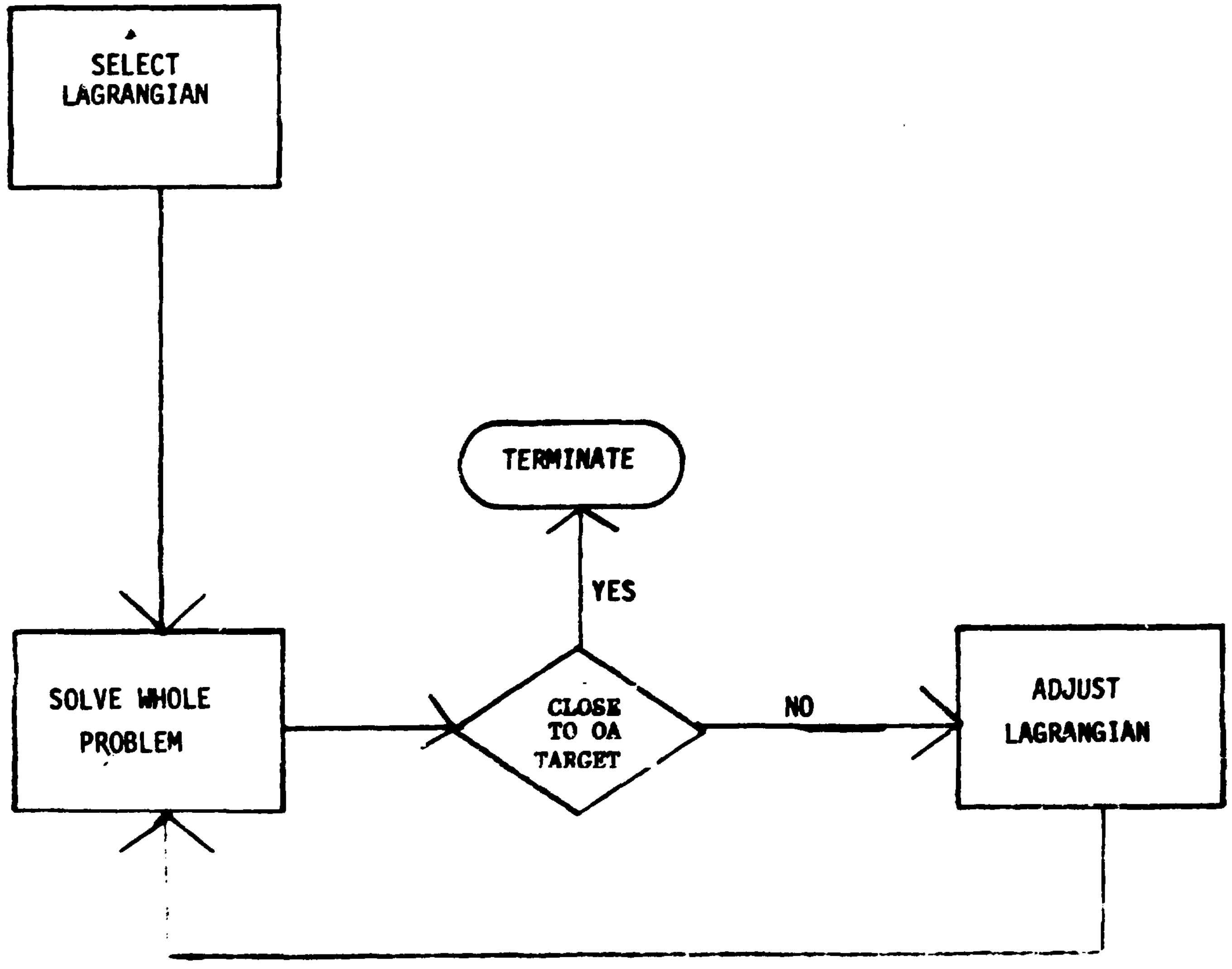
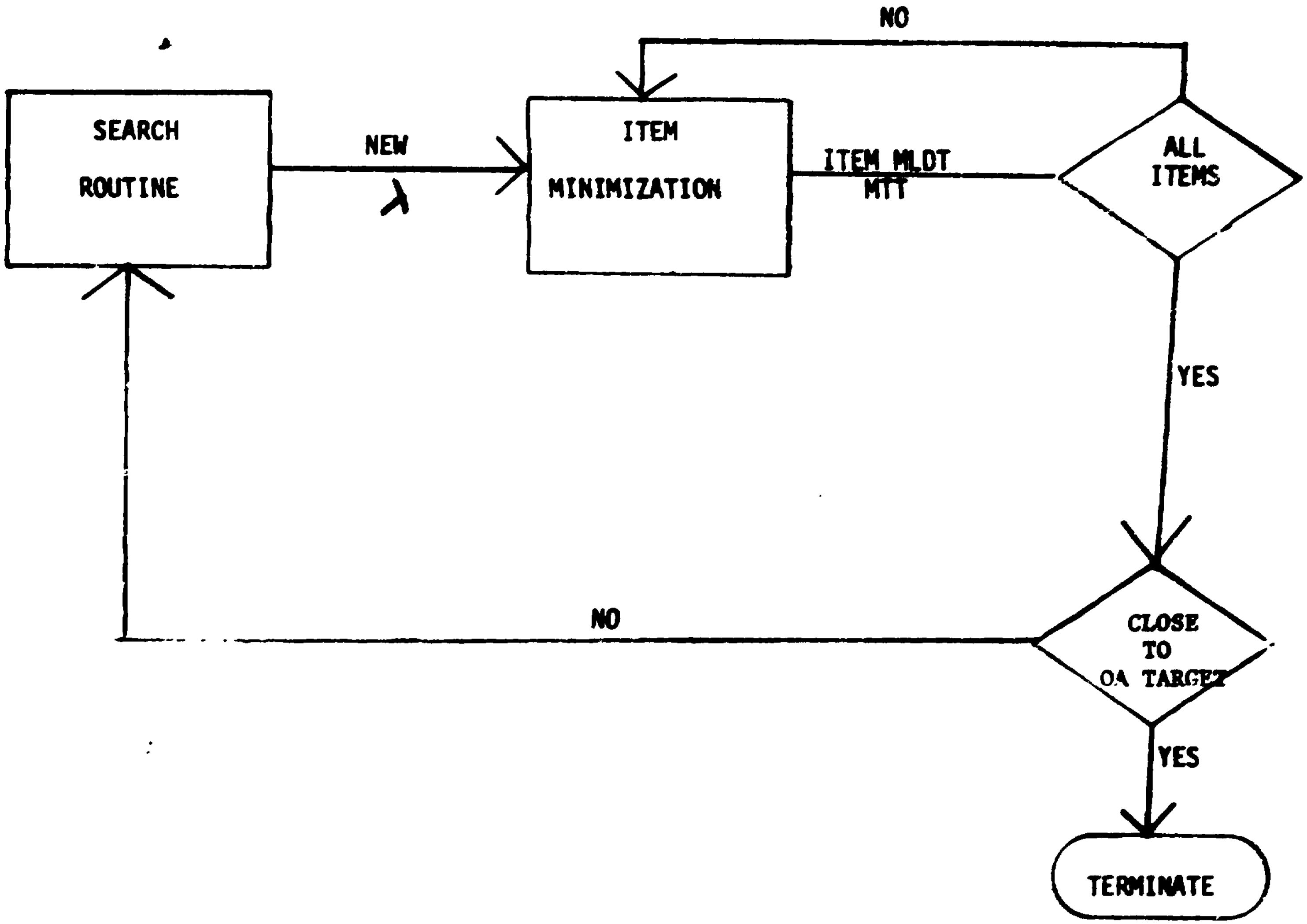


FIGURE 3.1

INITIAL SELECTION



IN SESAME SUPPLY MODEL, LEVEL OF REPAIRS OF END ITEM IS AN INPUT TO SEARCH ROUTINE

IN OATMEAL ITEM MINIMIZATION PROCESS DETERMINES END ITEM LEVEL OF REPAIR

FIGURE 3.2

APPENDIX A.

INPUTS TO OATMEAL

A.1 Cost Parameters and Operational Availability Data

The expressions on the right are as defined in Chapter 2. Numbers in parenthesis indicate the variable is a vector with number of elements as specified.

COSNSN	Item Introduction Cost + PVFAC x Item Maintenance Cost
COSBIN	PVFAC x Bin Cost Rate
COSREQ	PVFAC x Requisition Cost Rate
COSTRA(3)	Transportation Rates*: 1 is DSU to ORG, 2 is GSU to DSU, 3 is Depot to GSU
PVFAC	PVFAC
CHFAC	(1. + HCFAC x PVFAC)
AVTAR	Operational Availability Target; e.g. 0.95
MTR	Mean Time to Repair, in hours
MCTBF	Mean Calendar Time Between Failures, in days
CTDEL	"Contact Team Delay." Time lost when end item repair is not accomplished with ORG level resources, in days.

A.2 Supply System Data

These variables are all as defined in the SESAME User's Guide [10], end item card: CLMNTS(3), OST(4), OPSL(4), SSC, RSC. World wide density is input, and all OUPS are calculated from this and number of claimants (OUPS = density ÷ claimants).

A.3 Maintenance System Data

NEQ	Number of Test Equipments
NLRU	Number of Components, also labelled "LRU's"
NSRU	Numer of Modules, also labelled "SRU's"
NAPP	Number of Failure Modes, also labelled "applications"
ERRATE	Error or false removal rate. If ERRATE is 10%, failure rates are multiplied by 1.1 to get removal rates.
TERAT(4)	Ratio of work week hours for each echelon to hours at echelon 1. Thus TERAT (1) is always 1. This is used in computing requirements for test equipment.

A.4 Policy Constraints

A maintenance policy as it pertains to a given failure mode can be expressed as a triplet, (i,j,k), where i,j and k specify where respectively the end item,

---

*When Supply Structure Option Code is D or N, and there is direct ordering from Depot to DSU, OATMEAL will use max [COSTRA(2), COSTRA(3)]. COSTRA(2) will be applied to retrograde from DSU to GSU.

component, and module are repaired. Since there are only four echelons, a 5 denotes throwaway. Table 4.1 associates a number with each policy triplet.

The user inputs the array IPOL. Only, if IPOL(m), m = 1 to 25 is 1, is policy m a candidate; thus, if IPOL(3) is 0, the policy triplet (1,1,3) is not allowed.

A.5 Test Equipment Data

The following are input for each piece of test equipment:

EQCST(4)	[Purchase Cost + Maintenance Cost x PVFAC] as defined in Section 2.4.
IEQPEC	The equipment is common at all echelons above IEQPEC: If IEQPEC is 0, it is totally common, if IEQPEC is 4, it is totally peculiar.
IEQPLA	The equipment may only be placed at echelon IEQPLA or above.
EQSTK(1000)	Each entry consists of a decimal of the form n.x. "n" is an equipment number. "x" is the fraction of that equipment's annual throughput used per maintenance action. Entries are associated with specific components, modules and applications. If an entry with value 4.01 is associated with a component it means that when that component is used to fix a system, test equipment 4 is needed, and 100 such maintenance actions per year could be handled by equipment 4 if it were devoted exclusively to that type action. If an entry is associated with a module, it refers to maintenance of the module. If an entry is associated with an application, it refers to repair of the component using the module.

A.6 Component and Module Data

UP+	Unit Price x CHFAC
WGT	Weight in Pounds
IESS	Essentiality Code
WASH	Percent of removed items which will washout as unrepairable regardless of policy.
TAT(4)	Shop turn around time in days to fix module or component by echelon.

INDSTK	Last entry in EQSTK (defined above) associated with the item.
NSTACK	Number of entries in EQSTK associated with the item.
PARTSR	Number of new parts per module (0 for component)
PARTSP	Average price of parts
DOC	"One Time Repair Costs," such as manual preparation (documentation) costs. (See Section 2.4.2)
REPC(I)	The "Repair Cost$_i$" (See Section 2.4.2)
NNSN	If 0, item is new to system; fractional value can be used when RN > 1.
ID	Alphanumeric ID
RN	Repetition Number (Used when an "average" component or module represents a number, RN, of components or modules not entered individually).

A.7 Failure Mode Application Data

IDL	Identification number of component to which failure mode pertains. A component or module number is determined by the order in which it is read in; e.g. the 5th component.
IDS	Identification number of module.
FAIL	Number of failures per end item per year.*
TAT(4)	Shop turn around time to fix component if module fails.
NSTACK INDSTK	Reference entries in EQSTK.

A.8 Inputs to SESAME SUBROUTINES of OATMEAL

A.8.1 CURPARs

For components, the Lagrangian is used. (See Sections 3.5 and 3.6). For modules, the price of the component on which it appears is used, or a weighted average if the module appears on more than one component. For parts, the price of the module is used. This is consistent with how part and module backorders are costed out (Section 2.4.9).

A.8.2 WHOFIL and CONDEL

Wholesale stockage is computed for each item, and the expected WHOFIL and CONDEL which will result from this stockage are used for that item in computing retail stockage; thus WHOFIL and CONDEL vary by item and are consistent with the dollar cost of wholesale stockage.

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*When FAIL pertains to average component or module (RN greater than 1), FAIL would be multiplied by RN to get total failures.

Wholesale stockage is based on a reorder quantity of 1. The reorder point is based on a target stock availability computed as:

$$\frac{1}{2}\left(.60 + \frac{\text{CURPAR}}{\text{CURPAR} + \text{UP}}\right)$$

This is an average of .60 and the availability target appropriate at user level. It is consistent with the findings on optimum upper echelon availability targets documented in [3].

A.8.3 TATs and Retrograde

The user inputs shop repair times. Turn around times input to SESAME include retrograde times. It is assumed retrograde times between the echelons equal order and ship times between those echelons. It is also assumed the lower the echelon at which a repairable is removed, the lower the echelon at which it is repaired.

Example:

	ORG	DSU	GSU	WASHOUT
RTD	60%	40%		
MTD		40%	30%	30%

Assumption:

All ORG removals are fixed at DSU (40% of 60%) and GSU (20% of 60%).

DSU removals are fixed at GSU (10% of 40%) and are washed out (30% of 40%).

Finally, in a non-vertical system, where the GSU is repairing items for the DSU stock account, turn around time will include the time to get the good item from GSU to DSU.

The same assumptions, in fact the same computer subroutine, used to get retrograde times are also used to get retrograde costs. Instead of time being assessed for each retrograded item (and added to repair time), a cost is assessed based on the retrograde cost rate.

A.8.4 Replacement Task Distribution and Maintenance Task Distributions (RTD, MTD)

An RTD is a percentage breakout of the replacements of a component or module by echelon; similarly an MTD is a percentage breakout of repair of a component or module by echelon, including the throwaway/washout percent referenced by echelon "5". It is part of the EVALUATOR's job to build the RTD_i, MTD_i of a component i and the RTD_j, MTD_j of a module j from the policy variable values Y_{ij} of the failure modes that pertain to component i or module j.

Remember that,

$Y_{ij}(P,R,r)$ = percent of failures of module j in component i for which policy is to replace i at level P, repair i by replacing j at level R and repair j at level r.

Using these values and the proportion of failures of component i due to module j and the proportion of module j failures that occur in component i, one can build up the percentages, by echelon, of replace and repair associated with P, R and r type decisions for component i and module j. Note that in this procedure one must adjust the module RTD's and MTD's for instances when the next higher assembly component was thrown out.

The aggregation or buildup of task distributions is done by summations over the proper indices. For example, the RTD for component i at echelon k is found by a summation process over j,R,r of instances involving index i, and P = k.

A.9 Promotion of Modules

If the component is repaired at the same echelon as the end item and if there is 100% repair (no washout), it is assumed the component will not be stocked; instead it will be repaired so that the same component remains in the end item. This situation has the following ramifications:

a. Repair time for the component directly degrades operational availability.

b. Backorders of a module used to repair the component lengthen component repair time and so degrade operational availability. The module is "promoted," and must be treated as an LRU.

In the MIP Formulator, when an estimate of CURPAR is derived, the possibility of module promotion is not considered. Otherwise, all ramifications of module promotion are implemented.

APPENDIX B

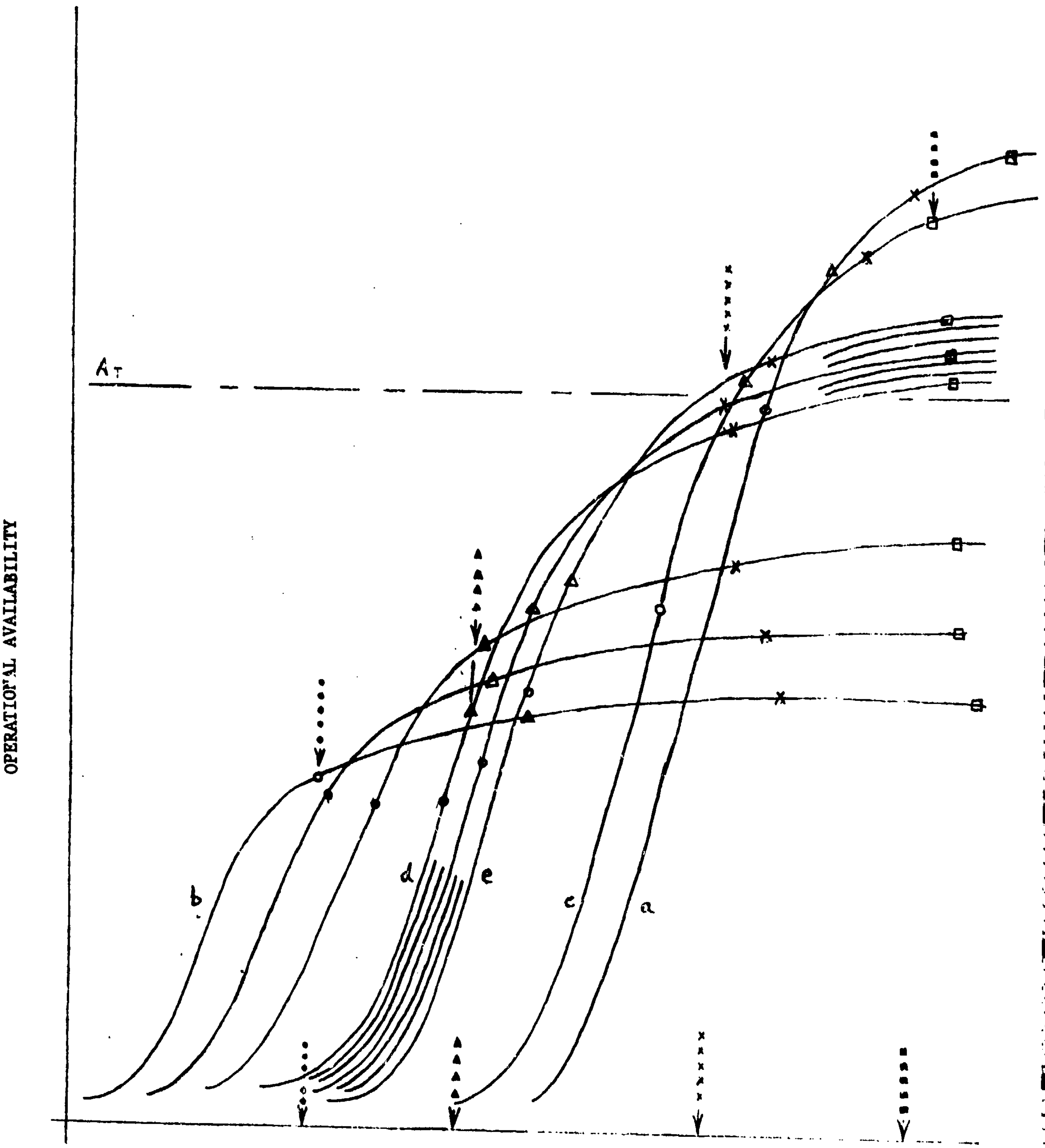
PROPERTIES OF LAGRANGIAN AND MAINTENANCE POLICIES

Relation of Supply Lagrangian to Maintenance Policy

Figure 4 depicts a family of availability vs cost curves. The horizontal axis consists of maintenance, transportation, supply costs - i.e., all those costs in the ORLA model, excluding backorder penalty costs, that would be affected by a particular maintenance posture - and the vertical axis represents the availability achieved as the Lagrangian penalty cost (SESAME curve parameter CURPAR) is varied and stockage costs increased. Each single curve represents one maintenance policy vector - a designation for every LRU and module in the system of where to replace and repair components. The number of combinations of designations could be enormous and the figure depicts this with a partial representation of closely spaced curve spectra. As one moves rightward, the curves represent increased use of fix forward (more parts fixed at lower echelon); repairing at ORG and DSU incurs relatively higher costs even for low availability (more TE, personnel, stockage quantities) but the potential for quick repair response allows higher availabilities to be attainable. Conversely, for curves beginning at the lefthand portion (more and more parts maintained and stocked at higher echelons - GSU, DEPOT) fixed costs are generally lower but availability can be increased (by stocking) only so much due to inherent transport delays of end items or unserviceable assemblies rearward.

The spectral properties of the curves would not be as pure as shown (for clarity); there would be crossing of curves due to transportation and maintenance cost tradeoffs. The figure can be considered a response surface on which one moves to find the best solution - achieving a target system availability while minimizing the total of all costs. The tools for conducting the search are a Lagrangian (tied to a multi-echelon stockage optimizer) to vary stockage quantities and availabilities, and a MIP to find the maintenance policy vector that minimizes costs, including the Lagrangian tied backorder cost. In other words, so that availability is considered in selecting policies, user level component backorders, and delays caused by repair of the end item above user level, are costed out using the Lagrangian and included in logistics costs.

In the discussion that follows, for consistency in the schematic exemplification, its's indicated that the MIP chooses the leftmost curve point for a given Lagrangian value - i.e. that which has minimum cost, excluding backorder costs.



OPERATIONAL AVAILABILITY
A_T
a
b
c
d
e
LOGISTICS COST
(excluding backorder cost)

FIGURE 4

The same argument below would follow if other points were indicated on the figure as the MIP choices.

Suppose a target availability is chosen to be A_T, as shown in the diagram. To find a Lagrangian one can choose an initial policy vector, say curve a representing the most fix forward concept; the choice for the Lagrangian would be o, since this value on curve a yields an availability near A_T. The MIP would then select curve b for the final policy vector (since its o is left most) but evaluation of the performance for that policy of rear repair would show that o or any value higher (△, x, □) could never reach the target availability. If one chose the next most right curve, c, the Lagrangian would be △, and the MIP would home in on curve d for that △ ; then to reach target the penalty parameter would have to be raised during an evaluation to a value between x and □, but at that point the policy is no longer optimal! Similary guessing policy curve d and thereby □, the MIP would settle on curve c, and moving down that curve to around point △ , indicates also that that policy is no longer the optimal one in that region near the target.

It became clear that we needed a procedure for choosing an initial policy or Lagrangian value such that the policy - Lagrangian value was in the neighborhood of the optimum on our response surface. In the figure's example a choice of curve d or curve e, which would lead to a chosen value near x, would then lead to a MIP policy curve that does not necessitate much if any change in the Lagrangian to achieve availability - and hence no need to perturb the final policy vector.

Properties of the Optimal Solution

Although Figure 4 is misleading in terms of generalizing from a pedagogical example, there may be, as indicated by x, , and o points in the region of target levels, several combinations of Lagrangian and policy vector that can lead to the availability at near minimum cost. And in terms of the cost - Lagrangian policy surface, it is probably flat around the optimum, i.e. sub-optimal policies might be quite satisfactory in terms of relative cost savings. So even if our policy-vector found by the procedure 3.6 and Appendix C is not purely robust, it is satisficing. Also we may allow the decision maker to make adjustments to the policy on an individual component basis; the evaluator will have a mode to assess perturbations to our final policy.

APPENDIX C

TEST EXPERIENCE WITH THE "λ" SEARCH

Three real world end items were investigated, an expensive tactical radio with counter-jamming features, a simple radar and a more complex radar. Table C.1 characterizes these end items in terms of number of components, modules, failure modes, and test equipments.

We were interested in how well the heuristic λ selection described in Section 3.6 would work. Our criteria was the cost of the solution found as compared to a solution found by looping, also described in Section 3.6. While doing this work we encountered an unexpected problem with the MIP procedure itself.

A MIP procedure has two objectives - finding an optimum solution, and guaranteeing that the solution found is truly optimum. To save running time, any solution which is guaranteed to be within some percent or dollar value of the best possible solution is usually accepted as optimum. We used a criteria of 0.5%, but also set a maximum on the amount of computer resources a MIP run was allowed to use, about $45.

In the second iteration of the loop procedure for the tactical radio, the MIP could not come up with a guaranteed optimum in the allotted time - in fact all it could guarantee was that the solution found was within 6.67% of optimum. After more than double our normal resource maximum was expended, and the MIP had gone through 306 iterations, no better solution was found. All we learned was that the solution already found was guaranteed to be within 6.48% rather than 6.67% of optimum. An additional MIP run, with a different APEX option (different search procedure) did find a solution which reduced the MIP objective function by 0.7%. In addition to the work reported here, the radio had been previously run a number of times as the MIP FORMULATOR program evolved, without difficulty. A user reports no problems encountered in the analysis of a successor to the tactical radio, albeit one with fewer pieces of test equipment.

The comparison of heuristic and looping solutions are found in Table C.2. Because of the problem with the radio, results were obtained for the radio with an operational availability (OA) target of 95%, as well as for the target of 90%; the additional target gave us another test case to investigate. Only in the case of the complex radar did the looping solution improve on the heuristic, and then only in terms of marginal improvement in availability per dollar.
We would acknowledge that these results may be less a tribute to the power

of the heuristic than to insensitivity of the maintenance policies chosen to the λ used. The λ of $0.01 for the simple radar is not as aberrant as it may seem, since field stockage rules, reflected in the SESAME stockage routines, dictate that certain levels of stockage be calculated regardless of how low λ is.

One other surprising aspect of the results was that in the loop for the complex radar, the λ values kept increasing. Intuitively, we had expected that as we increased the λ upon which the MIP inputs were based, the MIP would choose maintenance policies resulting in fewer backorders, so that the λ required in the EVALUATOR to achieve the OA target would decrease. Under the correct assumptions, this intuition can be buttressed by Lagrangian theory.

Here is what caused the anomaly for the complex radar. One component had a maintenance policy change during the looping process. At the lowest λ, maintenance policy (A) projected more component backorders, but was cheaper (including backorder cost) then the alternative policy (B). The evaluator raised the λ in order for policy A to achieve target availability by reducing the component backorders. At this next higher λ, the MIP chose policy B over A, since, even though policy A had fewer component backorders, its module stockage cost was high.

Finally, the λ had to be further raised in the evaluator to reduce backorders of the now chosen policy B (which, by the way, was a mixed policy; hence the proration scheme in Section 3.4 was used in the MIP). At this last λ (31,059,002), a final pass thru MIP and evaluator stabilized on policy B at a cost of $9,598,000. Note that this .2% increase in cost improved the unavailability by .6% (from .0148 to .0147).

TABLE C.1 EXAMPLE CHARACTERISTICS

EXAMPLE	NUMBER OF COMPONENTS	NUMBER OF MODULES	NUMBER OF FAILURE MODES	NUMBER OF TEST EQUIPMENTS
TACTICAL RADIO	19	61	61	15
SIMPLE RADAR	3	16	16	1
COMPLEX RADAR	11	37	37	5

TABLE C.2 HEURISTIC VS LOOP

CASE	FOR MIP INPUT	FROM EVALUATOR	SOLUTION	
			COST (THOUSANDS)	OA
TACTICAL RADIO	$9474	$7104	$110,011	90.82%
(OA = .90)	$7104	$7104	$110,205	90.82%
TACTICAL RADIO	$45,315	$34,598	$114,014	95.05%
(OA = .95)	$34,598	$34,598	$114,014	95.05%
SIMPLE RADAR	$.01	$4371	$58.9	98.01%
	$4371	$4371	$58.9	98.01%
COMPLEX RADAR	$1,175,743	$17,154,378	$9579	98.52%
	$17,154,378	$31,059,002	$9598	98.53%
	$31,059,002	$31,059,002	$9598	98.53%

APPENDIX D

COMPUTER COSTS AND RUN TIMES

Before discussing run times and costs, we will devote a section to a theoretical principle which avoided combinatorial problems in programming the assessment of maintenance policies over many items.

Principle of Independence in Use of SESAME Subroutine

One principle, that contained in the SESAME optimization process, inherently reduces the run times in the MIP. On the surface one might think that in any one cost evaluation step, specific maintenance policies on each LRU would have to be considered simultaneously in order to assess cost and performance for a specified Lagrangian value; therefore the number of combinations of policies over the LRUs would be enormous.

However, in the SESAME optimization process, given the Lagrangian value, the individual item supply availabilities are "set" based on the items' unit prices relative to this value. Each item (LRU) is optimized independently (multiechelon allocation of stockage quantities) to achieve its target. An item's optimal stockage of course will be dependent on its maintenance policy, but independent of the other items' policies. This principle allows, for a set Lagrangian value, a SESAME subroutine of the ORLA program to compute the optimal stockage costs for an item under some pure maintenance policy (e.g. 100% replacement at some echelon and 100% repair at some echelon) without having to simultaneously consider hybrid combinations of policies across all items. The ORLA "optimizer" uses the results of the SESAME module (stockage costs, backorders by item by pure policies), in conjunction with other logistical costs, to find the best maintenance policy vector across all items for a given Lagrangian.

Experience With Computer Costs

A commercial time sharing service was used for the work reported here. Costs reported are based on priority 02 which guarantees 12 hours response time. Actual response times are most often a few minutes and never exceed a few hours. The costs reflect a substantial volume discount. They do not include an input/output charge as we did not keep an accurate record of these. For the MIP runs, costs include a large surcharge for use of the APEX program; this surcharge is computed as a multiple of usage costs.

The cost of running the MIP FORMULATOR for the radio was about $6.50. Costs for the EVALUATOR were smaller. This was in line with expectations since the SESAME routines which are the heart of these programs run fast.

The range of costs encountered in running MIP for the radio is shown below. There were 97 constraints and 938 variables of which 30 were integer. Of the 30 integer 17 were binary, and the largest upper bound for any integer variable was 62. The different runs varied only in the coefficients of the objective function. The sensitivity of run costs to changes in coefficients has been noted by many other MIP users.

RUN	COST
Heuristic - OA = 90%	$38
Loop - OA = 90%*	$42
Heuristic - OA = 95%	$13
Loop - OA = 95%	$13

Reducing Running Times for the MIP

The logistician often knows a priori that certain solutions would be too costly or would otherwise be unacceptable. He can input this knowledge in two ways: he can specify the lowest echelon at which a piece of test equipment can be placed, or he can rule out certain policies; e.g. no end item repair above user level.

Preliminary analysis may be used to identify upper bounds on echelon test equipment requirements; i.e. the requirement if all repair using that equipment were performed at that echelon. Typically, the bound will be 1, transforming the integer into a binary variable.

This concept can be carried further with some degradation in the optimality of the solution. For each t_{ek}, associate t'_{ek}, where t'_{ek} is continuous and let M be a "large" integer.

Set

$$t'_{ek} \leq (t_{ek}) \times (M)$$

or

$$t'_{ek} \leq \left\{ \sum_{i=1}^{k} t_{ei} \right\} (M)$$

---

*Run stopped because limit on computer costs reached.

In the first case we permit continuous values for test equipment provided they exceed 1. In the second case continuous values less than 1 are permitted if at least 1 test equipment per facility has been deployed at a lower echelon. The rationale is that if we must round up to 1 at a higher echelon, we have not miscalculated too severely since the algorithm already had costed out integer quantities at a lower echelon where there are typically many more facilities. Furthermore, an optimum policy would not tend to purchase test equipment at a higher echelon when all requirements could be met by equipment already purchased for the lower echelon.

Under the simplified formulation we may add the constraint

$$\sum_{k=1}^{4} t_{ek} \leq 1$$

which further speeds the MIP. This is not an equality because of the possibility of component or module discard in which case the equipment is not needed at all.

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