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COMPARISON OF OPERATIONAL AVAILABILITY
MODELING BY
TIGER AND SESAME

by

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Comparison of Operational Availability Modeling
By TIGER and SESAME

by

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ABSTRACT

The Department of Defense (DoD) has begun to consolidate the services' similar logistic methodologies. The Joint Logistics Systems Center (JLSC) at Wright-Patterson Air Force Base in Ohio has been tasked by DoD with providing a supply support requirements computation system based on weapon system availability (i.e. readiness based sparing). JLSC canvassed DoD for the different requirements determination approaches used by the services. The Army's Selective Stockage for Availability Multi-Echelon Model (SESAME) and the Naval Sea Systems Command's (NAVSEA) model named TIGER were two applications found to be used in DoD for computing supply support requirements based on readiness sparing (RBS) concepts. This thesis compares TIGER and SESAME, focusing on their methodology for computing the steady-state operational availability for a weapon system for various supply support scenarios. SESAME allows for a four-echelon supply support system and computes operational availability for a weapon system at many locations. At present TIGER allows for only two echelons of supply support and computes operational availability for a weapon system at only one location.

TABLE OF CONTENTS

EXECUTIVE SUMMARY

The reduction in United States military forces and the shrinking of the Department of Defense (DoD) budget has caused DoD to consolidate its various missions and roles. Future military organizations will be increasingly a joint service in nature. As a consequence, DoD has begun to consolidate the services' similar logistic methodologies. The Joint Logistics Systems Center (JLSC) at Wright-Patterson Air Force Base in Ohio was tasked with trying to standardize the automated data processing systems used by DoD supply support organizations. DoD is also transitioning to a supply support requirements computation system based on weapon system availability; also known as readiness-based sparing (RBS) [Ref. 22;p. 3-7]. JLSC has been tasked by DoD in 1991 with providing a single system which has that capability. Their initial task is to provide a system to determine wholesale requirements. However, they will ultimately extend the system's capabilities to include determining both whloesale and retail requirements together.

JLSC canvassed DoD for the different requirements determination approaches used by the services. The Army's Selective Stockage for Availability Multi-Echelon Model (SESAME) and the Naval Sea Systems Command's (NAVSEA) model named TIGER are two applications found to be used in DoD which compute supply support requirements based on weapon system availability [Ref. 26]. Each program can compute the steady-state Ao of a given weapon system based on a specified level of supply support. A comparison

of these applications may help JLSC in developing a single model for DoD.

The objective of this thesis is to attempt to identify similarities and differences between the two models.

The models have other features in addition to computing Ao. For example, each has optimization routines to determine the number of parts to stock at supply support organizations. However, this thesis is limited in scope to the process by which the steady-state operational availability is determined by each of the models. That this thesis is confined to describing and comparing, to the extent that has been possible, the current ways in which SESAME and TIGER model operational availability is a caveat which should be emphasized.

The focus is on the expected time a weapon system operates before it fails, and the expected logistic and repair times which contribute to the delays in bringing the system back up since these are the elements needed to compute steady-state operational availability. Whenever possible, the steps used by the models to calculate Ao are explained. Unfortunately, only the formulas for a simple case were obtained for TIGER. However, sufficient information was obtained to conclude that, because of the differences in the models, comparison of the two under similar scenarios is, at best, limited.

TIGER computes Ao for a weapon system at one location while SESAME computes Ao for a weapon system at several locations. SESAME provides for four echelons of logistics support, while TIGER

has at most two echelons. SESAME explicitly models parts as capable of being repaired "as good as new" by repair facilities while TIGER does not. SESAME also has the capability to model procurement from vendors and wholesale logistic support. TIGER can do neither. TIGER's strength lies in its ability to handle non-series systems and multi-indenture levels. A useful area of research would be to try to model non-series redundancy at the end item level in SESAME.

Both models do compute Ao based on weapon system components that have operating times and, upon failure, have times required for replacement of the failed components. Included in the Ao computations are logistic delays which can postpone the repair or replacement of the failed weapon system components. It appears that both models use that information to compute Ao based on uptime divided by total uptime and downtime.

Documentation support for SESAME from its developers at USAMSSA was a valuable asset. Being able to talk directly with Dr. Kotkin and Martin Cohen, the authors of SESAME, allowed for a better understanding of the intricacies and input of SESAME. Documentation for TIGER was sparse but conversations with Dr. Matthesen of Alpha Solutions, Inc. were helpful.

Because of the differences between the models, it is inappropriate to suggest that JLSC accept one or the other as the "best of breed" at this time. However, information provided in this thesis should be useful to those who are concerned with deciding upon a single model.

I. INTRODUCTION

A. BACKGROUND

The reduction in United States military forces and the shrinking of the Department of Defense (DoD) budget has caused DoD to consolidate its various missions and roles. Future military organizations will be increasingly a joint service in nature. As a consequence, DoD has begun to consolidate the services' similar logistic methodologies. The Joint Logistics Systems Center (JLSC) at Wright-Patterson Air Force Base in Ohio has been tasked with trying to standardize the automated data processing systems used by DoD supply support organizations. DoD is also transitioning to a supply support requirements computation system based on weapon system availability; also known as readiness-based sparing (RBS) [Ref. 1:p. 3-7]. JLSC was tasked by DoD in 1991 with providing a single system which has that capability. Their initial task is to provide a system to determine wholesale requirements. However, they will ultimately extend the system's capabilities to include determining both wholesale and retail requirements together.

JLSC canvassed DoD for the different requirements determination approaches used by the services. The Army's Selective Stockage for Availability Multi-Echelon Model

(SESAME) and the Naval Sea Systems Command's (NAVSEA) model named TIGER are two applications found to be used in DoD which compute supply support requirements based on weapon system availability [Ref. 2]. Each program can compute the steady-state Ao of a given weapon system based on a specified level of supply support. A comparison of these applications may help JLSC in developing a single model for DoD.

B. OBJECTIVE

The objective of this thesis is to attempt to identify similarities and differences between the two models.

C. SCOPE

The models have other features in addition to computing Ao. For example, each has optimization routines to determine the number of parts to stock at supply support organizations. However, this thesis is limited in scope to the process by which the steady-state operational availability is determined by each of the models. *That this thesis is confined to describing and comparing, to the extent that has been possible, the current ways in which* SESAME *and* TIGER *model operational availability is a caveat which should be emphasized.*

The focus is on the expected time a weapon system operates before it fails, and the expected logistic and repair times which contribute to the delays in bringing the system back up

since these are the elements needed to compute steady-state operational availability. Whenever possible, the steps used by the models to calculate Ao are explained. Unfortunately, NAVSEA did not provide all of the requested TIGER documentation describing calculations used in its routines. However, sufficient information was obtained to conclude that because of the differences in the models, comparison of the two under similar scenarios was at best limited.

D. PREVIEW

Chapter II discusses the concept behind Ao and contains a brief description of the two models. Chapter III further describes the models, their inputs and the relationship of the inputs to Ao. Chapter IV examines the formulas used by SESAME and TIGER to compute Ao. Chapter V provides a comparison of SESAME and TIGER, both analytically and through the use of numerical examples. The results of these examples are also discussed. Chapter VI presents a summary of the thesis, conclusions based on the analysis of the two models, and recommendations for JLSC to consider when choosing between the models.

II. DESCRIPTIONS OF Ao, SESAME AND TIGER

A. OPERATIONAL AVAILABILITY (Ao)

As DoD reduces its budget, more efficient ways to invest spare parts are being sought. One way is through the use of Readiness Based Sparing. Readiness Based Sparing (RBS) is described as "the establishment of an optimum range and quantity of spares and repair parts at all stockage and user locations in order to meet approved, measurable, weapon system readiness, operational availability, or fully mission capable objectives." [Ref 1:p. L-21] DoD describes operational availability (Ao) mathematically as equation (2.1). [Ref. 3:pp. A1-A15]

$$Ao = \frac{uptime}{uptime + downtime}.$$

(2.1)

Blanchard defines operational availability as "the probability that a system or equipment, when used under stated conditions in an actual operational environment, will operate satisfactorily when called upon." [Ref. 4:p. 70]

NAVSUP Publication 553 [Ref. 5:pp. 2-7] interprets operational availability as equation (2.2).

$$Ao = \frac{MTBF}{MTBF+MTTR+MLDT};$$

(2.2)

where MTBF = Mean Time Between Failure;

MTTR = Mean Time To Repair; and

MLDT = Mean Logistics Down Time.

It can be seen from equation (2.2) that Ao can increase if MTBF is increased, or if MTTR and MLDT are decreased. The supply system cannot change MTBF or MTTR to change Ao since the engineering commands in DoD are responsible for the specification of MTBF and MTTR. However, the supply system can use readiness based sparing to reduce MLDT, thereby increasing Ao.

MLDT can be reduced by reducing the time that supply organizations take to provide spare parts where they are needed. There are two main ways the supply system can assist in decreasing this time; reducing the time to ship spares from supply centers to activities repairing downed equipment, and keeping on-hand inventories of spares at these activities. However, as more spares are kept as on-hand inventories, the costs of providing spares to all weapon systems increases.

The least number of spares is obtained by stocking them at a central resupply center. Spare parts' unit costs are, of course, not the only issue. The costs to transport the spares to the repair activities must also be considered.

As noted above, MLDT decreases the denominator of equation (2.2), thereby increasing Ao. However, MLDT can only be logically decreased by supply organizations to zero. As the limiting value of Ao as MLDT goes to zero is given by equation (2.3).

$$A_i = \frac{MTBF}{MTBF+MTTR}$$

(2.3)

This is the maximum value Ao can attain, assuming MTBF and MTTR do not change. Blanchard calls it the inherent operational availability. "Inherent availability is the probability that a system or equipment, when used under stated conditions in an ideal support environment (i.e., readily available tools, spares, maintenance personnel, etc.), will operate satisfactorily at any point in time as required. It excludes preventive or scheduled maintenance actions, logistics delay time and administrative delay time." [Ref. 4:p. 69] Once the value of MLDT reaches zero, the addition of further spares to an activity's on-hand inventory will not increase Ao.

B. SESAME

SESAME is an Army program which determines Ao for a weapon system comprised of end items, the end items' parts, and the spares used to replace parts that fail in the end items. An end item is a major component of a weapon system [Ref. 6].

An example of a weapon system which can be modeled by SESAME is a rocket launcher system made up of a launcher and a computer used to locally operate it [Ref. 6]. The launcher portion of the rocket launcher can be considered to be one end item in the weapon system. A computer which locally operates it can be considered to be a second end item. Both end items make up the rocket launcher weapon system. The weapon system can be deployed in different numbers at different locations or bases.

The Ao value for the weapon system is computed by SESAME for a given multi-echelon configuration by using the Ao's of the various end items in the weapon system. A weapon system can be located at different bases which provide different levels of logistic support for their end items. Therefore, similar end items can have different Ao's at different bases. SESAME averages the different Ao's obtained at the different locations to compute an overall, system wide Ao for the end item. The system wide Ao can be thought of as the expected Ao value of an end item chosen at random from a location. Then SESAME computes the weapon system Ao by multiplying the system-wide Ao's for each of its different end items together.

Another way to model a weapon system by SESAME can be described again using the rocket launcher weapon system. The weapon system is deployed at different locations as before. This time, however, the rocket launcher is not broken down into end items [Ref. 6]. The Ao of the weapon system is determined at each location. Its Ao will be different at different bases due to differences in levels of logistic support for the bases. The weapon system Ao is then calculated by averaging the Ao's it has at the different bases.

When deployed, a weapon system is supported by a logistic support network. The network is made up of different echelons of supply activities and repair facilities which work together to provide spares for failed end item parts. The support network spreads out from a top echelon wholesale activity/depot repair facility to second and third echelon intermediate support activities and finally to the organizational level's support activities which support the weapon system at its deployed location.

As the weapon system operates, its end items must also operate. However, the end items are subject to their own parts' failure and need for repair. The time it takes to repair the end items may differ based on their design and complexity. It also depends on the type of logistic support they receive wherever they are deployed. Because the amount and type of logistic support can vary at the different

locations where the weapon system is deployed, this can cause differences in the time it takes to repair an end item. The result is that the Ao of an end item at one location may be different from the Ao of the same end item at a different location. This affects the weapon system's Ao.

End items operate for a period of time and then fail. They can, however, be repaired and operated again. The end items fail when their internal components, called line replaceable units (LRU's), fail to operate during normal use. "An LRU is an essential secondary item which is removed and replaced at field level to restore the end item to operationally ready condition [Ref. 7:p. 1-6]." In SESAME, LRU's are replaceable repair parts in end items. When an LRU fails, it can be removed from the end item and replaced with a working spare LRU. The failed LRU can be discarded, or, depending on its design, be repaired at some repair facility in the support network so that it is essentially "as good as new" and used again. LRU's which can be repaired to working order are called repairables.

SESAME models a logistics support structure which provides logistic support to each end item in a weapon system at each base. There are four echelons of support modeled by SESAME. From lowest to highest, they are: the organizational echelon which provides support to the deployed weapon system locations (ORG), the direct support echelon (DSU), which provides intermediate support to the organizational echelon, the

general support echelon (GSU), which provides intermediate support to the direct support echelon, and the wholesale activity and repairables depot facility echelon which provides support to the next lower echelon of support. When the wholesale supply activity cannot produce a spare, it procures one from a vendor.

The user does not have to always model a four echelon support structure. He needs only to include the number of echelons required to model an assumed scenario. For example, he may model only three echelons represented by a wholesale/depot activity, an intermediate support activity echelon (DSU), and an organizational support activity echelon (ORG).

Elements of the support structures may themselves be at different locations and bases. One echelon of support, for example, may be co-located at one base with a weapon system, while another echelon in the same support network is located at another base. However, different echelons of support may be located at the same base. Each echelon is identified separately, however.

Figure 2.1 provides an example of a support structure with four echelons of support.

As noted above, each echelon in the support structure can provide support to the echelons below it in the support network. At the top of the support structure, the wholesale activity and the depot activity can support all of the

locations in the network. In Figure 2.1, DSU1 can provide support to echelon ORG1 and ORG2. Support activities in the same echelon do not provide support laterally. For example, in Figure 2.1, ORG1 cannot provide support to ORG2.

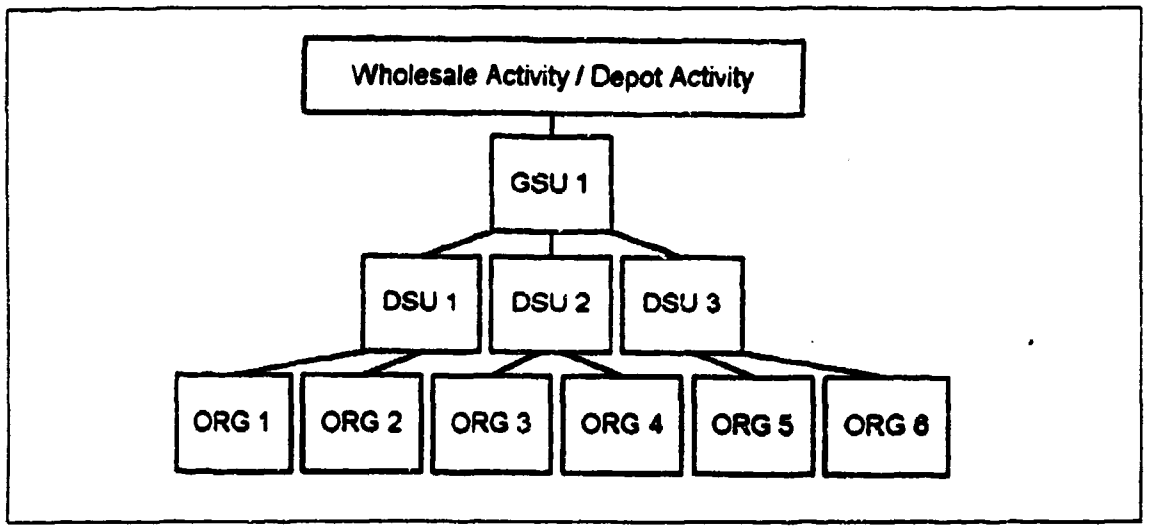

Figure 2.1. A Example of a Four-Echelon Support Structure.

Support activities provide inventories of LRU spares and/or LRU repair facilities. If an LRU fails in an end item, a replacement LRU can be drawn from inventory. And, if the LRU itself can be repaired, it can be sent to a repair facility for refurbishment and reuse as a spare.

Shipping LRU's from inventories or repair facilities takes time. It also takes time to repair LRU's at the repair facilities. These times are called logistic and repair facility delays. They cause the end item repair to be postponed until a spare is made available. The delays, therefore, contribute to the overall downtime of the end item

and, consequently, the weapon system.

The Ao value determined by SESAME for a given multi-echelon configuration is ultimately determined by the length of time its end items operate before they fail, causing the weapon system to fail. It is also determined by the length of time they remain down awaiting parts and being repaired. The logistician can help reduce the delay by providing inventories of spares at different levels of the support echelons.

C. TIGER

Tiger 9.2A (September 1993 Version) is a "computer model tool which can be used to mathematically assess operational availability and reliability in existing systems, and to determine readiness based sparing (RBS) allowances for either new or existing systems." [Ref. 8:p. 1-1] Although called a simulation, the newer version of "TIGER no longer utilizes the Monte Carlo simulation of randomly generated equipment events." Instead, the procedure involves computing "state occupancy and transition rates, solved for by using differential equations." [Ref. 8:p. G-1]

An example of a weapon system modeled by TIGER could be an observer airplane located at a particular base. The plane can be described as an assembly of major components such as the fuselage, wings, tail section, engine, and landing gear, all of which must function together to make the plane fly. Each of these major components can themselves be broken down into

smaller components. This breakdown continues until a level is reached where a component has its own measurable mean time before failure and a mean time to repair. TIGER calls this type of component an "equipment". Equipments can have lists of parts which can be replaced when they fail [Ref. 8].

Spares for these equipment parts are first drawn from an inventory at the base if such an inventory exists. If a spare is not available at the base when required, the base supply department requisitions one from the next higher level of support which, in TIGER, is always off base. These are the only two echelons of logistic support for the weapon system. In addition, there are no repair facilities to restore repairables to "as good as new" condition for reuse.

TIGER computes the Ao for the plane from the failure times and repair times of its equipments. The delays encountered in receiving spares from the off base echelon to complete the repairs at the base are also included in the Ao computations.

The user inputs the weapon system into TIGER using a top-down approach, breaking the weapon system down into its components. A component can be described as any aggregation of items which work together to perform a function. This approach is analogous to block diagramming as shown in Figure 2.2.

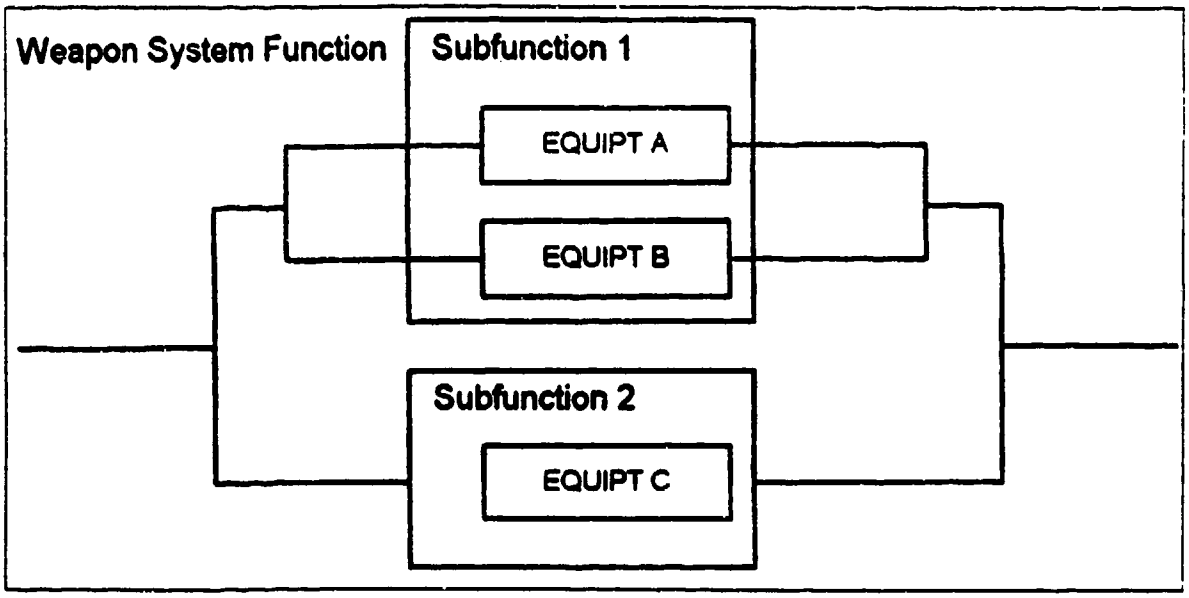

Figure 2.2. Block Diagramming of a Weapon System.

The first "level of indenture" consists of the "functions". Functions are described as "being able to represent a system, subsystem, equipment group, or equipment." [Ref. 9] Because they are broadly defined, they can represent a "functioning" part of a weapon system. They may represent individual equipments in a weapon system. They may also represent an aggregate of subfunctions which are included in the next lower level of indenture in a weapon system block diagram. Subfunctions may also represent systems, subsystems, equipment groups or equipment. Subfunctions can operate in series or redundantly with other subfunctions. Equipment performing as part of a subfunction may fail, causing the subfunction to not be performed.

The weapon system continues to be broken down into lower and lower indentures in block diagram form until the major equipment components are identified which have estimated MTBF and MTTR[1] values associated with their operation and, ultimately, influence the weapon system's Ao. An equipment may also have an associated list of internal components (LRU's) which cause the equipment to fail when they fail. When the equipment goes down, the LRU's must be removed and replaced to bring the equipment back up.

TIGER assumes a single weapon system at only one location. As mentioned above, the weapon system is allowed to have two echelons of logistic support. The first echelon includes an organizational level of support which can provide an inventory of spares at the weapon system location. In the following chapters, this location will, at times, be referred to as the "on board" location. The second echelon of support provides spares to the organizational support location. In this thesis, this location will, at times, be referred to as the "off ship" location. The logistics support from either location appears to only be spare parts inventories. Depot or intermediate levels of repair of repairables does not appear to be modeled in TIGER.

In summary, the weapon system operates and fails as its

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[1] MTTR for the equipment is described as "the average active repair time of the equipment, in hours. It includes diagnostic action, but not administrative or supply delays." [Ref. 9]

components operate and fail. Inventories of spare LRU's reduce the delay to the organizational level of repair of downed equipment. But if a spare is not in stock, repair of the equipment is delayed until one arrives.

III. DESCRIPTION OF INPUT FOR Ao COMPUTATIONS

A. SESAME

1. Ao Calculations

Recall that SESAME computes Ao for a weapon system comprised of one or more end items. Each weapon system may be deployed at different locations. The model first determines an end item's Ao for these locations. Then SESAME determines a system wide Ao for each end item by averaging the Ao's computed at the different locations. Finally, the weapon system Ao is calculated by multiplying the system wide Ao's of the different end items in the weapon system together.

The calculation of an end item's Ao at a given location is based on its mean calendar time before failure (MCTBF), its mean time to repair (MTTR), and its mean logistic down time (MLDT). MCTBF is the mean calendar time between failures of an end item measured in days. It represents the amount of normal usage time an end item experiences before it fails. There are no ratios applied to MCTBF in SESAME to account for intermittent usage of the weapon system. The author believes, therefore, that the user must account for intermittent usage before entering MCTBF data values. The MCTBF is either entered by the user or computed by SESAME, as described later in the thesis. MTTR is the mean time to

repair an end item and is measured in days. MTTR is input by the user. Mean logistic down time (MLDT) is the down time an end item experiences while awaiting parts for repair. It also is measured in days and is computed by SESAME.

MLDT is a function of "expected total time-weighted backorders divided by total annual demand." [Ref. 10] As described by Dr. Meyer Kotkin of the U.S. Army Material Systems Analysis Activity's Inventory Research Office, in Philadelphia, Pennsylvania, it is the "weighted average of individual lower indenture repair units (LRU) waits. This is the same as the expected value of LRU time-weighted backorders divided by the LRU removal rate." [Ref. 11] The "individual LRU waits" Kotkin describes are the delay times required to provide a working spare to a downed end item, such as order and shipping time or rework time.

Backorders occur if requirements for spares cannot be immediately filled by the logistics support structure. When backorders are incurred, they delay an end item's repair. The number of backorders outstanding for a given LRU at a given instant in time is a function of the logistic delays experienced by an LRU. Some locations may experience longer logistic delays than other locations. This can be caused, for example, by different levels of spare inventories at the different locations or by long shipping times to remote bases. This causes an end item's Ao to be different at different locations.

A separate Ao is calculated for each end item at each of its deployed locations, using the respective MCTBF, MTTR, and MLDT values. A "system wide" Ao for each end item is then calculated using the Ao's determined at each location. If an end item is supported at more than one location, the Ao's calculated at each location are weighted by the number of identical end items the location supports. "The system Ao can be thought of as the probability that a randomly selected end item at a base is up. That probability for a particular end item being at a particular location is equal to the quantity of the end item supported at the location divided by the total quantity of the end item in the weapon system." [Ref. 12]

Finally, each of the Ao's of the different end items which make up the weapon system are multiplied together to form the weapon system's Ao.

2. Logistic delay times

A logistic delay is the time a repairman waits for a spare part which is needed to repair a downed end item. If a spare part is available, he does not experience any logistic delay time. But if a spare has to be shipped to him from an inventory at another location in the support structure, the repairman must wait until the spare arrives before commencing repair on the end item.

The support structure is a network of locations. Each location may be supported by another location at a higher

echelon. SESAME allows for four echelons of support. The locations that support the lowest echelon locations are called the organizational support locations (ORG's). The next higher echelon contains the direct support locations (DSU's). DSU's support one or more of the ORG locations. The next higher echelon consists of general support locations (GSU's). GSU's support the DSU locations. They do not support ORG locations, however. The highest echelon is the combined wholesale supply activity and repairables depot facility echelon. It provides support to the GSU location in a four-echelon support structure. If the support structure has less than four echelons, it provides support to the next lower echelon. The support provided by the support locations at each echelon includes providing inventories of spares to replace failed end item parts and providing repair facilities used to refurbish failed end item parts. A given location may provide one or both of these capabilities.

If the end item fails at the same location (ORG) which has a support facility with spares available in inventory, SESAME assumes there is no order and shipping time delay. This means a spare is assumed to be instantaneously available to repair the downed end item. If a spare parts repair facility exists at the same location where an end item has gone down, there is also assumed to be no delay in getting the failed repairable part to the repair facility.

Non-zero order and shipping times are assumed to exist

when the support facility is located at a higher echelon than that of the failed end item. SESAME calls the one-way mean order and shipment time of a spare sent between echelons "OSTE". It also represents the time it takes to ship a refurbished repairable part from a repair facility. It does not account for the time it takes to send the failed repairable part to the facility. OSTE times are further classified as follows: OSTE-O which is the mean order and shipping time for an end item's parts between the direct support echelon and the organizational echelon. OSTE-DS is the mean order and shipping time for an end item's parts between the general support echelon and the direct support echelon. OSTE-G is the mean order and shipping time for an end item's parts between the wholesale activity's/depot facility's support echelon and the general support echelon. Figure 3.1 illustrates these various shipping times.

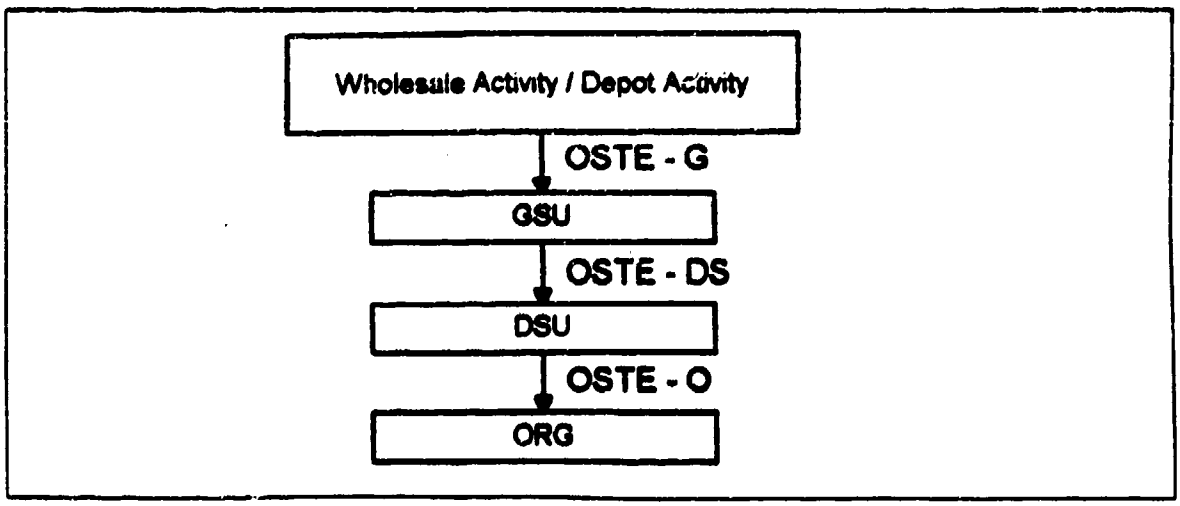

Figure 3.1. Mean Order and Shipping Times Between Echelons.

Shipments are constrained to move along the paths in the support structure network. Shipments are not allowed to "bypass" echelons. Shipments can pass between higher and lower echelons but not between locations at the same echelon. For example, an ORG cannot ship directly to another ORG. In addition, to send a spare from the GSU to the ORG in Figure 3.1, the spare must go from the GSU to the DSU, then from the DSU to the ORG.

The OSTE time for any end item's part is the same regardless of location. As shown in Figure 3.2, the same end item's part X, for example, will experience the same OSTE of 10 days from DSU1 to either ORG1 or ORG2.

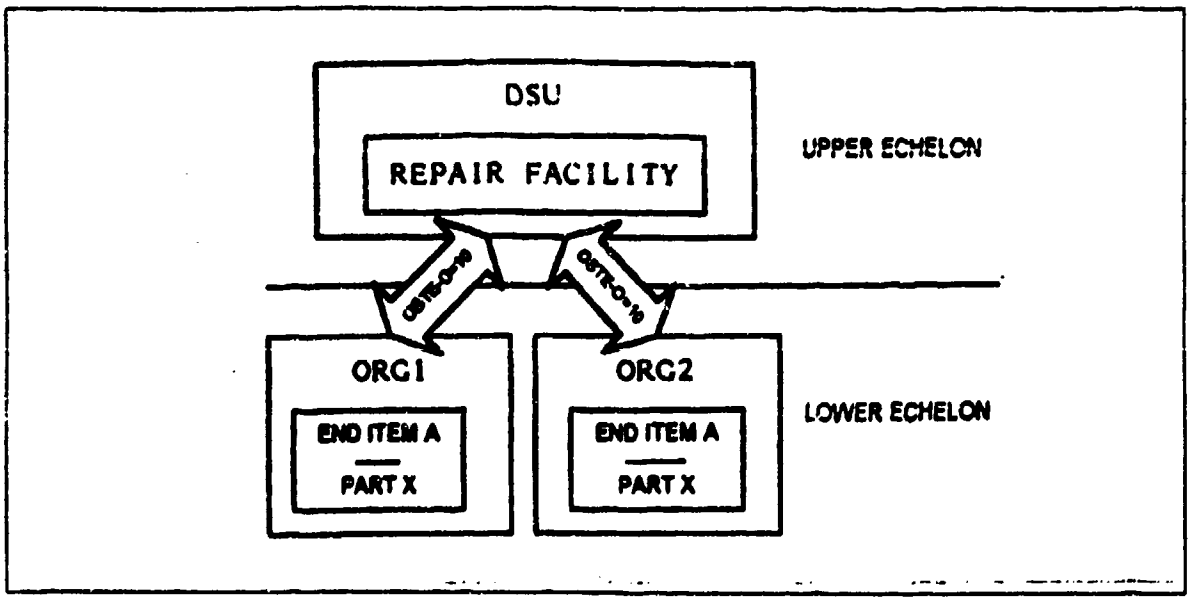

Figure 3.2. Use of Different Mean OSTE-O Times at Different Lower Echelon Sites.

As shown in Figure 3.3, however, the OSTE for the parts of different types of end items may be different at the same base.

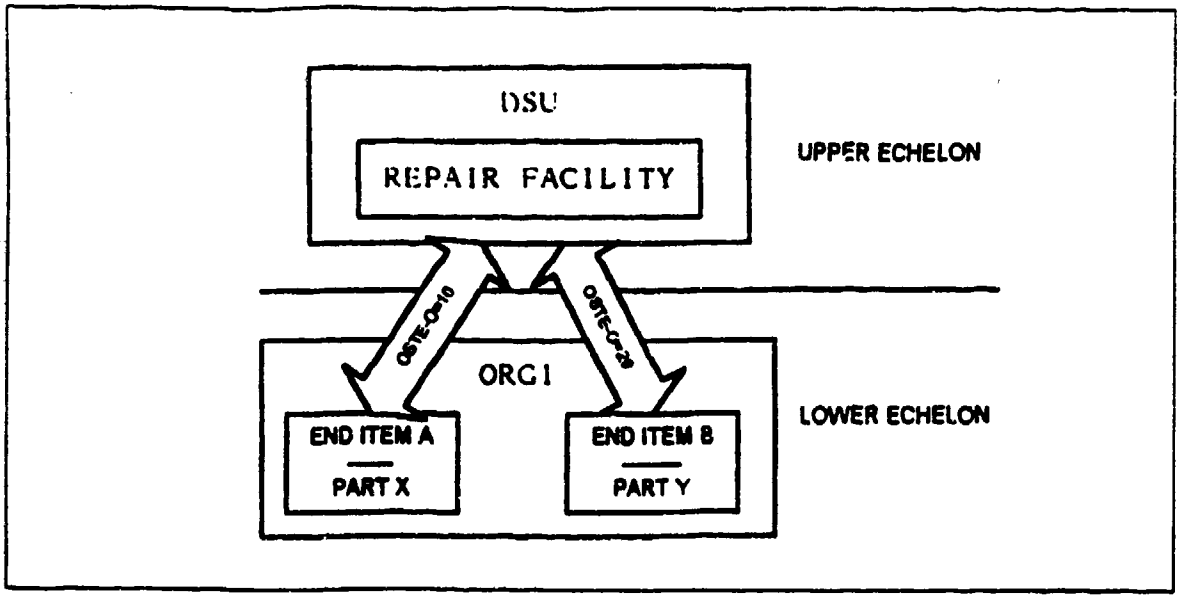

Figure 3.3. Use of Mean Different OSTE-O Times for Different End Items at the Same Site.

SESAME also provides the user with the ability to override the OSTE assumption. It does so by allowing a mean order and shipping time which is unique between a support location and an end item's location. This is called OSTU. Whenever parts are shipped to this end item location, they experience the particular mean OSTU value attributed to that location. All parts from the same end item experience the same mean OSTU times. SESAME does allow, however, for parts from different types of end items to have different mean OSTU times at the

same location. Figure 3.4 illustrates an example where the OSTE has been overridden by the OSTU value.

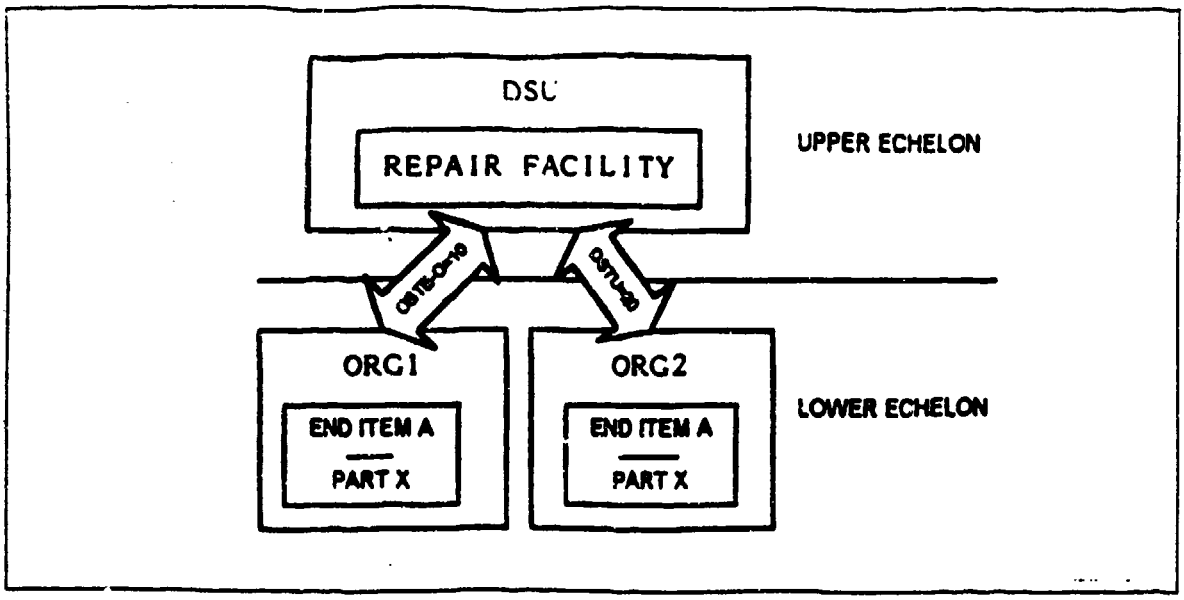

Figure 3.4. Example of an OSTU Value Overriding OSTE.

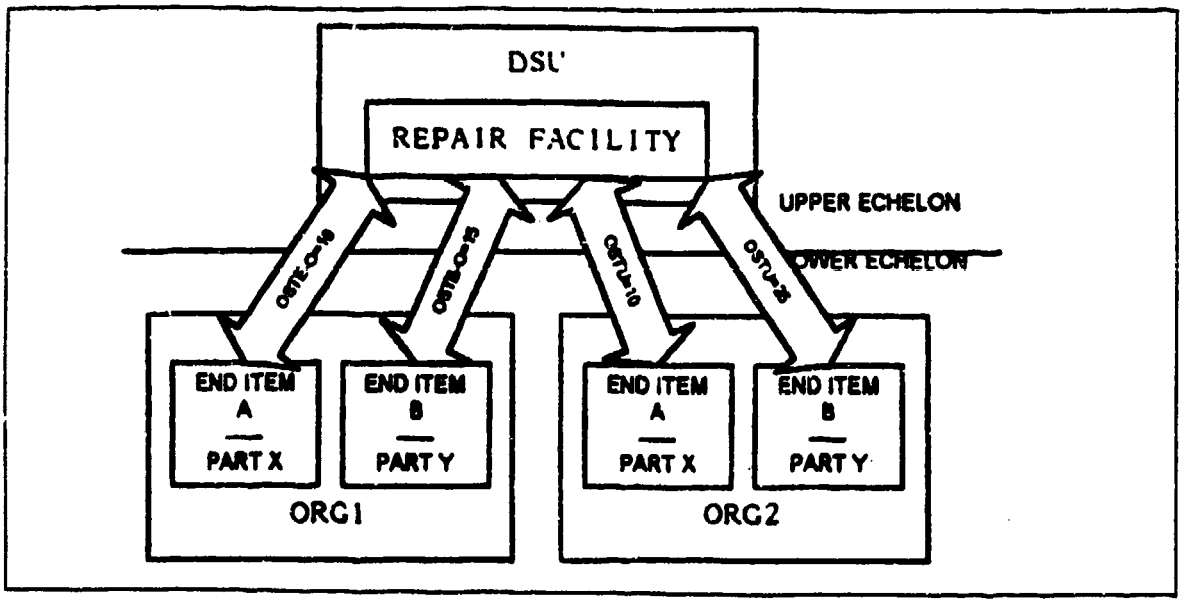

Figure 3.5. OSTU and OSTE Values for Different End Items.

Figure 3.5 shows different OSTU values for different end items.

The user has to tell SESAME to use either OSTE values or OSTU values when both are input. If the user specifies OSTE, SESAME will use OSTE delay values. If the user specifies OSTU, SESAME will use OSTU delays values. When the user does not specify either, SESAME uses the OSTE delay values. When the user chooses the OSTU values, but the OSTU values have been left blank for some reason, SESAME defaults to the respective OSTE value based on the location's echelon [Ref. 13:p. 12]. Finally, if the user also leaves the OSTE values blank, SESAME defaults OSTE-G, OSTE-DS and OSTE-O to 15 days, representing a "standard order and shipping time".

3. Repair cycle times

Failed repairable parts are sent to repair facilities in the support structure where the parts are completely restored to "like new" working condition. Repair cycle time is the amount of time it takes a repair facility to refurbish a repairable failed part. The author, however, believes that the repair cycle time should include the time to ship the failed repairable from the location of failure to the repair facility. The order and shipping times discussed above pertain only to the shipment of a restored repairable from the repair facility back to the end item location.

SESAME allows a repair facility at each echelon in the

support structure. Figure 3.6 provides an example of this.

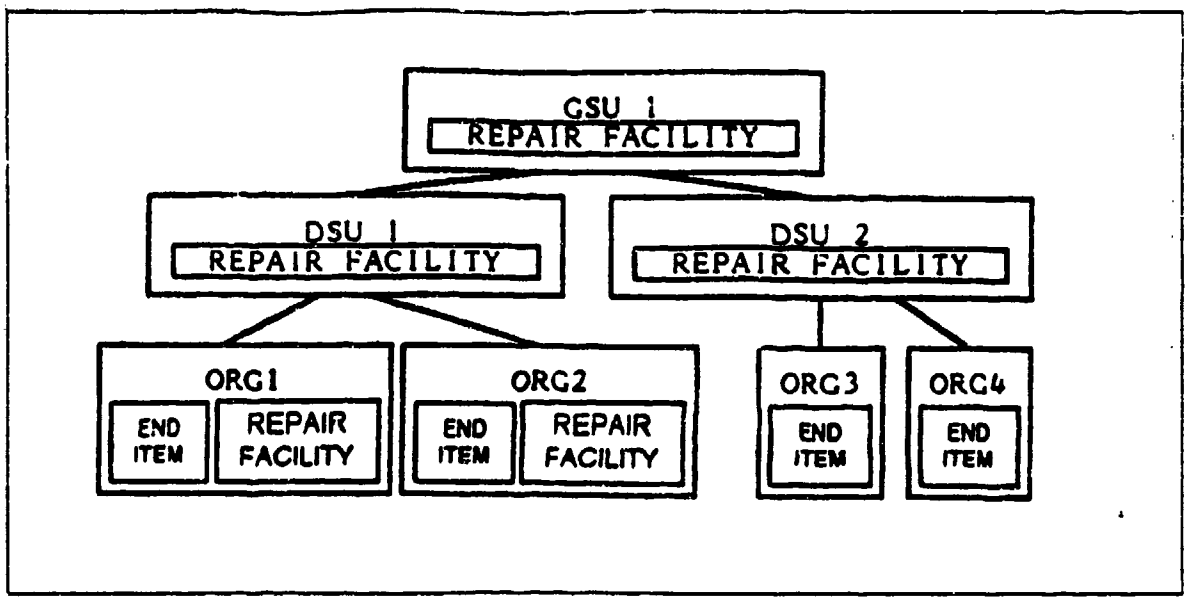

Figure 3.6. An Example of A Repair Facility Support Structure.

Repairables can be sent to a repair facility at the same location where they failed or they can be sent to a different repair facility located at a higher echelon in their support structure. However, parts cannot be sent to facilities outside the path of the support structure supporting their failure location. For example, in Figure 3.6, a part from location ORG1 can be refurbished at the ORG1 repair facility, location DSU1, or location GSU1. A repairable from location ORG1 cannot be sent to the repair facility at DSU2 or ORG2 because those facilities do not support ORG1.

SESAME provides for one of three types of mean delay times for each repair facility. These are "REPCYE", "REPCYU", and "REPCYP". Repair Cycle Time End Item (REPCYE) is a mean repair cycle time which applies equally to all parts of a given end item. Its value can be different, however, for each echelon having a repair capability. Parts from different types of end items are also allowed to have different REPCYE values.

There are four REPCYE values allowed for each end item as shown in Figure 3.7. From lowest echelon to highest, they are; REPCYE-O for repair facilities at the organization support echelon, REPCYE-DS for the repair facilities at the direct support echelon, REPCYE-G for the repair facilities at the general support echelon, and the REPCYE-DEP time for the

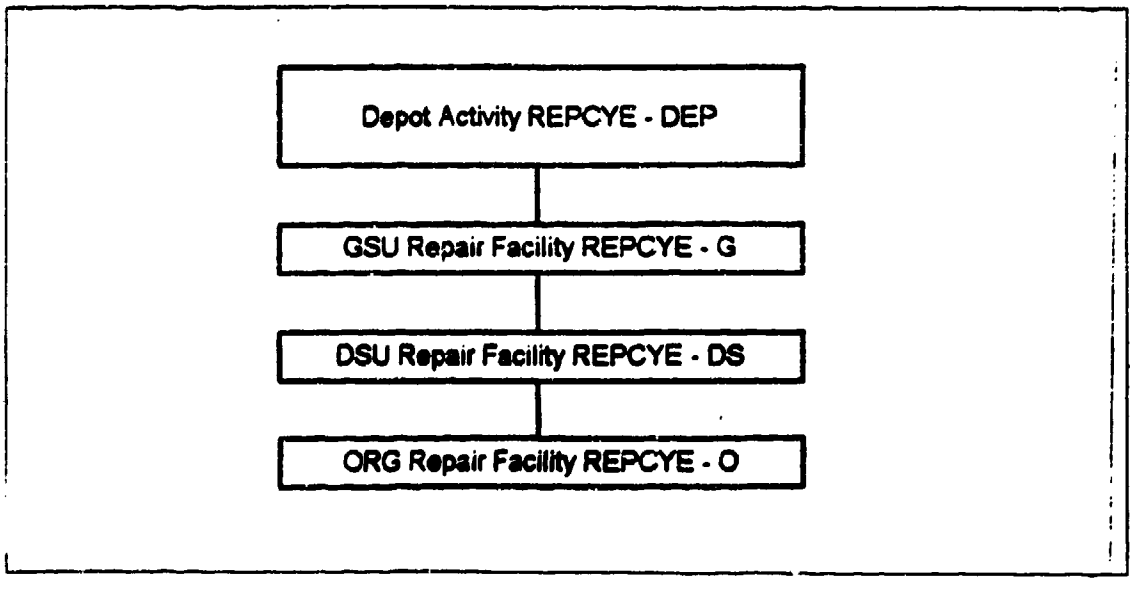

Figure 3.7. Mean Repair Cycle Times (REPCYE) for Each Echelon.

depot repair facility.

SESAME provides for an REPCYP value for each part. The mean Repair Cycle Time Part (REPCYP) can be used to override the REPCYE time. It provides a different repair cycle time for each part in an end item. Since a part can be repaired at repair facilities located at four different echelons, it can have four different REPCYP values, one for each echelon; namely, REPCYP-O, REPCYP-DS, REPCYP-G, and REPCYP-DEP.

SESAME provides the user with one more type of mean repair cycle time override, called the Repair Cycle Time Support Unit (REPCYU). It allows a unique repair cycle time to be assigned to a particular repair facility. For example, if a particular location is expected to be extremely fast in refurbishing an end item's parts, this short mean repair cycle time for the repair facility can be used. REPCYU assumes all of the parts of a particular end item will require the same mean cycle time when repaired at a repair facility having a REPCYU value. Different end items are allowed to have different REPCYU values at such a repair facility.

The user has to tell SESAME to use either the REPCYE, REPCYP, or the REPCYU values. The user can only choose one of the three per run. SESAME will then use that type of repair cycle time. However, if the user tells SESAME to use the REPCYP values and some are blank, SESAME uses the corresponding REPCYE value. If the user tells SESAME to use the REPCYU values, and some are blank, SESAME uses the

respective REPCYE value. If the user does not tell SESAME which value to use, SESAME uses the REPCYP value. But again, if the REPCYP values are blank, the corresponding REPCYE value is used. If the user leaves all of the repair cycle times blank, SESAME defaults to 0 days for each support facility except the depot. The depot defaults to 90 days. Repair facilities with a mean repair cycle time of zero cannot be used to repair any parts. If the user makes a mistake and has a part shipped to a repair facility where the repair cycle time is zero, SESAME will stop and provide an error message.

As an end item's parts fail at a given location, a certain percentage of them may be sent to a repair facility at one echelon of support while the remainder are sent to a repair facility at another echelon. Figure 3.8 illustrates the

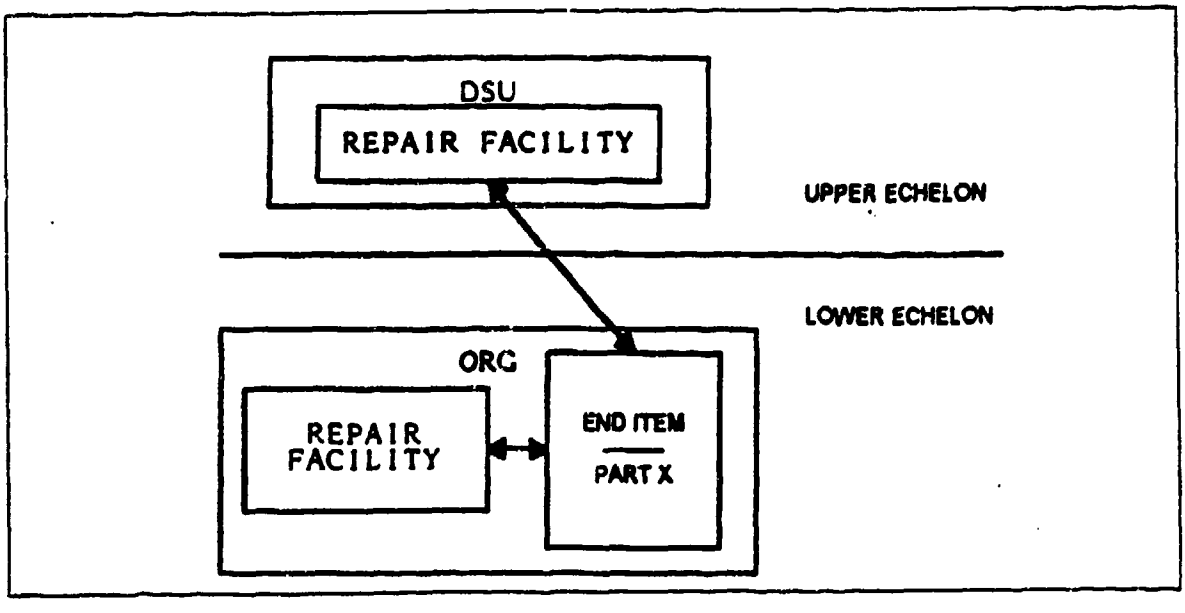

Figure 3.8. Use of Multiple Repair Facilities.

process.

As the same part X in Figure 3.8 fails repeatedly, a percentage of the failures are sent to the repair facility at location ORG and the rest are sent to the repair facility at location DSU. These percentages are usually based on contractor and maintenance personnel estimates [Ref. 25].

If the repair cycle times are different at different repair facilities, the end item experiences an average repair cycle time delay at the failure location equal to the percentage-weighted lengths of mean repair cycle times the part experiences at each facility. And, if the shipping times from these repair facilities are also different, the percentage-weighted order and mean shipping times the part experiences from each facility is used to compute an average order and shipping time. Therefore, the end item's MLDT at the location reflects this average repair cycle time at each facility and plus the average order and shipping time from each facility.

4. Washout rates and procurement lead times for consumable items and worn out repairables

The user can specify parts to be "consumables". Consumables are parts designed to be discarded after failure. The user can also specify parts to be worn out repairables. Worn out repairables are repairables which have been damaged to the point they can no longer be economically repaired at

any echelon. Specifying parts as consumables or as worn out repairables is accomplished by introducing a washout rate (WASH). The washout rate is the percentage of parts that, when they fail, cannot be repaired. For example, a consumable item is never repaired. Therefore, it would obviously have a washout rate of 100%. Worn out repairables typically have a washout rate between 5 and 15 percent.

When a part is washed out, a replacement for it is obtained from either the wholesale activity's inventory, or procured from a vendor outside of the military when the wholesale activity is out of stock. In SESAME, any procurement from a vendor occurs at the highest echelon of the support structure. A lower echelon support location cannot procure its spares from vendors. Lower echelon support locations are also not allowed to bypass higher support echelons and deal directly with the wholesale activity to receive spares. They must follow the paths in the support structure network to access the wholesale activity.

When discussing the wholesale activity, it is necessary to discuss "fill rate". And, when procuring spares from a vendor, it is necessary to discuss "procurement lead time."

The fill rate is the expected percentage of the time the wholesale activity will be able to fill a requisition. It is also referred to as the supply material availability (SMA) [Ref. 5] In SESAME, the user can enter the wholesale

activity's fill rate based on management information reports which provide the statistic [Ref 14]. SESAME defaults to 85%, a standard fill rate expected from wholesale activities [Ref. 13:p. 15]. An 85% fill rate, for example, means that the wholesale activity can provide a spare part from stock 85% of the time. The remaining 15% of the time, the wholesale activity is out of stock and must procure the spare from a vendor.

The procurement lead time at the wholesale level, called the "CONDEL" by SESAME, "specifies the conditional delay, in days, to procure a spare from a vendor when the wholesale level is out of stock." [Ref. 13:p. 15] Every part, regardless of the end item it is from, is assumed to be subject to the same procurement lead time. SESAME defaults to a procurement lead time of 120 days.

When a washed out part is replaced from the inventory of the wholesale activity, the only delay replacing the parts is the time it takes to send the replacement parts to the next echelon level of support. When the wholesale level is out of stock, the part must be replaced by a vendor. The delay to replace a part from a vendor is equal to the procurement leadtime plus the time to ship them to the next echelon of support. SESAME uses the total expected delay as the delay in replacing a washed out part from the wholesale activity. The total expected delay in replacing a washed out part is the sum of the product of 0.85 and the time it takes for the wholesale

activity to provide the replacement parts from stock and the product of 0.15 and the time it takes for the vendor to provide the replacement parts (i.e., CONDEL).

The user is allowed to enter only one fill rate and procurement lead time per run. Therefore, SESAME treats all parts being replaced, regardless of type or location, with the same fill rate percentage and procurement lead time delays.

B. TIGER

1. Ao Calculation

The equations TIGER uses to calculate operational availability are not available in the documentation provided with the software. While the code was written in Fortran, it is virtually impossible to understand what the calculation process is from this code due to lack of any explanation within the code as to what is being computed. Fortunately, simple examples of the equations used in TIGER were obtained from the contractor, Alpha Solutions, and are presented in Chapter IV.

TIGER appears to follow the standard Ao calculations discussed earlier when tested under simple scenarios. These calculations use the reliability and maintenance data for the weapon system's equipment. These data include mean time between failures (MTBF), mean time to repair (MTTR), and various delay times which postpone organizational level repair of the components.

Output provided by TIGER includes the system Ao, system mean downtime, system mean up time, and the availability figures for the different levels of indenture of the reliability block diagram.

For simple scenarios without spares, it appears the operational availability for a given block diagram can be expressed by equation (3.1).

$$Ao = \frac{MTBF}{MTBF+MTTR+OST\ delays\ +REPAIR\ delays}. \qquad (3.1)$$

When a deployed weapon system is assumed to have a pool of spare parts available on site, the availability increases as expected. However, as noted above, the equations used to compute this increase in the Ao value have not been provided by NAVSEA.

Recall that MTBF is only allowed to be input for the equipment level of the weapon system block diagram. It represents the mean number of hours that the equipment operates until it fails. MTBF can be a value from 0.1 to 10,000,000 hours [Ref 8:p. 2-52].

The MTBF can be affected by several ratios the user can input into TIGER at different levels of indenture on the block diagram. One of these ratios is called the "duty factor." The "duty factor" is input by the user at the

function level of indenture in the weapon system. The duty factor is described as "the fraction of full times that this function is operating. For example, a duty factor of 0.75 means the function operates 75% of the time. As a consequence, it will fail proportionally less often then an equipment which has a duty factor of 100% (i.e., is running all the time). A parent function's duty factor applies to all lower indenture subfunctions and equipment. So, if a subfunction has a duty cycle, it will affect the operation of all of its lower indenture subfunctions and equipment by extending their MTBF's. The effect on MTBF at the equipment level is to create an "MTBF effective", which is = (MTBF input)/duty factor." The user is allowed a duty factor value between 0.1% and 100% [Ref. 9]. This "MTBF effective" value appears to be that used by TIGER for the MTBF in Ao computations for the equipment.

Another ratio which effects MTBF is called the "duty cycle". The duty cycle is input at the equipment level of the weapon system's block diagram. Duty cycle is briefly described in the TIGER user's manual as "the ratio of the operating (stress) time to the time the equipment is subject to failure [Ref. 8:p. 2-52]." This author interprets this as a ratio which affects the MTBF of an equipment. If an equipment is not subject to failure for the entire time a weapon system is subject to failure, then the duty cycle changes the MTBF of the equipment. It is different from the

duty factor since it affects only that equipment to which it is applied. From this author's testing, the duty cycle also appears to be divided into the equipment's MTBF in determining the effective MTBF to be used in Ao computations. Since an equipment can be a lower indenture component of a subfunction, the subfunctions "duty factor" will affect the equipment's input MTBF by dividing it to create an effective MTBF. If the equipment also has a "duty cycle", which also divides into the input MTBF, the effective MTBF will be equal to (MTBF input)/(duty factor * duty cycle) [Ref. 9]. This can, therefore, extend the MTBF of the equipment if it is not subject to failure over the entire length of time the weapon system is operated.

A time which can extend the time a weapon system remains up is called "allowable downtime." Allowable downtime affects the function level of indenture of a weapon system. It is described as "the tolerable hours of downtime of a subfunction before its downtime causes the parent function to go down. The default is 0.0." [Ref. 8:p. 2-45] Allowable downtime will effectively increase the mean up time of the system.

Recall that MTTR is also entered at the equipment level of the weapon system's block diagram. Equipment is repaired at the weapon system's location, which can also be called the organizational level. MTTR for the equipment is described as "the average active repair time of the equipment,

in hours. It includes diagnostic action, but not administrative or supply delays." [Ref. 9] TIGER defaults to zero, if a value of MTTR is not specified by the user [Ref. 8:p. 2-27].

The remainder of total downtime includes logistic and repair delays. These are discussed further in the next subsections.

2. Logistic delays

Logistic delays can effect every indenture of the weapon system. The delays will contribute to the overall downtime experienced by the whole weapon system.

Logistic delays for the equipment level of the weapon system include a normal mean order and shipping time (OST) and an urgent mean resupply time. Normal OST is for stock replenishment of on board inventories. Urgent resupply time is the time it takes to provide downed equipment with a spare from a supply location "off ship" when there are no spares on board. The equipment level order and shipping times delay affects all orders the same, regardless of the type of part being ordered. TIGER 9.2A (September 1993 version) has a problem recognizing equipment OST data and will ignore the OST time delay when computing Ao [Ref. 15].

The logistic delays allowed for a part include the same type of delays listed for equipments. They are normal OST times and urgent resupply times. The OST times are

similar to the equipment's order and shipping times, except that the delays are attributed to the shipment time associated with a particular type of part within the equipment. Therefore, a particular part can have its own unique normal and urgent resupply times.

The logistic delays are affected by what is called a "sparing policy." The sparing policy is what TIGER uses in lieu of specified stock levels when replacing failed equipment parts. There is one policy chosen by the user per run and every part has the same sparing policy. The range of sparing policies available to the user goes from having zero spares on board (i.e., no on-board inventory) to having unlimited spares on board [Ref. 8:p. 2-22]. If the overall sparing policy calls for unlimited spares on board, then there are no logistics delays. TIGER 9.A (September 1993 version) also does not recognize any supply administrative delay time [Ref. 15]). If the overall sparing policy is to have zero spares on board, then delays awaiting a part to arrive on board can occur. In order to override the overall sparing policy for a particular part, the user has to provide a specified number of spares for it on board. Then if a spare is needed, TIGER will check the on board spares inventory for that part.

3. Repair delays

Repair delays are allowed to occur when, even though a spare is available, attempts to repair a piece of equipment

are difficult and result in delays in returning the equipment to an operational level. Repair delays are allowed to occur at different levels of indenture in the weapon system. Such delays are illustrated in Figure 3.9.

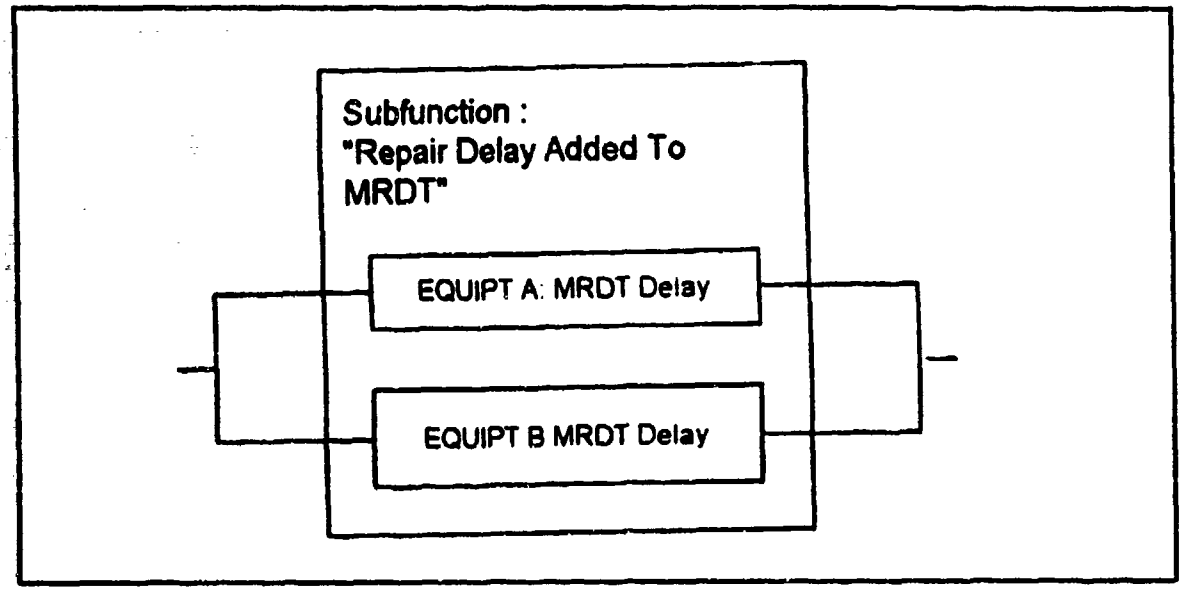

Figure 3.9. An Example of the Indenture of Repair Delays.

At the upper level of indenture of the weapon system's block diagram (called the subfunction), a repair time delay can be added which is broadly described as a "repair delay added to the mean repair delay time (MRDT) or Shop's delay. An example is the time required to reach hard to access equipment." [Ref. 8:p. 2-45]

MRDT is described as "the average delay from detection of a failure to commencing active repair at the organizational level. It includes administrative and operational delays, but not diagnostics." [Ref. 9] This apparently represents the

time delays encountered when a repair shop is used to fix downed equipment. The delays, such as paperwork delays, are incurred when using the shop. TIGER defaults this value to zero [Ref. 8:p. 2-55].

4. Repairables and procurement lead time

It is not apparent that the refurbishment of component parts which could be repaired are modeled by TIGER. It is also not apparent that TIGER models the case where such repairable parts may no longer be economically repaired. Neither the user's manual nor the preprocessor's help routine in TIGER provides information to model such repairables being refurbished when they fail. This suggests replaceable components of a weapon system are exclusively consumable items. "What can be done in trying to model a repairable is to manipulate one of the other delay times available to try and provide a delay time comparable to a repair cycle time." [Ref. 16]

There does not appear to be a procurement lead time other than the OST times used to acquire a part which is not available on board. This means that when a spare cannot be obtained on board, a spare is received from off ship. The order and shipping delays do not distinguish the spare received off ship as being provided by a commercial vendor or a supply facility.

IV. Ao COMPUTATIONS

A. SESAME

1. SESAME's Programs

SESAME uses three separate programs called INPUT, MATH, and OUTPUT to compute weapon system Ao. INPUT reads in the user's information and prepares the information in SESAME format. The MATH program takes the output provided from INPUT and calculates Ao. OUTPUT takes the information MATH produced and writes it to various output reports.

2. MCTBF and MTTR

SESAME calculates Ao for an end item at a particular location using the equation

$$Ao = \frac{MCTBF}{MCTBF+MTTR+MLDT}. \quad (4.1)$$

The mean calendar time between failures (MCTBF) of an end item can be input directly by the user. If MCTBF is not provided by the user, SESAME uses an MCTBF, called Derived MCTBF (DMCTBF), which it calculates, using the equation[2] [Ref. 10]

[2]If MCTBF is input by the user, SESAME does not override it with DMCTBF, even if the two are different [Ref. 14].

$$DMCTBF = \frac{QPWSEI}{EIDEM};$$

(4.2)

where DMCTBF = the MCTBF calculated by SESAME for an end item at a particular location. Its units are in days;

QPWSEI = the quantity of end items required to be up in order for the weapon system to be up [Ref. 13:p. 17]; and

EIDEM = the sum of all of the end item parts' effective maintenance factors (MFE). Its units are in failures per year. It is described by equation (4.3).

QPWSEI is the number of end items that must be operating concurrently for the weapon system to be up. Suppose, for example, that two identical end items are connected in series, then both are required to be up for the weapon system to be up. Therefore, QPWSEI would be equal to two [Ref. 13:p. 18].

The equation for EIDEM is

$$EIDEM = \sum_{i=1}^{n} MFE_i;$$

(4.3)

where i = part index;

n = the number of different parts in the end item; and

MFE_i = effective maintenance factor for part i.

A part MFE is the expected number of failures of the part per day [Ref. 7:p. 5-13] and is calculated by SESAME using inputs from the user. The equation for a part's MFE is

$$MFE = \frac{(FF1/100) * FF3 * USEMODP}{365.25}; \quad (4.4)$$

where FF1 = the part's failure factor. It represents the number of failures for the part per hundred of such end items per year. It can be 7 digits long if no decimal points are used. A positive value is mandatory [Ref. 13:pp. 28,99];

100 = a scaler; It converts FF1 from failures per hundred end items per year into failures per end item per year;

FF3 = an area's environmental failure factor scaler;

USEMODP = a peacetime usage modifier; and

365.25 = the average number of days per year.

FF3 is an environmental factor for a given geographical area in which an end item is expected to operate. It can be entered and used for each part in an end item. It allows for changes in failure rate experienced by a weapon system's end items when the weapon system is operated in different geographic locations. There are six available fields. These fields represent CONUS, Europe, Pacific, Southern Command, Alaska, and "other" [Ref. 13:p. 28]. FF3 is a value between 0 and 99, and is input by the user [Ref. 13:p. 99]. If any of the six available FF3 fields are left blank or zero, SESAME defaults it to 1.0.

USEMODP is a scaler value between 0 and 99 and is input by the user to modify FF1. USEMODP has a value other than 1.0 only when the usage data gathered for the end item indicates that the operational tempo experienced by the weapon system's end item is different then average peacetime usage [Ref. 14]. USEMODP is the same for all of an end item's parts. If blank or zero, SESAME defaults to 1.0 [Ref. 5:p. 20].

The mean calendar time to repair (MTTR) of an end item is directly input by the user. SESAME defaults to zero if no entry is made by the user. [Ref. 13:p. 20]

3. Mean Logistic Down Time (MLDT)

"MLDT is the weighted (by a part's removal rate) average of individual LRU waits." [Ref. 11] The formula for

MLDT is based on Little's Formula from queuing theory [Ref. 17:p. 346]. Little's Formula describes expected line size, E[Line Size], as equal to E[Arrival Rate]*E[Wait] in a steady state. The expected wait time is, therefore, equal to the E[Line Size] divided by the expected Arrival Rate. For a particular LRU at a given location, the expected delay time is given by equation (4.5) [Ref. 11].

$$E[WAIT] = \frac{E[LRU\ REMOVAL\ BACKORDERS\ OUTSTANDING\ AT\ ANY\ TIME\ INSTANT]}{LRU\ REMOVAL\ RATE}. \tag{4.5}$$

MLDT for an end item is determined by equation (4.6) [Ref. 10].

$$MLDT_j = \frac{\sum_{i=1}^{n} TBO_{ij}}{\sum_{i=1}^{n} TDEM_{ij}}; \tag{4.6}$$

where $MLDT_j$ = the mean logistics delay time for an end item at a particular base j;

TBO_{ij} = total expected number of backorders at any instant of time (equivalent to the expected unit years of shortage

incurred per year [Ref. 18: p 185]) for part i at base j;

$TDEM_{ij}$ = total expected annual demand of an end item's part i at base j;

i = the end item's part index; and

n = the number of different parts in an end item.

Knowing the failure rate of the parts and the logistic delay times in providing a spare, one can determine the expected quantity of parts in the pipeline for a given location by using Little's Formula. This "pipeline quantity" is the expected number of replacement parts that are either coming from an inventory of spares or from a repair facility [Ref. 19]. From work by Kotkin [Ref. 17], TBO is a function of both the number of parts s in inventory and the pipeline quantity X at a base j and is given by the equation (4.7) [Ref. 17:p. 38].

$$TBO = Pr(X > s).$$

(4.7)

SESAME assumes that the pipeline quantity follows a negative binomial distribution. The pipeline quantity can, therefore, be computed at each base.

SESAME computes pipeline quantities at the upper support echelons first, and continues these computations down to the organizational level (ORG). This ultimately provides the total expected pipeline quantity for the end item's parts at the ORGs, which is used to determine the expected number of backorders at the ORGs. Starting at a DSU, for example, SESAME computes the expected pipeline quantity as the number of parts in the DSU's repair facility and the expected number being shipped to it from the next higher echelon. SESAME then uses this to determine the number of backorders at the DSU. SESAME then computes the "basic pipeline" quantities at each ORG [Ref. 11]. These "basic pipeline" quantities represent the expected number of an end item's parts in the ORG's repair facility plus the number in shipment from the DSU to the ORG. SESAME finally creates a total expected pipeline quantity for each ORG by combining the ORG's basic expected pipeline quantity with a respective portion of the DSU's backorders. The portion of the DSU's expected backorders that an ORG receives is equal to the proportion of demands on the DSU that is generated by the ORG relative to other ORG demands on the DSU by other ORG's. This allows the conditional mean and conditional variance of the pipeline quantity distribution at the ORG, called the "extended mean" and "extended variance", to be computed. These are given by equation (4.8) and (4.9) [Ref. 10].

$$EXTENDED\ MEAN = OMEAN + SHARE * EBO \ ; \tag{4.8}$$

where OMEAN = the ORG expected pipeline quantity;

EBO = the DSU expected backorder quantity; and

SHARE = the portion of the DSU expected backorder quantity which is expected to be sent to that ORG.

$$EXTENDED\ VARIANCE = OVAR + (SHARE * (1 - SHARE) * EBO) + BOVAR * SHARE * SHARE) \ ; \tag{4.9}$$

where OVAR = the variance of the ORG's basic pipeline quantity; and

BOVAR = the variance of the DSU's backorders quantity.

The extended mean and variance are used to determine the parameters for the negative binomial of the total pipeline quantity.

The negative binomial distribution is described by equation (4.10).

$$p(n) = \binom{n-1}{r-1} * p^r * (1-p)^{n-r};$$

(4.10)

where n = the random variable representing the total pipeline quantity; and

r,p = the negative binomial parameters given by equations (4.11) and (4.12).

$$p = \frac{EXTENDED\ MEAN}{EXTENDED\ VARIANCE}.$$

(4.11)

$$r = EXTENDED\ MEAN * p/(1-p).$$

(4.12)

The mean and variance of the pipeline quantities will be the same unless there is competition by several ORGs for the same spares available at higher echelons of support. When the mean and variance are the same, the negative binomial reduces to the Poisson.

The process of adding spares at the support locations can be thought of as a recursive process. SESAME begins the process by computing the number of backorders at any instant

of time when there are no spares available at the ORG site. It then adds spares one at a time until some desired number of spares on-hand is reached. This might be a consequence of trying to achieve a specified Ao for the end item.

If there is no stock at a given location or support echelon below the wholesale level, the total expected number of backorders at any instant in time for an end item is determined using the equation (4.13).

$$TBOo_j = \sum_{i=1}^{n} [\ MFE_i * [\sum_{k=1}^{m} MTD_{ki} * (OST_{ki} + REPCY_{jk})$$

$$+ (WASH_i)\,[WHOFIL * (OST_{wj}) + (1 - WHOFIL) * (CONDEL + OST_{wj})]\ ];$$

(4.13)

where i = index of the end item's different parts;

n = the total number of the end item's different parts;

k = index of a repair facility;

m = total number of support echelon repair facilities;

$TBOo_j$ = total backorders for an end item at deployed location j with zero spares;

MTD_{ki} = decimal fraction of part i repaired at

the support echelon repair facility k;

OST_{kj} = the order and shipping time to send the parts from the repair facility k back to location j;

$REPCY_{jk}$ = represents the level of the repair facility;

$WASH_i$ = the fraction of repairable parts i which are damaged beyond repair;

WHOFIL = the decimal fraction of spares expected to be available at the wholesale activity (the fill rate);

(1 - WHOFIL) = the decimal fraction of spares needing to be procured from a vendor;

CONDEL = the procurement lead time to procure a part vendor; and

OST_{wj} = the order and shipping time from the wholesale activity to location j.

"When spares are added into inventories at the support locations, TBO can be calculated based on the knowledge of the pipeline quantity distribution, and the amount of stock." [Ref. 11:p. 39] From the model developed by Kotkin [Ref. 17], TBO is a function of a given asset level[3] and pipeline quantity distribution with the mean and variance given by

[3]asset level is equal to (on hand stock) + (stock on order) + (parts being repaired at repair facilities) - (backorders) [Ref. 11]

equations (4.14) and (4.15) [Ref. 11:p. 39].

$$E[B(s)] = E[B(s-1)] - Pr(X > s-1); \quad (4.14)$$

$$Var[B(s)] = Var[B(s-1)] - Pr(X \leq s-1) * (E[B(s)] + E[B(s-1)]); \quad (4.15)$$

where B(s) = number of backorders at any instant of time given an asset level of s; and

X = number of parts in the pipeline.

To illustrate the iterative process, consider, for example, the case of a Poisson pipeline distribution. Adding the first spare to the ORG level changes the expected number of backorders according to the equation (4.16).

$$E[B(1)] = E[B(0)] - Pr(X > 0); \quad (4.16)$$

where E[B(1)] = the expected number of backorders with 1 spare available in inventory at the

ORG;

E[B(0)] = the expected number of backorders with 0 spares available in inventory at the ORG (determined using equation (4.13)); and

Pr(X>0) = the Poisson probability of having a pipeline quantity X greater than zero.

For the Poisson process, Pr(X>0) can be represented by equation (4.17).

$$Pr(X > 0) = 1 - p_x(0); \quad (4.17)$$

where $p_x(0)$ = the Poisson probability of zero units of a part in the pipeline. The mean of the distribution will be the same as the mean of the backorders with zero spares, and is, therefore, equal to equation (4.13).

X = the random variable representing the pipeline quantity;

When another spare is added to the ORG level, the expected number of backorders at any instant in time is given by equation (4.18).

$$E[B(2)] = E[B(1)] - Pr(X>1);$$

(4.18)

where $Pr(X>1) = 1 - F_x(1)$

$= 1 - p_x(1) - p_x(0)$.

Notice that as each spare is added, the expected number of backorders decreases by $Pr(X>s-1)$, where s-1 was the previous number of spares and s is the current number after adding one more.

If the pipeline distribution is not Poisson (i.e., if the mean and variance given by equations (4.8) and (4.9) are not equal), the negative binomial distribution is used in the same manner as described above to determine the expected number of backorders as spares are added.

For a given level of parts in inventories at a given ORG, SESAME calculates the total expected number of backorders at any instant of time for each part of an end item at that ORG. It then adds all of the parts' expected number of backorders together to determine the total number of backorders at any instant of time associated with the end item at a specific location.

When inventories are added at the intermediate activities, the number of backorders accumulated there can also be calculated using equations (4.14) and (4.15). The

number of backorders at the intermediate activity is a function of the pipeline quantities from higher echelon support activities replenishing it and the quantity in repair facilities at the intermediate location. Adding intermediate inventories reduces the number of backorders at the intermediate support activities. This in turn reduces the number of backorders apportioned to an ORG, which reduces the total number of backorders at the ORG Therefore, adding intermediate inventories reduces the total number of backorders at the ORG.

The total expected annual demand rate of an end item's parts is a function of the failure rates of each of its parts and can be computed from equation (4.19).

$$TDEM = \sum_{i=1}^{n} (FF1/100)_i * (FF3)_i * \ldots EMODP);$$

(4.19)

where TDEM = the total demand rate of all of an end item's parts (units/year);

i = part index; and

n = the number of parts in the end item.

Once TBO and TDEM are determined for an end item at a given location, the end item's MLDT at that location can be calculated using equation (4.6).

4. Part redundancy within an end item

If a part within an end item is redundant, the Ao for the end item at a given location will be determined differently. "For redundant parts within an end item, SESAME calculates the probability that a sufficient number of units of the part will be non-functional to cause the end item to go down." [Ref. 13:p. 67] "When there is no redundancy, one backorder equates to one end item down. When there is redundancy, that is no longer true since there can be a backorder and the end item can still be up. SESAME first determines the distribution of the number of existing backorders for a part at a location using the negative binomial distribution. If there are more backorders for an end item's parts than the amount needed to keep the end item up, then the end item is considered down. If there is more than one similar end item at a location, the number of backorders are distributed amongst the end items to determine how many of them are down. A backorder is distributed to an end item only once, and are distributed amongst the end items until they are all assigned." [Ref. 20] SESAME uses the hypergeometric distribution to determine the number of end items down based on a given number of backorders because the process of distributing backorders to end items is similar to sampling (distributing) without replacement [Ref. 16].

The Ao for multiple identical end items at a given location having redundant parts is determined by equation (4.20) [Ref. 11]

$$1 - \frac{\textit{Number of the same type of end items down at a location}}{\textit{Total number of the same type of end items at a location}}.$$

(4.20)

"If there are non-redundant parts in the end item, the Ao reflecting only these parts is computed using the pipeline quantity distribution and available spares", which was described in Section 3 of this thesis. That Ao is then multiplied by the Ao determined by the redundant parts [Ref. 13:p. 67].

5. End item Ao and Weapon System Ao

SESAME first calculates the Ao for each end item at each location because similar end items can have different operational availability values at different locations. It then uses equation (4.21) to determine the end items's system-wide Ao.

$$Ao_k = \sum_{j=1}^{n} (NEISUP_j)/NEISUP_{total} * (Ao_j);$$

(4.21)

where Ao_k = the average system-wide Ao for the k^{th} end item;

j = the location index;

m = the number of locations at which an end item is supported;

$NEISUP_j$ = the number of end items supported at a location j; and

$NEISUP_{total}$ = the total number of end items supported at all locations.

Next, SESAME determines the weapon system Ao. The weapon system Ao is the product of the different end items' system-wide Ao's and is described by equation (4.22) [Ref. 10]; namely

$$Ao = \prod_{k=1}^{z} Ao_k^{QPWSEI_k}; \qquad (4.22)$$

where Ao = the weapon system Ao;

Ao_k = the end items's system-wide Ao;

k = the end item index;

z = the number of different end items in the weapon system; and

$QPWSEI_k$ = the quantity per weapon system of the end

item that must be operating concurrently for the weapon system to be up [Ref. 13:p. 17].

This author believes that if the weapon system is represented in SESAME by its end items, the Ao for each weapon system should first be calculated at each deployed location. This can be accomplished by multiplying the end items' Ao's together at each location. Then, the final average weapon system Ao can be calculated by averaging all of the deployed weapon systems' Ao values. This allows the final weapon system Ao to represent the average deployed weapon system Ao. Equations (4.23) and (4.24) can be used.

$$Ao_j = \prod_{i=1}^{n} Ao_{ij};$$

(4.23)

where j = index of deployed location j;

Ao_j = weapon system Ao at location j;

i = index of weapon system's ith end item;

Ao_{ij} = ith end item's Ao at location j;

n = total number of end items in a weapon system.

$$Ao = \sum_{j=1}^{m} \frac{Number\ of\ weapon\ systems\ deployed\ at\ location\ j}{Total\ number\ of\ deployed\ weapon\ systems} * Ao_j$$

(4.24)

where j = index of deployed location j;

m = total number of locations which deploy the the weapon system;

Ao_j = weapon system Ao at location j; and

Ao = the overall average Ao of the weapon system.

B. TIGER

TIGER will calculate the operational availability over time for a weapon system and a specified mission. However, the interest in this thesis is the steady-state A_o since the model is being compared to SESAME, which is only capable of determining a steady-state A_o. The TIGER code is not as well documented as SESAME and it was difficult to obtain the same level of information and insight about model intricacies as were obtain from Dr. Meyer Kotin, the coauthor of SESAME with Martin Cohen of the Army's Inventory Research Office in Philadelphia. Fortunately, Professor Alan McMasters was able to talk with TIGER's developer, Dr. James P. Matthesen of Alpha Solutions, during a trip to Washington, DC, the end of April. Dr. Matthesen explained that the reason for developing the Version 9 for TIGER was because the Joint Chiefs of Staff

(JCS) and NAVSEA wanted a model to do readiness based sparing in a dynamic environment. Version 8 was a Monte Carlo simulation model and would be very difficult to used for any sort of optimization. Therefore, Matthesen decided to return to Markov chain modeling and to the use of the associated Markov state space differential equations to provide a time dependent A_o. Tiger 9 is even more generalized in that distributions other than the exponential can be selected by the user.

To illustrate the new model, he provided the equations for one of the simple scenarios to be considered in Chapter V as a comparison test between SESAME and TIGER. The specific scenario is that of one weapon system (one equipment) which contains one part which can fail during use. A single spare part is also allowed to be available at the organizational level. Spares needed for replacing the spare part are shipped (resupplied) from the next higher support echelon.

The differential equations are:

$$
\begin{aligned}
P_{10}' &= -\lambda P_{10} + \mu P_{00} + \sigma P_{11} \; ; \\
P_{00}' &= -\mu P_{00} + \sigma P_{01} \; ; \\
P_{11}' &= -\lambda P_{11} + \mu P_{01} - \sigma P_{11} \; ; \\
P_{01}' &= \lambda P_{10} + 2\sigma P_{02} - \mu P_{01} - \sigma P_{01} \; ; \\
P_{02}' &= \lambda P_{11} - 2\sigma P_{02} \; .
\end{aligned}
$$

(4.25)

where:

P_{ij} = the probability of being in state i,j at any instant of time;

P_{ij}' = dP_{ij}/dt;

i = 1, meaning one part is installed in a weapon system (an equipment) that is up (i.e., the installed part is working), or 0, meaning that zero parts are installed in an equipment that is up (i.e., the equipment has failed) and the part is being replaced at the organizational level or the equipment is awaiting a replacement part from the next echelon;

j = number of parts in resupply (i.e., in shipment from the next echelon);

λ = 1/MTBF,

μ = 1/MTTR,

σ = 1/OST.

The use of only two subscripts deserves an explanation. Each state assumes that there are two good parts somewhere; this includes being in the weapon system (equipment). There are always two good parts because whenever one needs to be replaced it is exchanged, via resupply, for a good part from the next echelon.State 00 corresponds to the weapon system (equipment) being down because its part has failed and that

the organizational level. A second spare part is also on hand to be used when the next failure occurs. State 01 also corresponds to the weapon system (equipment) being down because its part has failed and that part is being replaced at the organizational level. In this state, however, there is no extra spare on hand. There is a spare being shipped from the next echelon. State 10 corresponds to the weapon system being "up" (i.e., the part in the weapon system is working) and a spare is also on hand. State 11 also corresponds to the weapon system being up. However, there is no on hand spare. There is one being shipped from the next echelon. Finally, State 02 corresponds to the weapon being down but no on hand spare is available to replace the failed one. Therefore two spares are being shipped from the next echelon, one to replace the failed one and another to be an on-hand spare.

Matthesen said that the probability distributions for the various times (for failures, repair and order and ship times) in these equations are assumed to be exponential as are those in SESAME.

It should be obvious from the description of the various states that the ordering policy assumed at the organization level is S, S-1; that is, when a spare at the organizational level is installed to fix a failure then a replacement is immediately requested from the next echelon. It may not arrive, however, before the next failure occurs.

The steady-state balance equations for this case are:

$$\lambda P_{10} = \mu P_{00} + \sigma P_{11} ;$$

$$\mu P_{00} = \sigma P_{01} ;$$

$$\mu P_{01} = (\lambda + \sigma) P_{11} ;$$

$$(\mu + \sigma) P_{01} = \lambda P_{10} + 2\sigma P_{02} ;$$

$$\lambda P_{11} = 2\sigma P_{02} .$$

(4.25)

Solving for P_{00} using these equations, and the fact that

$$P_{00} + P_{01} + P_{10} + P_{11} + P_{02} = 1,$$

gives:

$$P_{00} = \frac{\lambda+\sigma}{\lambda+\sigma+2\mu+\mu(\frac{\lambda}{\sigma}+\frac{\sigma}{\lambda})+\mu^2(\frac{1}{\lambda}+\frac{1}{\sigma})+\frac{\lambda}{2}(\frac{\mu}{\sigma})^2}$$

(4.26)

The other state probabilities can then be easily obtained by substituting this formula into the balance equations.

The operational availability can be obtained from:

$$A_0 = \frac{P_{10}+P_{11}}{P_{00}+P_{01}+P_{10}+P_{11}+P_{02}}$$

(4.27)

And, since the denominator sums to 1.0, this equation reduces to

$$A_o = P_{10} + P_{11}.$$

(4.28)

The case where there no spares allowed to be on hand is simpler. In this case there is only one good part assumed to be somewhere. The states are reduced to State 00, State 10, and State 01. State 10 corresponds to the weapon system (equipment) being up. State 01 corresponds to the system being down and repair having to wait until a part is received from the next echelon. State 00 corresponds to the equipment being down and in repair (i.e., a good part is being installed). The differential equations are:

$$P_{10}' = -\lambda P_{10} + \mu P_{00} ;$$

$$P_{00}' = -\mu P_{00} + \sigma P_{01} ;$$

$$P_{01}' = \lambda P_{10} - \sigma P_{01} .$$

(4.28)

The balance equations are then:

$$\lambda P_{10} = \mu P_{00} ;$$

$$\mu P_{00} = \sigma P_{01} ;$$

$$\lambda P_{10} = \sigma P_{01}.$$

(4.29)

The resulting state probabilities are:

$$P_{00} = \frac{\frac{1}{\mu}}{\frac{1}{\lambda}+\frac{1}{\mu}+\frac{1}{\sigma}} = \frac{MTTR}{MTBF+MTTR+OST}$$

$$P_{01} = \frac{\frac{1}{\sigma}}{\frac{1}{\lambda}+\frac{1}{\mu}+\frac{1}{\sigma}} = \frac{OST}{MTBF+MTTR+OST}$$

$$P_{10} = \frac{\frac{1}{\lambda}}{\frac{1}{\lambda}+\frac{1}{\mu}+\frac{1}{\sigma}} = \frac{MTBF}{MTBF+MTTR+OST}$$

(4.30)

In this case, the operational availability formula becomes the classic:

$$A_0 = \frac{uptime}{uptime+downtime} = P_{10} = \frac{MTBF}{MTBF+MTTR+OST}$$

(4.31)

In contrast to SESAME, a weapon system (equipment) has an input MTBF. Then, when the equipment fails in the simulation version, TIGER decides through a series of Bernoulli trials which parts need to be replaced in accordance with their individual replacement rates. In this way, parts replacement rates are not confused with equipment failure rate. Other models assume the system fails whenever any part in it fails. Matthesen thinks that is too simplistic an approach for

complex systems. He used an automobile as an analogy. When something fails it is common to replace several parts, or in some instances, to replace no parts at all. This process is also part of TIGER 9.2.

V. SESAME AND TIGER COMPARISONS

A. Ao CALCULATIONS

The basic Ao formulation appears to be similar for both SESAME and TIGER. Both models follow equation (5.1).

$$Ao = \frac{UPTIME}{UPTIME + DOWNTIME}; \quad (5.1)$$

with uptime = mean time between component failures; and

downtime = mean down time caused by delays including repair time.

The result is equation (5.2) for SESAME.

$$Ao = \frac{MCTBF}{MCTBF+MTTR+MLDT}; \quad (5.2)$$

where MCTBF = mean calendar time before failure. This is uptime measured in days;

MTTR = mean time to repair;

MLDT = mean logistic downtime; and

MTTR + MLDT = the downtime delays for the end item, measured in days.

The Ao formula used in TIGER is equation (5.1). For the no spares on-hand case at the end of the previous chapter, it reduces to equation (5.2) with MLDT = OST. Otherwise, the downtime term of (5.1) is used to represent all of the downtime experienced by a weapon system. This downtime figure includes the actual time it takes to repair the equipment in the weapon system when all needed spares are available to complete the repair. But it also includes the downtime caused by other delays. The other delays include, for example, the order and shipping time it takes to obtain a spare part from the next echelon to replace the one which failed in the equipment.

B. ECHELON STRUCTURE AND INPUT DATA

It appears that the input data for SESAME and TIGER are similar. SESAME uses a user-supplied value for the time an end item operates before failing (MCTBF). It will also compute an MCTBF, called derived MCTBF, or DMCTBF, for use as an end item's operating time if the user does not provide one. It also uses a user-supplied value for the time it takes to repair the end item once it has failed (MTTR). As mentioned above, the units of time are calendar days during normal operation of the weapon system. There are no ratios applied

to MCTBF in SESAME to account for intermittent usage of the weapon system as there are in TIGER. The author believes, therefore, that the user must account for intermittent usage before entering MCTBF data values.

TIGER is similar to SESAME in that it uses a user-supplied value for the time equipment operates before failing (MTBF). It does not, however, compute an MTBF if one is not provided. It also uses a user-supplied value for the time it takes to repair equipment (MTTR). Both are measured in hours. In contrast to SESAME, there are user-supplied ratios allowed in TIGER which can be used to represent the percentage of time the equipment actually operates in the weapon system. These ratios alter the mean times before failure of equipments to reflect intermittent operation of the equipment.

The remaining times used in computing Ao are represented differently in SESAME and TIGER. SESAME allows for four echelons of support to provide working spares to downed end items. Each echelon of support allows for time delays to provide these spares. In SESAME, the choices for modeling delays include several different order and shipping times, several different repair cycle time delays for repairables, and procurement lead times for spares procured from a vendor. These delays are all associated with providing a spare to repair a failed end item. Any other logistic delays which contribute to downtime in a weapon system have to be incorporated into one of the available choices. In addition,

any delay not associated with providing a part to repair an end item must be accounted for by the mean time to repair that end item.

TIGER allows only two echelons of spare support and considers only one weapon system (equipment) at only one location. The delays in providing spare support affect only that one location. They include delays to reach the equipment to repair it, administrative delays by a repair shop involved in its repair, and supply delays in providing a spare for the repair. Each have their own input values. These are summed to determine the total downtime of the equipment.

SESAME and TIGER both compute Ao for a weapon system. But the way a weapon system is represented in each model is different. SESAME models an aggregate weapon system comprised of individual weapon systems deployed at different locations. Each individual weapon system is comprised of major components called end items which have internal replaceable parts. SESAME calculates the Ao for the aggregate weapon system based on the aggregate operational availabilities of the individual weapon system's end items deployed at all locations. The different types of end items in an individual and, hence, aggregate weapon system are, therefore, assumed to work in series.

As mentioned above, TIGER considers only one weapon system at only one location. The Ao calculated for the weapon system is the operational availability for the weapon system at that

particular location. However, the weapon system can be broken down into many levels of indenture, which allows TIGER to compute Ao for non-series situations.

Ultimately, the level of indenture reaches the equipment level. These major components of the weapon system are similar to end items in SESAME, with internal, replaceable parts.

C. REDUNDANCY

The ways TIGER and SESAME model redundancy in a weapon system are different. SESAME cannot model redundancy at the end item level. Similar end items are assumed to operate individually or in series. Different end items in a weapon system can be modeled only in series. Redundancy can be modeled, however, at the parts level within an end item.

TIGER allows the major components and equipment within a weapon system to be modeled in series or in parallel. The parts within the equipment do not appear capable of being modeled redundantly, however.

D. SUPPORT STRUCTURE

As mentioned above, SESAME allows for more than one echelon of support for a weapon system. This includes having the weapon system's support activities at different locations. The support can be either as inventories of spares or as repair facilities for repairable spare parts. SESAME also

includes a wholesale support activity which allows out of stock parts to be procured from a vendor.

TIGER has only two echelons of supply support for a weapon system. Support comes from inventories at the location of the weapon system or from spares shipped to the location from the second echelon of support. The second echelon of support provides spares after a given delay time. It is not explicitly a procurement lead time from a vendor or the order and shipping time from a supply activity. It is simply a delay each time a spare part is required on board, either in inventory or for use in downed equipments.

E. REPAIRABLES

SESAME models both consumables and repairables in a weapon system. Removal of the repairables, the repair cycle time they spend at the repair facility, the washout of some, and the return to service of others can all be modeled in SESAME. Repair can be accomplished at various repair facilities in the support structure. However, shipment of failed repairables to the repair facility is not accounted for by any of the various available order and shipping times. It must be accounted for in the repair cycle time.

TIGER, Version 9.2A considers its repair parts to be only consumable items.

F. DOCUMENTATION AND CUSTOMER SERVICE

At this point in time, SESAME has better documentation available than TIGER. SESAME's code is also easier to follow and understand because it is better documented. In addition, this author's questions on SESAME referred to the U.S. Army Material Systems Analysis Activity's (USAMSAA) Inventory Research Office in Philadelphia were always quickly responded to by USAMSSA personnel. Advice, references, and help were always provided when needed. Dr. Meyer Kotkin, in particular, provided valuable insight to the author on the intricacies of SESAME (Dr. Kotkin and his colleague Martin Cohen wrote SESAME). TIGER did not yet have any detailed documentation to explain the model derivations. The two examples in the preceding chapter do provide clues as to the equations which make up the model. Dr. Jim Mattheson of Alpha Solutions indicated that the equations become much more difficult as more equipments make up a weapon system and more parts make up an equipment. In addition, the code is not well documented and is, therefore, difficult to follow and understand.

G. RESULTS OF SIMILAR SCENARIOS

The author attempted to make a direct comparison of Ao results computed by TIGER and SESAME using similar scenarios. It was discovered that this, too, was difficult because, as discussed in the earlier sections of this chapter, each program modeled different types of weapon systems under

different conditions.

To make a comparison using a basic scenario, it was necessary to meet each of the model's capabilities and features. Some limiting constraints had to, therefore, be established for each model.

SESAME was restricted to the following;

a. the weapon system is deployed at only one location;
b. there are only two echelons of supply support (ORG and DSU), with unlimited spares available from the upper echelon; and
c. all end item's parts are consumables.

TIGER was restricted to;

a. the weapon system has only one level of indenture;
b. the components in the weapon system have to be equipment without subfunctions;
c. if there are several equipments, they have to operate in series; and
d. an unlimited spares policy is assumed from the upper echelon.

Two scenarios were developed that could be used as comparisons while still adhering to the constraints listed above. The first was to assume a one component weapon system. On the first run of this scenario, the lower echelon support activity used in each program had zero spares in stock. This forced all spares to be drawn from the upper echelon of supply. Subsequent runs were then made which added stock to

the lower echelons of supply before each run. Stock was added in single unit increments until the inherent operational availability was reached for the weapon system (i.e., the mean logistics delay time reached zero).

The second scenario was similar to the first. A single weapon system was assumed. However, in this scenario the weapon system in SESAME consisted of two similar end items in series and the weapon system in TIGER consisted of two similar equipments in series. Again, the lower echelon support location started out having zero spares. Subsequent runs were then made which added stock in single unit increments to the lower echelon of supply before each run. Stock was added until the inherent operational availability was reached for each weapon system.

For both scenarios, SESAME's end items were assumed to have an MCTBF of 73 days and an MTTR of 2 days. TIGER's equipments were assumed to have the same MTBF and MTTR. Both models assumed an order and shipping time from the upper echelon of support to the organizational level of support of 20 days.

Tables 5.1, 5.2, 5.3 and 5.4 present the results of the runs. The time units for system uptime and downtime are calendar days.

Table 5.1. SESAME RESULTS FROM SCENARIO #1.			
# SPARES	SYSTEM Ao	SYSTEM UP TIME	SYSTEM DOWNTIME
0	0.768	73	22.00
1	0.942	73	4.50
2	0.971	73	2.22
3	0.973	73	2.01
4	0.973	73	2.00

Table 5.2. TIGER RESULTS FROM SCENARIO #1.			
# SPARES	SYSTEM Ao	SYSTEM UP TIME	SYSTEM DOWNTIME
0	0.769	73	22.00
1	0.917	73	6.63
2	0.966	73	2.56
3	0.973	73	2.01
4	0.973	73	2.00

Table 5.3. SESAME RESULTS FROM SCENARIO #2.				
# SPARES	END ITEM Ao	END ITEM UP TIME	END ITEM DOWNTIME	SYSTEM Ao
0	0.768	73	22.00	0.590
1	0.917	73	6.60	0.841
2	0.963	73	2.77	0.928
3	0.972	73	2.10	0.945
4	0.973	73	2.01	0.947
5	0.973	73	2.00	0.947

Table 5.4. TIGER RESULTS FROM SCENARIO #2.				
# SPARES	EQUIPT Ao	SYSTEM Ao	UP TIME	DOWNTIME
0	0.769	0.591	36.5	25.3
1	0.878	0.771	36.5	10.8
2	0.948	0.900	36.5	4.08
3	0.969	0.939	36.5	2.36
4	0.973	0.947	36.5	2.03
5	0.973	0.947	36.5	2.03

In the first scenario (Scenario #1, Table 5.1 and 5.2), the weapon system's Ao was calculated using the system's up time and downtime from each model. When there were no spares available at the lower echelon, the system downtime equaled the order and shipping time delay plus the time to repair the weapon system component. In this case both TIGER and SESAME had the same system Ao.

In the remaining cases in which stock was added, TIGER and SESAME calculated Ao as being the same or nearly the same. The major differences in Ao occurred when there were only one or two spares in stock at the lower echelon. In each case, TIGER provided an Ao lower than SESAME. The biggest difference occurred when there was only one spare in stock. TIGER was smaller by a little over 2%.

In addition, each system Ao for both TIGER and SESAME reached the inherent availability value when the same numbers of spares were available in stock at the lower echelon support location. The weapon system in each model required four spares to reach the value.

In the second scenario (Scenario #2, Tables 5.3 and 5.4), the system Ao was calculated as the square of the weapon system's two identical components' operational availabilities for each model. Each system Ao for both TIGER and SESAME again reached the inherent availability value when the same numbers of spares were available in stock at the lower echelon support location. The weapon system in each model required

five spares to reach the value.

When there were no spares at the lower echelon, the system Ao and components' Ao's were calculated to be the same in each model. When the number of spares was one to four, the system Ao's were not and TIGER computed a lower Ao value. The biggest difference in the results for each model was again at a stock level of one spare. This time the difference in the computed system Ao was 7%.

Tables 5.1 through 5.4 were shown to Dr. Jim Mattheson at Alpha Solutions and he was asked if he knew why the models might give such different results. Since the case of one spare available at the organizational level showed the largest difference between the model results from TIGER and SESAME, he derived the differential equations which would apply for the first scenario. These are shown in Chapter IV as equation (4.25). Then, to get the steady-state Ao, the balance equations given by equation (4.26) were used to derive the various state probabilities. Finally, Ao was computed using equation (4.29) and the same MTBF, MTTR, and OST as scenario #1. The result was that Ao is equal to 0.948. He also calculated the no spares case and got 0.768 using equation (4.32). These results indicated that TIGER 9.2A was not correctly computing Ao (and, of course, neither is SESAME for the one spare case but it is closer than the TIGER result). When Professor McMasters visited Alpha Solutions in April, he was told that there were clearly programming problems with

Version 9.2A. Since then, the scenario #1 one spare case has been used to guide their search for programming errors. In a telephone conversation with Mr. John Miller of Alpha Solutions an 3 June 1994, Professor McMasters was told that the programming problems have not yet been resolved. When they are, a new PC version of Tiger will be released.

In summary, the number of scenarios which could be used to make direct comparisons between the two models are severely limited. This is due for the most part to the fact that SESAME Version 9.2A has very limited multi-echelon capability. This is being remedied by Alpha Solutions. However, the date when their multi-echelon version will be released is not known. For the runs that were made, the results were either the same, or nearly the same. If there were differences in the results, TIGER calculated lower Ao values than SESAME. The TIGER results are incorrect and are being used to by Alpha Solutions to debug the Version 9.2A. Until the programming problems are resolved and correct results are provided, there is also no way of knowing how well SESAME performs.

VI SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

A. SUMMARY

The author compared how TIGER and SESAME compute the steady state operational availability for a weapon system. A description of both models and examples of the scenarios each is capable of modeling to compute Ao are given. The input values for the weapon system and their impact on Ao are discussed. The differences between the two models in their capabilities and inputs are highlighted. Where possible the calculations and equations each model uses to compute Ao are explained. In addition, similar scenarios were developed and used in each model in order to compare the results.

B. CONCLUSIONS

The author concluded that the two models have quite different capabilities. Currently TIGER is designed to compute Ao for a weapon system at one location while SESAME can compute Ao for a weapon system at several locations. TIGER assumes the weapon system fails and then determines which parts caused it. SESAME assumes a single specific part's failure is the cause of a weapon systems's failure. SESAME also provides for four echelons of logistic support, while TIGER, at present, has at most two echelons. A multi-echelon (more than two) version of TIGER is being developed.

SESAME also explicitly models parts as capable of being repaired "as good as new" by repair facilities while TIGER does not. It also has the capability to model procurement from vendors and wholesale logistic support. TIGER can do neither. A repair capability will be incorporated in the new multi-echelon version of TIGER and, presumably, procurement from vendors will also be included. It is not known when this version will become available.

Both models do compute Ao based on weapon system components that have operating times and, upon failure, have times required for repair. Included in the Ao computations are logistic delays which postpone the repair of the failed weapon system components. It appears that both models use that information to compute Ao based on uptime divided by total uptime and downtime. Unfortunately, neither model computes Ao correctly except in the limiting cases of no spares on-hand and an infinite number of spares on hand.

Documentation support for SESAME from its developers at USAMSSA was a valuable asset. Documentation for TIGER is currently quite limited. Improved documentation is being developed

C. RECOMMENDATIONS

Each model can compute Ao for a weapon system at a particular location with given logistic support. Because SESAME has more of a supply support focus and very good

documentation, it appears its use might be more beneficial to JLSC in the near future. However, the final computation of the weapon system's Ao should be changed to determine weapon system Ao first at each deployed location and then use that information to determine the overall weapon system Ao. TIGER's current strength lies in its ability to handle non-series systems and multi-indenture levels. A useful area of research would be to try to model non-series redundancy at the end item level in SESAME.

This thesis had shown that both models leave much to be desired. They are difficult to compare for a variety of reasons. In particular, until the programming problems in TIGER are resolved, there is no way of knowing how well SESAME performs in computing Ao.

Much more detailed study of both models is needed before one should be selected as the "best of breed" by JLSC for determining steady state Ao. JLSC should also study the optimization of spares by each model at different echelons of support in order to fully understand the readiness based sparing capabilities of each model.

Finally, SESAME could serve as an interim model until the new multi-echelon version of TIGER is completed if there is a need for JLSC to select a model in the near future.

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