CECOM-TR-91-6
June 1991

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ACHIEVING A SYSTEM OPERATIONAL AVAILABILITY REQUIREMENT (ASOAR) MODEL METHODOLOGY

Bernard C. Price

SYSTEMS ANALYSIS DIVISION

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SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form OMB 0704-0188

1a. REPORT SECURITY CLASSIFICATION: Unclassified

1b. RESTRICTIVE MARKINGS:

2a. SECURITY CLASSIFICATION AUTHORITY:

2b. DECLASSIFICATION/DOWNGRADING SCHEDULE:

3. DISTRIBUTION/AVAILABILITY OF REPORT: Approved for public release; distribution is unlimited

4. PERFORMING ORGANIZATION REPORT NUMBER(S): CECOM-TR-92-6

5. MONITORING ORGANIZATION REPORT NUMBER(S):

6a. NAME OF PERFORMING ORGANIZATION: US Army Communications-Electronics Program Analysis & Evaluation

6b. OFFICE SYMBOL (If applicable): AMSEL-PE-SA

7a. NAME OF MONITORING ORGANIZATION:

6c. ADDRESS (City, State, and ZIP Code): US Army Communications-Electronics Command, Program Analysis & Evaluation Directorate, ATTN: AMSEL-PE-SA, Ft. Monmouth, NJ 07703

7b. ADDRESS (City, State, and ZIP Code):

8a. NAME OF FUNDING/SPONSORING ORGANIZATION:

8b. OFFICE SYMBOL (If applicable):

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER:

8c. ADDRESS (City, State, and ZIP Code):

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO.

11. TITLE (Include Security Classification): Achieving a System Operational Availability Requirement Model Methodology

12. PERSONAL AUTHOR(S): BERNARD C. PRICE

13a. TYPE OF REPORT: Technical Report

13b. TIME COVERED: FROM ______ TO ______

14. DATE OF REPORT (Year, Month, Day): June 1991

15. PAGE COUNT: 56

16. SUPPLEMENTARY NOTATION:

17. COSATI CODES

FIELD	GROUP	SUB-GROUP

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number): Macro-Level RAM Analysis, Early-on LSA, Operational Availability

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

The Achieving a System Operational Availability Requirement (ASOAR) model is a macro-analysis tool. It is basically used for an early-on Logistics Support Analysis (LSA) and macro-level Reliability, Availability and Maintainability (RAM) analysis. ASOAR can determine whether a weapon system operational availability (Ao) requirement is attainable. If attainable, ASOAR estimates optimal end item operational availabilities from the system requirement. This paper describes the methodology applied in the ASOAR model Version 3.0 and a discussion of model verification.

As an early-on LSA tool, ASOAR requires only system and end item level input data, not Line Replaceable Unit (LRU) input data. ASOAR usage provides concepts for major logistics support savings in attaining a system operational availability requirement. It outputs cost effective logistics downtimes and LRU order fill rates at the most forward level of supply support for each end item and the system. It also outputs optimal end

20. DISTRIBUTION/AVAILABILITY OF ABSTRACT: [X] UNCLASSIFIED/UNLIMITED [ ] SAME AS RPT [ ] DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION: Unclassified

22a. NAME OF RESPONSIBLE INDIVIDUAL: BERNARD C. PRICE

22b. TELEPHONE (Include Area Code): 908-532-8752

22c. OFFICE SYMBOL: AMSEL-PE-SA

DD Form 1473, JUN 86 — *Previous editions are obsolete.* — SECURITY CLASSIFICATION OF THIS PAGE

19. ABSTRACT (Continued)

item Ao goals usable as the Ao input to an end item sparing to availability model or an end item maintenance concept optimization model.

As a macro-level RAM analysis tool, ASOAR can aid in the selection of a system Ao requirement. The cost effective logistics downtime outputs in achieving Ao goals can improve RAM Rational analyses. It can output the effective system reliability and maintainability based on the weapon system reliability block diagram configuration design. ASOAR also outputs the effective reliability of redundant end item configurations relative to attaining its cost effective end item Ao.

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ABSTRACT

The paper describes the methodology applied in the Achieving a System Operational Availability Requirement (ASOAR) model. The purpose of the ASOAR model methodology is to cost effectively prorate a system Operational Availability (A_o) requirement to end item A_o goals. In addition, it determines the degree of supportability necessary to achieve each A_o goal. The effective reliability and maintainability of the system and effective reliability of redundant configurations are also determined.

ACKNOWLEDGMENTS

The following individuals have been responsible for developing the ASOAR model from the methodology contained within this paper. I wish to express my gratitude to Jesse Williams, Gerald Gerstel, and Anthony DiGregorio for their dedication to develop and test a computer program usable by others for attaining system A_o requirements optimally. Their testing of the ASOAR model yielded some methodology refinements not previously considered when the methodology was first developed and published. I also wish to thank U.S. Army Major James Drake for reviewing the methodology which led to an important correction.

INTRODUCTION

The ASOAR methodology and model was developed to provide the Department of Defense (DoD) with a tool that would be instrumental in determining optimum weapon system secondary item inventories that meets the explicit weapon system A_o objectives. ASOAR cost effectively prorates end item A_o requirements from the system requirement. End items are the primary items procured by or furnished to the system developer to make the weapon system.

Sparing optimization models that spare optimally to availability already exist. However, these models minimally require data that describes attributes of the Line Replace Units (LRUs) comprising the end item being modeled. LRUs are those secondary items spared forward to restore an end item. However, since systems typically contain many end items, system LRU data is generated from many sources and therefore obtained fragmentarily at best. Since ASOAR establishes optimal end item availability requirements from the system A_o requirement, a sparing optimization model can then be used anytime after an end items's LRU data becomes available to optimally provision LRU spares to achieve the ASOAR derived end item availability requirement.

The methodology of the ASOAR model can also be used to analyze the system design reliability configuration of end items relative to achieving the A_o requirement. If critical, essential end items are configured serially, restoring the failed end item from a down condition restores the weapon system to an up condition. If critical, essential end items are configured redundantly, a failure to the redundant end item may not cause the system to go down if another available end item can appropriately perform the function. ASOAR will compute the effective reliability of redundant end item configurations based on downtimes necessary to attain the end item availability goal. The effective system reliability and maintainability are also determined from the system configuration of end items.

The ASOAR model is a macro-analysis tool whose methodology mainly requires just system and end item level input data. This permits the ASOAR model to be the earliest on Reliability, Availability and Maintainability (RAM) analysis tool available. Detailed LRU data is not needed to compute the cost effective end item A_o goals.

The basic methodology for computing the cost effective end item A_o from the system requirement starts with a system configured with end items in series and system restoral accomplished by removing and replacing LRUs at the operating level. Computational adjustments to the basic methodology will be necessary when the system is not comprised of different end items serially configured, is not always restored by LRUs placed at the operating level, or has scheduled maintenance.

A. BASIC MATHEMATICAL THEORY DERIVING OPTIMAL END ITEM AVAILABILITY GOALS.

For a system configured with end items in series and having system restoral accomplished by removing and replacing LRUs at the operating level, eight basic equations will be needed to compute estimated optimal A_o goals for each end item. As the methodology and explanation develops in the text, these basic equations will be highlighted with numbers. Supporting equations used for derivation to enhance understanding will be noted with letters.

The methodology starts with the determination of the system Mean Calendar Time Between Failure (MCTBF). MCTBF is the reciprocal of the calendar time failure rate of an item. Since failure rates of all critical end items in a series configuration can be summed to yield the system failure rate, the system MCTBF can be similarly determined applying basic Equation 1.

$$\frac{1}{MCTBF_{system}} = \frac{1}{MCTBF_1} + \frac{1}{MCTBF_2} + \ldots + \frac{1}{MCTBF_n} \qquad (1)$$

The reliability requirement of each end item comprising the system can usually be found in the Reliability section of each end item's equipment specification. Since the reliability requirement is generally expressed in terms of Mean Time Between

Failure (MTBF) or operating time per failure, a conversion accounting for planned system operating tempos is necessary to express reliability in terms of MCTBF.

The methodology also determines the system Mean Time to Restore (MTR). An MTR represents the average amount of time an item would be down if spares were always on-hand to restore the item to an operable condition. The system MTR depends on each end item's relative contribution to system failure and their associated restoral time. For serially configured end items, the weighted average of each end item's failure frequency which causes the system to fail multiplied by their respective MTR determines the system MTR. This is basic Equation 2.

$$MTR_{system} = \frac{MCTBF_{system}}{MCTBF_1} \times MTR_1 + \ldots + \frac{MCTBF_{system}}{MCTBF_n} \times MTR_n \qquad (2)$$

The maintainability requirement of each end item comprising the system can usually be found in the Maintainability section of each end item's equipment specification. The maintainability requirement is expressed in terms of Mean Time To Repair (MTTR) which is the restoral time in an ideal support environment. Additional restoral time is necessary for converting to an MTR to account for delayed restoral time in obtaining on-hand spares from storage, not always having appropriately skilled personnel available, lack of complete and correctly written technical manuals, and not always having functioning tools and test equipment available.

An A_o requirement is an expression of the user's need. A_o represents the probability that an equipment will be in an operable or committable condition at any random point in time. A_o is measured as the total calendar time that the equipment is in an up condition divided by the total calendar time being measured. Uptime represents the time that the equipment is operable or capable of operating if were to be used. The calendar time that the equipment is not in uptime is considered downtime Equipment A_o is expressed by derivational Equation A.

$$A_o = \frac{\text{Uptime}}{\text{Uptime} + \text{Downtime}} \qquad \text{(A)}$$

A_o is mathematically equivalent to the amount of uptime per equipment failure divided by the sum of the amount of uptime per equipment failure plus the amount of downtime per equipment failure. Therefore, Equation B is mathematically equivalent to Equation A.

$$A_o = \frac{\text{Uptime/Failure}}{\text{Uptime/Failure} + \text{Downtime/Failure}} \qquad \text{(B)}$$

The required A_o of a system can often be found in a requirements document such as Required Operational Capability (ROC) documentation. The system A_o approximates the operational readiness expected of a weapon system. The amount of uptime per system failure is the system MCTBF. The amount of downtime per system failure is the system MTR and the Mean Logistics Downtime (MLDT) of the system. MTR represents the downtime related to always having the appropriate spares on-hand to restore the equipment to an operable or committable condition. MLDT represent the additional downtime accrued per failure due to not always having appropriate LRU spares forward at the operating level when the equipment fails. The required system A_o expressed by Equation C is mathematically equivalent to Equation B.

$$A_{o\ system} = \frac{MCTBF_{system}}{MCTBF_{system} + MTR_{system} + MLDT_{system}} \qquad (C)$$

Analogous to Equation 2, the MLDT of a system comprised of serially configured end items depends on the weighted average of each end item's failure frequency which causes the system to fail multiplied by their respective MLDT. The logistics support implications and determination of MLDT will be further explained in another section of this paper.

$$MLDT_{system} = \frac{MCTBF_{system}}{MCTBF_1} \times MLDT_1 + \ldots + \frac{MCTBF_{system}}{MCTBF_n} \times MLDT_n \qquad (D)$$

Since the system A_o, MCTBF and MTR expressions are essentially specified, the system target MLDT ($MLDT_{target}$) can be determined by transposing Equation C. This becomes basic Equation 3.

$$MLDT_{target} = \frac{(1-A_{o\ system}) \times MCTBF_{system} - A_{o\ system} \times MTR_{system}}{A_{o\ system}} \quad (3)$$

The system target MLDT specifies the average amount of calendar time permissible per failure to lack spares and still meet the system A_o requirement. If the target MLDT is a negative number, the system A_o requirement is not achievable.

When applying a sparing optimization model, computations determining the quantity and placement of LRU spares leads to the largest amount of availability gain per unit cost of sparing. Conversely, since increasing availability reduces downtime, optimizing the quantity and placement of spares leads to the largest reduction of MLDT for the least amount of sparing cost. The cost to failure rate ratio of an LRU is a key parameter which can aid in approximately determining the selection of LRUs for sparing forward. When reducing MLDT with a sparing optimization model, LRUs within a higher indentured item are compared relative to each other to determine the selection of those LRU spares with the lesser cost per failure rate ratio.

A simple example may better illustrate this point. Suppose an end item consisting of LRU 1 and LRU 2 are in a series configuration without spares of either item. Suppose the MLDT per failure of each LRU are approximately the same. LRU 2 costs twenty times more than LRU 1 and LRU 2 has twice the failure factor of LRU 1. Due to twice the failure frequency and equal downtime per failure, LRU 2 causes twice as much downtime when neither are spared. A spare of LRU 2 would be twice as effective in reducing MLDT, but costs twenty times more than a spare of LRU 1. Impacting only half as much downtime with twenty times less cost (1/2 x 20 = 10), the first spare of LRU 1 costs ten times less per unit reduction of MLDT making LRU 1 the more cost effective choice to spare.

Applying the logic cited in the above example, the MLDT of LRU 2 would have to be ten times greater than LRU 1 to make LRU 2 as cost effective to spare. The comparative LRU cost to failure rate ratios approximates the relative amount of MLDT that must be proportionately reduced to equalize their cost effectiveness for sparing forward.

$$\frac{\text{Cost } LRU_1/\text{FR } LRU_1}{\text{Cost } LRU_2/\text{FR } LRU_2} \approx \frac{\text{MLDT } LRU_1}{\text{MLDT } LRU_2} \qquad \frac{1/1}{20/2} = \frac{1}{10} \qquad \text{(E)}$$

This implies that the greater the LRU cost to failure rate ratio is, the less likely the LRU will be spared. Less sparing yields more MLDT and less A_o. Transposing Equation E and generalizing for all LRUs within the end item yields Equation F.

$$\frac{\text{MLDT LRU}_1}{\text{Cost LRU}_1/\text{FR LRU}_1} \simeq \cdots \simeq \frac{\text{MLDT LRU}_x}{\text{Cost LRU}_x/\text{FR LRU}_x} \simeq \cdots \simeq \frac{\text{MLDT LRU}_n}{\text{Cost LRU}_n/\text{FR LRU}_n} \qquad \text{(F)}$$

For a system with end items serially configured, it becomes important to estimate the average LRU cost (Cost LRU) and average LRU failure rate (FR LRU) of the significant failure rate LRUs in each end item. Since insignificant failure rate LRUs will impact A_o less and very high cost assemblies with insignificant failure rates are unlikely to have their LRUs stocked forward, counting these assemblies can skew the average LRU cost to failure rate ratio estimate to be higher than necessary. Therefore, the estimated average LRU cost in an end item is approximately the estimated cost of the end item minus the estimated costs for high cost assemblies with relatively insignificant failure rates (Cost) divided by the number of significant failure rate LRUs in the end item (No. LRU).

$$\text{Cost LRU}_x \simeq \frac{\text{Cost}_x}{\text{No. LRU}_x} \qquad \text{(G)}$$

The average significant LRU failure rate in an end item can also be estimated by dividing the end item's failure rate by the number of significant failure rate LRUs in the end item.

$$FR\ LRU_x \simeq \frac{1}{MCTBF_x} / No.\ LRU_x = \frac{1}{MCTBF_x \times No.\ LRU_x} \quad (H)$$

The average cost to failure rate ratio of LRUs in an end item can be derived by dividing Equation G by Equation H.

$$\frac{Cost\ LRU_x}{FR\ LRU_x} \approx \frac{Cost_x}{No.\ LRU_x} \times MCTBF_x \times No.\ LRU_x = Cost_x \times MCTBF_x \quad (I)$$

The average LRU cost to failure rate ratio in an end item is simply the product of the end item's cost minus the total cost of high cost assemblies with relatively insignificant failure rates and the end item's MCTBF. Notice that the number of LRUs in the end item conveniently drops out which precludes the necessity to gather this depth of data. However, data for estimated costs of high cost, relatively insignificant failure rate assemblies should still be obtained for determining a more accurate LRU forward sparing optimization. This is the only data needed below the end item indenture level.

When optimizing sparing to a weapon system instead of an end item, the same cost effectiveness principles to approximating forward sparing still applies. However, the average end item LRU cost to failure rate ratio and the MLDT of each end item serially comprising the system are used. Analogous to Equation F and substituting Equation I, Equation J shows that each end item's average LRU cost to failure rate ratio proportionally approximates the relative amount of each end item's MLDT that must be reduced to equalize the cost effectiveness of their LRUs spared forward.

$$\frac{MLDT_1}{Cost_1 \times MCTBF_1} \approx \cdots \approx \frac{MLDT_x}{Cost_x \times MCTBF_x} \approx \cdots \approx \frac{MLDT_n}{Cost_n \times MCTBF_n} \qquad (J)$$

With Equation J, the MLDT of each end item can be expressed in terms of the MLDT of a specific end item.

$$MLDT_1 \approx \frac{Cost_1 \times MCTBF_1 \times MLDT_x}{Cost_x \times MCTBF_x}$$

$$MLDT_n \approx \frac{Cost_n \times MCTBF_n \times MLDT_x}{Cost_x \times MCTBF_x} \qquad (K)$$

Substituting Equation K into Equation D, the system's MLDT can be expressed in terms of the MLDT of a specific end item.

$$MLDT_{system} \approx \frac{MCTBF_{system}}{MCTBF_1} \times \frac{Cost_1 \times MCTBF_1 \times MLDT_x}{Cost_x \times MCTBF_x} + \ldots +$$

$$\frac{MCTBF_{system}}{MCTBF_n} \times \frac{Cost_n \times MCTBF_n \times MLDT_x}{Cost_x \times MCTBF_x} \qquad (L)$$

Cancelling appropriate end item MCTBFs in Equation L and using the distributive property of mathematics, terms can be factored out of each expression to yield Equation M.

$$MLDT_{system} \approx MLDT_x \times \frac{MCTBF_{system}}{MCTBF_x} \times \frac{(Cost_1 + \ldots + Cost_n)}{Cost_x} \qquad (M)$$

Letting the system cost represent the sum of the cost of each different critical end item in the system less the total cost of high cost assemblies with relatively insignificant failure rates, the system cost for cost effective LRU forward sparing is expressed below:

$$Cost_{system} = Cost_1 + \ldots + Cost_n \qquad (N)$$

Substituting Equation N into Equation M and transposing, the cost effective target MLDT of each end item can be solved. The result approximates the cost effective MLDT of an end item to be equal to the system target MLDT times the end item's average LRU cost to failure rate ratio divided by the average LRU cost to failure rate ratio of the system. This is basic Equation 4.

$$MLDT_x \approx \frac{MLDT_{target} \times MCTBF_x \times Cost_x}{MCTBF_{system} \times Cost_{system}} \qquad (4)$$

Applying a simple example similar to the example previously used, Equation 4 can be verified. Suppose a system is composed of two end items in a series configuration. The cost of End Item 2 minus the total cost of its relatively high cost, very low failure rate assemblies is twenty times greater than End Item 1 and End Item 2 has twice the failure rate of End Item 1.

$Cost_1 = 1 \qquad Failure\ Rate_1 = 1 \qquad MCTBF_1 = 1$

$Cost_2 = 20 \qquad Failure\ Rate_2 = 2 \qquad MCTBF_2 = 1/2$

$Cost_{sys} = 21 \qquad Failure\ Rate_{sys} = 3 \qquad MCTBF_{sys} = 1/3$

$$MLDT_1 \approx \frac{MLDT_{target} \times 1 \times 1}{1/3 \times 21} = \frac{MLDT_{target}}{7}$$

$$MLDT_2 \approx \frac{MLDT_{target} \times 1/2 \times 20}{1/3 \times 21} = \frac{10 \times MLDT_{target}}{7}$$

This example as with the previous example verifies that the target MLDT of End Item 1 is approximately a tenth of the target MLDT of End Item 2 to equalize their cost effectiveness for sparing forward. The smaller end item MLDT relates to more forward sparing and a higher A_o goal desired for the end item.

After computing the cost effective target MLDT of each end item, the initial estimated optimal A_o goal of each end item in the system can be solved applying basic Equation 5.

$$A_{ox}\ est \approx \frac{MCTBF_x}{MCTBF_x + MTR_x + MLDT_x} \qquad (5)$$

The creation and testing of the ASOAR model to produce results similar to the Army's standard sparing optimization model yielded a refinement to this basic methodology. When serially configured end items within the system are failure independent, the multiplication of the end item availabilities computes the system A_o. After the initial estimated A_o of each end item are determined, these end item availabilities are multiplied together to yield the estimated system A_o as shown in Equation 6.

$$\prod_{x=1}^{n} A_{ox} \text{ est} = A_o \text{ system est} \tag{6}$$

The estimated system A_o is then compared to the system A_o requirement. If the absolute value difference shown by Equation 7 is very small and within the value of some specified tolerance, the approximately optimal end item A_o goals have been determined.

$$| A_o \text{ system} - A_o \text{ system est} | \leq \text{tolerance ?} \tag{7}$$

If the absolute value difference is not within the tolerance value, the MLDT of each end item in Equation 5 needs to be multiplied by the same constant adjustment factor for the product of their A_o to be very close to the weapon system A_o requirement. The adjustment factor value is determined from the ratio of the system target MLDT of Equation 3 to a new estimated system MLDT. MLDT system est is found by substituting the estimated system A_o of Equation 6 into Equation 3. The adjusted MLDT of each end item is computed by Equation 8.

$$\text{Adjusted MLDT}_x = \frac{\text{MLDT}_{target}}{\text{MLDT}_{system\ est}} \times \text{MLDT}_x \tag{8}$$

Applying the adjusted MLDT of each end item into Equation 5 yields the new estimated A_o goals of each end item in the system. The product of the new estimated end item availabilities will be much closer to the system A_o requirement. Should their absolute difference still not be within the tolerance value, the ASOAR model will continue to iterate adjustments using Equations 5 through 8 until the approximately optimal end item A_o goals are determined.

B. RELATIONSHIPS OF LOGISTICS SUPPORT TO THE REQUIRED OPERATIONAL AVAILABILITY (A_o).

Two additional basic equations will be used to relate logistics support to the A_o requirement. As shown by Equation C, the A_o of a system is dependent on its designed reliability and maintainability and the logistics associated to supporting the system. The system target MLDT to achieve the system's A_o requirement is determined by Equation 3. The system target MLDT specifies the average amount of calendar time permissible per failure to lack spares forward and still meet the A_o requirement. The system A_o requirement is not attainable if the system target MLDT turns out to be a negative number.

If an LRU spare is on-hand to restore a failure, no logistics downtime is accrued. However, if the appropriate LRU spare is not available to restore a failure, the logistics downtime accrued is the time for the forward support level to obtain this spare. The percentage of time the appropriate LRU is in operating level stock to restore a failed end item is the order fill rate ($FILL_1$). MLDT can be estimated by multiplying the probability of not filling an order from operating level stock ($1-FILL_1$) times the operating level's Mean Time to Obtain ($MTTO_1$) LRU spares. This is shown by Equation O.

$$MLDT_1 = FILL_1 \times 0 + (1-FILL_1) \times MTTO_1$$

$$MLDT_1 = (1-FILL_1) \times MTTO_1 \quad (0)$$

Order fill rates at support levels which are not the most forward level supply is best viewed as Stock Availability (SA). SA represents the percentage of demands for LRUs that can be filled by stock stored at the support level. SA at the most forward level of supply is typically inappropriate unless every demand for an LRU is used to restore the system from a down condition. Order fill rates of the appropriate LRUs used to restore the equipment to an up condition is most pertinent at the forward level of supply support.

The mean time to obtain LRU spares can either be inputted into the ASOAR model or computed by ASOAR. If inputted, MTTO is often estimated as the order and ship time to receive LRUs stored at the next higher level of supply plus some additional mean delay time for that level of support's time to obtain spares from maintenance or resupply because its stock availability is also not 100%. If $MTTO_1$ is computed, Equation 9 is used by ASOAR.

$$
\begin{aligned}
MTTO_1 = {} & PCTREP_1 \times RCT_1 + (1-PCTREP_1) \times OST_2 \\
& + PCTREP_2 \times RCT_2 \times (1-SA_2) \times (1-PCTREP_1) \\
& + [1-(PCTREP_1 + PCTREP_2)] \times (1-SA_2) \times OST_3 \\
& + PCTREP_3 \times RCT_3 \times (1-SA_2) \times (1-SA_3) \\
& \quad \times [1-(PCTREP_1 + PCTREP_2)] \\
& + (PCTREP_4 + PCTNREP) \times (1-SA_2) \times (1-SA_3) \times OST_4 \\
& + PCTREP_4 \times RCT_4 \times (1-SA_2) \times (1-SA_3) \times (1-SA_4) \\
& \quad \times (PCTREP_4 + PCTNREP) \\
& + PCTNREP \times (1-SA_2) \times (1-SA_3) \times (1-SA_4) \times BOMTTO \qquad (9)
\end{aligned}
$$

The numbered subscripts in Equation 9 represents the support levels for supply or maintenance. The following support levels are represented by the numbered subscripts.

1 = Operating or Organizational (ORG) Level or Most Forward Level of Support

2 = Direct Support (DS) Level

3 = General Support (GS) Level

4 = Depot, Contractor, or Wholesale Support Level

The following defines the variables used to compute the operating level's mean time to obtain a spare.

RCT = Average Repair Cycle Time at # support level

PCTREP = Percentage of LRUs Repaired and returned to stock at # support level

PCTNREP = Percentage of LRUs Not Repaired or returned to stock

SA = Average LRU Stock Availability at # support level

OST = Average Order and Ship Time from # support level to the next lower support level

BOMTTO = Wholesale support level's Mean Time to Obtain a Back Order

The percentage of LRUs repaired and returned to stock at each support level represents the mean Maintenance Task Distribution (MTD) of the equipment's LRUs. The percent of LRUs discarded or not repaired and returned to stock plus the MTD percent at each support level adds up to 100%. This special condition shown by Equation P is forced to be heeded when inputting to the ASOAR model.

$$\sum_{s=1}^{4} PCTREP_s + PCTNREP = 1 \qquad (P)$$

For four levels of support, inputs to all the variables in Equation 9 are needed to compute the MTTO of the most forward level of supply support. When support conditions with less than four levels of support applies, the ASOAR model automatically sets appropriate variable values to zero and does not request their input. The following is a summary of inputs impacted by the support conditions.

1. For 4 Level Support, all inputs are needed.
2. For no GS, $SA_3 = OST_3 = PCTREP_3 = RCT_3 = 0$.
3. For no DS, $SA_2 = OST_2 = PCTREP_2 = RCT_2 = 0$.
4. For no DS and GS, the inputs of conditions 2 and 3 are 0.
5. For no ORG, $PCTREP_1 = RCT_1 = SA_2 = OST_2 = 0$.
6. For no ORG and GS, the inputs of conditions 2 and 5 are 0.
7. For no ORG and DS, $PCTREP_1 = RCT_1 = SA_2 = OST_2 = PCTREP_2 = RCT_2 = SA_3 = OST_3 = 0$.

As previously discussed, the mean time to obtain LRU spares can either be inputted into the ASOAR model directly as an estimate or computed by the model from other logistic support inputs. Since the target MLDT is computed by Equation 3 and $MTTO_1$ is estimated or computed, Equation 0 can be transposed to determine the equipment's target order fill rate. This is shown as Equation 10.

$$FILL_{target} = 1 - \frac{MLDT_{target}}{MTTO_1} \qquad (10)$$

The system target order fill rate defines the percentage of time that the appropriate LRU must be spared at the operating level to restore the system when it fails. The higher the target order fill rate, the more expensive secondary item inventories must be to achieve the weapon system A_o requirement.

For the case where a system is configured with end items in series, Equation 10 also computes the target order fill rates of each end item. The target MLDT of each end item can be determined by substituting the end item's MCTBF, MTR and optimal A_o goal previously computed into Equation 3. Each end item order fill rate computed by the ASOAR model defines the percentage of time that the appropriate LRU must be spared at the most forward level of support to restore that particular end item when it caused the system to fail.

C. HANDLING OTHER EQUIPMENT CONFIGURATIONS OR SUPPORT POSSIBILITIES.

Computational adjustments will sometimes be necessary prior to applying the basic equations derived for prorating a system A_o requirement to approximate optimal end item A_o goals. If the system is comprised of some similar end items, restored by spares placed at a centralized forward location, or is supported with periodic maintenance; computational adjustments become necessary to achieve accurate results. The special equations and computational adjustments in this section are used to estimate an equivalent baseline. These special equations or adjustments will be noted with the special case number followed by a letter.

Ten special cases of other configurations or support possibilities causing computational adjustments will be presented. Cases 1 through 4 covers equipment configuration adjustments which adjusts an end item network configuration to an equivalent MCTBF. Cases 5 and 6 covers periodic maintenance adjustments which translates maintenance downtime to an equivalent A_o adjustment. Cases 7 through 10 covers centralized forward support adjustments which adjusts the forward support of multiple systems to an equivalent system. The following is the listing of the ten special cases.

1. Common End Items
2. Hot Standby Redundant End Items
3. Cold Standby Redundant End Items or End Item Spares at Operating Level
4. Degradational Redundancy or Capacity Availability
5. System Scheduled Maintenance Downtime or Preventive Maintenance
6. End Items Scheduled Maintenance Downtime or Preventive Maintenance
7. Multiple Systems Restored with LRU Spares at Operating Level
8. Systems Restored with LRU Spares at DS
9. Systems Restored with End Item and LRU Spares at DS
10. Systems Restored with End Item Spares at DS and LRU Spares Stocked Forward at GS

CASE 1: COMMON END ITEMS.

This case implies that there are R similar end items and all of them must be operational for the system to be in an up state. A characteristic of design standardization is to utilize common items to perform similar functions. One benefit from standardization is the economy of using a spare LRU to restore any of the common end items and hence restore the system. The cost of a spare does not change, but the probability that the spare will be used increases when it supports more than one end item. To handle the adjustment for standardization, the R common end items are combined to represent one end item. This equivalent end item will have the adjusted MCTBF shown in Equation 1A, but its equivalent cost remains the cost of just one end item.

$$\text{Adjusted } MCTBF_{x} = MCTBF_{x}/R \qquad (1A)$$

CASE 2: HOT STANDBY REDUNDANT END ITEMS.

This case implies that at least R out of N similar end items must be operational to consider the system as being in an up state. With hot standby redundancy, a maximum of N end items are operating at the same time. Computations for determining optimal end item A_o goals requires the redundant network of like end items be combined to represent one end item. This one end item will have its equivalent cost remain as $Cost_x$, but its equivalent MCTBF is very complex and dependent on the Mean Downtime (MDT) per failure of the end item.

MDT is equal to the end item's MTR plus its MLDT. The MDT of an end item can be computed using Equation 2A.

$$MDT_x \approx MTR_x + (1-FILL_{1x}) \times MTTO_{1x} \quad (2A)$$

The order fill rate of LRU spares and the mean time to obtain spares at the operating level typically drive the end item's MDT. Since the MCTBF of a redundant network will depend on its MDT, the logistics support of redundant end items becomes a key factor in determining the network's reliability. To obtain an initial estimate of the end item MDT, its order fill will initially be set to 0. When the target MLDT of the optimal end item availability goal is determined, it will be compared to the maximum MLDT of the redundant end item network. If the target MLDT exceeds this maximum MLDT, then Equation 2B adjustments apply.

$$MLDT_x \max = \frac{MTTO_x + MTR_x}{N-R+1} - MTR_x$$

If $MLDT_{x\ target} > MLDT_x \max$,

then $FILL_{1x\ target} = 0$ and $MLDT_{x\ target} = MLDT_x \max$ (2B)

The maximum MLDT of a redundant network is less than $MTTO_x$ because more than one failure to the similar end items can occur and not cause the system to fail. After the first failure occurs, an order is placed which may or may not arrive before the second failure occurs. Depending the number of redundant end items which is N-R, the second failure may cause the system to fail. If the system were to fail, its logistics downtime would be less because the previous order for a spare LRU is due in. For a system failure with one redundant end item, the MDT is approximately half of what the MDT would be with no redundancy. For a system failure with two redundant end items, the MDT is approximately a third of what the MDT would be with no redundancy because two previous orders for spare LRUs are due in.

If the target MLDT of the optimal end item availability goal does not exceed the maximum MLDT of the redundant end item network, the target order fill will be computed using Equation

2C. For a redundant network, the target order fill rate of Equation 2C is substituted for Equation 10.

$$FILL_{1x} = 1 - \frac{(N-R+1) \times (MLDT_{x\ target} + MTR_x) - MTR_x}{MTTO_x} \qquad (2C)$$

The target order fill rate is then compared to the order fill rate applied in Equation 2A. If the target order fill rate is greater, the order fill rate in Equation 2A will be iteratively increased until it eventually matches the last target order fill rate of the optimum end item availability goal using Equation 2C.

Whenever the end item's MDT is estimated using Equation 2A, the reliability or probability of an end item to succeed a mission of MDT duration is computed using Equation 2D.

$$Rel = P(success) = e^{(-MDT_X/MCTBF_X)} \qquad (2D)$$

The unreliability or probability of an end item failing to last the duration of MDT_x is the complement of the computed reliability.

$$Unrel = 1 - P(success) = 1 - e^{(-MDT_X/MCTBF_X)} \qquad (2E)$$

Knowing the reliability and unreliability of an end item to perform the duration of a MDT, the network reliability for an R of N hot standby redundant network of the similar end items can be solved using the Binomial Distribution.

$$\text{Network Rel} = (\text{Rel})^{N} + \frac{N!}{(N-1)!} \times (\text{Rel})^{N-1} \times \text{Unrel} + \ldots$$

$$+ \frac{N!}{(N-R)\ R} \times (\text{Rel})^{R} \times (\text{Unrel})^{N-R} \qquad (2F)$$

This network reliability describes the percentage of time the redundant network should be lasting longer than the end item's mean downtime per failure. With the network reliability and MDT computed, the equivalent MCTBF of the R of N network can be derived. The equivalent MCTBF of a redundant network of like end items is the Network MCTBF. The Network MCTBF is related to the network reliability using Equation 2G. Taking the natural logarithm of both sides of the Equation 2G yields Equation 2H. Equation 2I transposes Equation 2H to determine the equivalent MCTBF of the redundant network. This MCTBF for the end item is then applied in the basic mathematical theory used to derive optimal end item A_o goals.

$$\text{Network Rel}_x = e^{(-\text{MDT}_X/\text{Network MCTBF}_X)} \qquad (2G)$$

$$\text{Ln}(\text{Network Rel}_x) = \frac{-\text{MDT}_x}{\text{Network MCTBF}_x} \qquad (2H)$$

$$\text{Network MCTBF}_x = \frac{-\text{MDT}_x}{\text{Ln}(\text{Network Rel}_x)} \qquad (2I)$$

CASE 3: COLD STANDBY REDUNDANT END ITEMS OR END ITEM SPARES AT OPERATING LEVEL.

Both hot and cold standby redundancies imply that R of N similar end items must be operational to consider the system as being in an up state. However, the difference between these types of redundancies is that the hot mode attempts to have a maximum of N end items operating and the cold mode has a maximum of R end items operating. End items spared at the operating level can be treated like a cold standby redundancy.

The first difference between hot standby redundancies and cold standby redundancies is that a failure to any end item in the cold standby redundancy causes system downtime until the system is switched to use an operating redundant end item. Therefore, a cold standby redundant network of end items will automatically apply an unscheduled maintenance downtime adjustment. This adjustment is dependent on the frequency of unscheduled maintenance downtime occurrences and the maintenance time to switch end items per occurrence.

The Mean Calendar Time Between Maintenance (MCTBM) denoting the frequency of unscheduled maintenance occurrences is determined from the MCTBF of operating R end items.

$$MCTBM_{*} = MCTBF_{*}/R \qquad (3A)$$

The Mean Down Time to Switch (MDTS) end items together with the MCTBM from Equation 3A causes a maintenance availability adjustment ($A_{o\ maintenance}$) as shown by Equation 3B.

$$A_{o\ maintenance} = \frac{MCTBM_x}{MCTBM_x + MDTS_x} \qquad (3B)$$

The maintenance availability adjustment causes a modification to the system A_o requirement or system A_o target last used in Equation 3. The maintenance availability adjustment is utilized to determine a new system A_o target ($A_{o\ system\ target}$). The new target system A_o derived from Equation 3C is then applied in Equation 3 to compute a new MLDT target.

$$A_{o\ system\ target} = \frac{A_{o\ system}\ \text{(from Equation 3)}}{A_{o\ maintenance}} \qquad (3C)$$

The second difference between hot and cold standby redundancy is in the computation of the Network MCTBF. The computational adjustments and procedure using Equations 2A, 2B, 2C, 2G, 2H, and 2I are also applicable to Case 3. However, a Poisson Distribution for constantly operating R end items in the cold standby redundancy mode is used to compute the network reliability rather than the Binomial Distribution. Therefore, Equations 2D, 2E, and 2F are not utilized in Case 3.

To determine the network reliability, the average number of demands (Dem) expected over the duration of the end item's MDT established by Equation 2A must be computed using Equation 3D.

$$Dem = R \times MDT_x / MCTBF_x \tag{3D}$$

Applying the Poisson Distribution to the average number of demands over the end item's MDT duration directly determines the network reliability for a R of N cold standby redundant network of similar end items.

$$\text{Network Rel} = e^{-Dem} + Dem \times e^{-Dem} + \ldots + \frac{Dem^{(N-R)} \times e^{-Dem}}{(N-R)!} \tag{3E}$$

Substituting the Network Rel determined by Equation 3E into Equation 2I yields the Network MCTBF of the cold standby redundant network. This equivalent MCTBF for the end item is then applied in the basic mathematical theory used to determine optimal end item A_o goals.

The target LRU order fill rate applying Equation 2B or Equation 2C is also utilized in lieu of Equation 10. If Equation 2C applies rather then 2B, the order fill rate in Equation 2A is iteratively increased until it eventually matches the last target order fill rate of the optimum end item availability goal using Equation 2C.

CASE 4: DEGRADATIONAL REDUNDANCY OR CAPACITY AVAILABILITY.

Degradational redundancy is used to describe the existence of a state of operation where the system can be between the levels of being fully up and fully down. This is analogous to operating at less than 100% of the required capacity, but operating at some percent of upness greater than 0%.

Degradational redundancy or capacity availability applies to both hot standby and cold standby redundancies. In fact, when Case 4 is utilized, the ASOAR model user must explicitly note which kind of redundancy applies.

When the degradational network applies an R of N hot standby redundancy as its operating mode, all the equations and procedures of Case 2 applies with the exception of Equation 2F. A Binomial Distribution with percentages or Probabilities of Upness associated to each state between R and N shown as Equation 4A is used in lieu of Equation 2F.

$$\text{Network Rel} = P(\text{Upness})_N \times (\text{Rel})^N$$

$$+ P(\text{Upness})_{N-1} \times \frac{N!}{(N-1)!} \times (\text{Rel})^{N-1} \times \text{Unrel} + \ldots$$

$$+ P(\text{Upness})_R \times \frac{N!}{(N-R)\ R} \times (\text{Rel})^R \times (\text{Unrel})^{N-R} \qquad (4A)$$

When the degradational network applies an R of N cold standby redundancy as its operating mode, all the equations and procedures appropriately applied to Case 3 are used with the exception of Equation 3E. A Poisson Distribution with the percentages or Probabilities of Upness associated to each state between 1 and R shown as Equation 4B is used in lieu of Equation 3E.

$$\text{Network Rel} = P(\text{Upness})_R \times \left[e^{-Dem} + Dem \times e^{-Dem} + \ldots + \frac{Dem^{(N-R)} \times e^{-Dem}}{(N-R)!}\right] + P(\text{Upness})_{R-1} \times \frac{Dem^{(N-R+1)} \times e^{-Dem}}{(N-R+1)!} + \ldots + P(\text{Upness})_1 \times \frac{Dem^{(N-1)} \times e^{-Dem}}{(N-1)!} \quad (4B)$$

It should be noted that the Probability of Upness associated to the states where all N items are operating in a hot standby redundant mode or all R item are operating in a cold standby redundant mode does not necessarily have to be 100% up. If the equipment design is sometimes inadequate to handle the full required capacity with all end items in the network operating, then the system does not have to reflect that it is fully up.

CASE 5: SYSTEM SCHEDULED MAINTENANCE DOWNTIME OR PREVENTATIVE MAINTENANCE.

This case implies that there is system preventative maintenance or the periodic relocation of the system which transitions the system to a down state. With preventative maintenance, the system is serviced at a specified time interval. With the periodic relocation of the system; the system is torn down, transported and set up after some duration of time or usage.

The scheduled maintenance adjustment is dependent on the average frequency of scheduled maintenance and the average amount of system downtime associated to the scheduled maintenance event. Therefore, the mean calendar time between maintenance and the Mean Maintenance Downtime (MMDT) of the system are needed inputs. These variables cause a maintenance availability adjustment ($A_{o\ maintenance}$) as shown in Equation 5A.

$$A_{o\ maintenance} = \frac{MCTBM_{system}}{MCTBM_{system} + MMDT_{system}} \quad (5A)$$

The maintenance availability adjustment causes a modification to the system A_o requirement or system A_o target last used in Equation 3 to determine a new system operational availability target ($A_{o\ system\ target}$). The new target system A_o derived from Equation 5B is then applied to Equation 3 to compute a new $MLDT_{target}$.

$$A_{o\ system\ target} = \frac{A_{o\ system}\ \text{(from Equation 3)}}{A_{o\ maintenance}} \qquad (5B)$$

CASE 6: END ITEMS SCHEDULED MAINTENANCE DOWNTIME OR PREVENTATIVE MAINTENANCE.

This case is analogous to Case 5 when dealing with end item preventative maintenance that causes the system to not be available. Case 6 can also be used to account for additional end item downtime due to some other unforeseen reason such as the possibility of switching to hot standby redundant end items when the time to switch over is significant. It should be noted that switching time associated with cold standby redundancy is already incorporated in Cases 3 and 4.

The MCTBM of the end item and the MMDT of the end item that causes the system to not be available are needed inputs. These variables cause a maintenance availability adjustment shown as Equation 6A.

$$A_{o\ maintenance} = \frac{MCTBM_x}{MCTBM_x + MMDT_x} \qquad (6A)$$

The new target system A_o is found using Equation 5B and then is applied to Equation 3 to compute a new $MLDT_{target}$.

CASE 7: MULTIPLE SYSTEMS RESTORED WITH LINE REPLACEABLE UNIT (LRU) SPARES AT OPERATING LEVEL.

This case implies that the Ao requirement covers a Number of Identical Systems (NSYS) being serviced by an organizational level to transition any of these systems to an up state after going down. A benefit from having multiple systems is the economy of using a spare LRU to restore similar end items from having common systems. If the Ao requirement is for an individual system and several individual systems are serviced by the same operating level, no computational adjustments are needed because the ASOAR output covers the individual system. The difference not displayed by ASOAR is that LRU demand rates are higher for multiple systems which generally causes an increase in the spares requirement to attain the same LRU order fill rates.

If the Ao requirement is for a system configured with multiple systems rather than the requirement being for each individual system, a computational adjustment is necessary. To handle this adjustment, the NSYS common systems are combined to represent one system. This equivalent system will have adjusted MCTBFs for all the end items as determined by Equation 7A.

$$\text{Adjusted } MCTBF_x = MCTBF_x/NSYS \text{ for } x = 1, \ldots, N \qquad (7A)$$

CASE 8: SYSTEMS RESTORED WITH LINE REPLACEABLE UNIT (LRU) SPARES AT DIRECT SUPPORT (DS).

This case implies that Y systems are serviced by a centralized area to transition any of these systems to an up state after going down. The DS level is considered the centralized support which stores the LRU spares and is the most forward level of supply. Systems are not to be accompanied with operating level LRU spares stockage.

Without operating level spares, system restoral by using LRU spares stocked at the DS level can occur by different maintenance schemes. One scheme might be to use a Contact Maintenance Team where maintenance personnel will travel with the spare LRUs to the system to restore it. Another scheme might be to utilize the DS level as a Direct Exchange point where the failed LRUs are brought and exchanged for spare LRUs to restore the system. Finally, another scheme might be to use the DS level as a maintenance shop where failed systems are always evacuated to for restoral.

Since LRU spares are not stored at the operating level, an additional delay time to restore the system occurs before replacement by appropriate LRUs can be accomplished. The equivalent system will also have adjusted MTRs for all the end items by adding the DS level Mean Restoral Delay Time (MRDT) to the Mean Time To Restore as shown by Equation 8A.

$$\text{Adjusted } MTR_x = MRDT_2 + MTR_x \text{ for } X = 1,\ldots,N \quad (8A)$$

With LRUs spared forward at the DS level, LRU order fill rates determined by the ASOAP model apply to the DS level of stockage. The DS level mean time to obtain spare LRUs substitution described by 8B is applied to Equations 9 and 10.

$$\text{Substitute } MTTO_2 \text{ for } MTTO_1 \quad (8B)$$

CASE 9: SYSTEMS RESTORED WITH END ITEM AND LINE REPLACEABLE UNIT (LRU) SPARES AT DIRECT SUPPORT (DS).

This case is similar to Case 8 except the DS level stores both LRU spares and end item spares call floats. System restoral is primarily accomplished by using end item floats or the spare LRUs when the end item float is not available. The time to restore the system using end item floats is represented by the DS level Mean Restoral Delay Time. Since the number of end item Floats (F_x) are similar to cold standby redundant end items for the Y systems, Case 3 is applied to determine each end item MCTBF. When applying Case 3 to account for the end item floats, the following substitutions described by 9A are applied.

Substitute: Y for R and $(Y + F_x)$ for N if $F_x > 0$
Substitute: $MRDT_2$ for each $MDTS_x$ if $F_x > 0$
Substitute: $MCTBF_x$ for each $MCTBM_x$ if $F_x > 0$ (9A)

After accounting for all end items having floats, the system target Ao adjusted by Equation 3C represents the Ao for a single system. To compute the system target Ao for Y systems as if they are operating in series, the substitution of 9B is used.

Substitute: $(A_{o\ system\ target})^Y$ for $A_{o\ system\ target}$ (9B)

End items without floats that do not have LRUs forward at the operating level will apply Case 8 to account for their additional delay time to restore the system.

Since end items without floats are also being computed as if Y systems are operating in series, end item MCTBFs for Y systems are to be used initially. Therefore, Equation 9C is applied to end items without floats.

$$\text{Network } MCTBF_x = (MCTBF_x \ / \ Y) \text{ if } F_x = 0 \qquad (9C)$$

After the equivalent MCTBF for Y operating systems are determined and used to obtain results, adjusted MCTBFs for a single system is computed by Equation 9D for all end items.

$$\text{Adjusted } MCTBF_x = \text{Network } MCTBF_x \times Y \qquad (9D)$$

After the equivalent operational availabilities for Y operating systems are determined and used to obtain results, adjusted availabilities for a single system is computed for each end item applying Equation 9E. $A_{o\ system\ target}$ is the system A_o for a single system.

$$\text{Adjusted } A_{ox} = (A_{ox})^{1/Y} \qquad (9E)$$

With LRUs spared forward at the DS level, LRU order fill rates determined by the ASOAR model apply to the DS level of stockage. Thus, the substitution of 8B applies to Equations 9 and 10.

CASE 10: SYSTEMS RESTORED WITH END ITEM SPARES AT DIRECT SUPPORT (DS) AND LINE REPLACEABLE UNIT (LRU) SPARES STOCKED FORWARD AT GENERAL SUPPORT (GS).

This case implies that Y systems are serviced by a centralized area to transition any of these systems to an up state after going down by using end item floats rather than LRUs. The centralized area storing the end item floats is considered the DS level.

This case differs from Case 9 because LRU spares are not located at the same centralized support. Instead, LRU spares are located at a more centralized area considered the GS level. The GS level services Z DS levels to restore failed end items. Assuming that the failed end items are evacuated to the GS level for maintenance, restored and then returned to the DS level, additional delay time is added to the Mean Time To Restore an end item. The additional delay occurs sending the end item to the GS level before repairing and sending the working float back to the DS level. Therefore, the equivalent system will have adjusted MTRs for all the end items by adding twice the Mean Shipping and Handling Time (MSHT) between DS and GS to the Mean Time To Restore as shown by Equation 10A.

$$\text{Adjusted } MTR_x = (2 \times MSHT_{2-3}) + MTR_x \text{ for } X = 1,\ldots,N \qquad (10A)$$

D. METHODOLOGY VERIFICATION.

The methodology within ASOAR contains some approximations. The key simplifying assumption is that the relative cost to failure ratios of the end items drives the weapon system's LRU sparing optimization at the most forward level of supply support. Therefore, the basic methodology of ASOAR was tested by comparing it to results obtained by using the Army's standard sparing optimization model.

A pseudo-system consisting of 7 end items with known LRU data was modeled with the Selected Essential-Item Stockage Availability Method (SESAME) model using the same curve parameter for each end item. The outputted system A_o from SESAME was used as the ASOAR model input. The end item A_o outputs of ASOAR were then compared to end item A_o outputs computed by SESAME. This test was repeated three times with different order of magnitude curve parameters. The results showed that the A_o values for serial end items computed by the ASOAR model were close to the A_o values computed by the SESAME model which had optimally spared the LRUs in those end items. Summary comparisons of the computed end item A_o using SESAME and ASOAR on the pseudo-system are displayed in Tables 1 through 3.

The ASOAR model itself was exercised to test out the computer code in the basic methodology and all the special cases. ASOAR model results were compared against hand calculations to verify that equations and algorithms were programmed correctly. The results also yielded by the ASOAR model passed common sense tests.

Multiple special case runs were done to represent more complex systems. The inputting order of the special cases were varied. Results showed that special Cases 1 through 6 are independent of input sequence. Special Cases 7 through 10 which deal with multiple systems serviced by the most forward level of supply support are dependent on input sequence and should be inputted last.

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Percentage of Line Replace Units Repaired .... PCTREP

Reliability, Availability and Maintainability .... RAM

Repair Cycle Time .... RCT

Required Operational Capability .... ROC

Stock Availability .... SA

Selected Essential-Item Stockage Availability Method ... SESAME

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