THE APPLICATION OF A READINESS-BASED SPARING MODEL TO FOREIGN MILITARY SALES

THESIS

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Abstract

Current Foreign Military Sales (FMS) models provide stock levels that result in a very low system availability or a funding requirement that exceeds the overall budget. The purpose of this research was to determine if an inventory model exists that can be used in FMS reparable sparing to provide a more efficient and economical inventory purchase. The Aircraft Sustainability Model (ASM) is such a model, providing the most aircraft availability possible from a given inventory investment by computing the optimal number of spare parts to buy for each item.

FMS data was obtained from two sources - the International Data System (IDS) and the International Weapon Item Projection System (IWIPS). Both systems are currently used in FMS reparable sparing to provide stock level requirements to customer countries. The data obtained from these FMS systems included part data, program data, and actual recommended stock level quantities calculated by the respective FMS systems.

The ASM when compared to the current FMS models computed reasonable stock levels and provided better aircraft availability for a given level of expenditure. The comparison verified that the ASM is preferable to current FMS reparable sparing techniques in the computation of stock level requirements.

THE APPLICATION OF A READINESS-BASED SPARING MODEL TO FOREIGN MILITARY SALES

I. Introduction

General Issue

The sale of a weapon system and its associated spare parts and accessories to an allied foreign country can constitute "an investment in the national security and well-being of the United States" (DISAM, 1992:6).

Foreign Military Sales (FMS) provide our allies with the means of defending their own nations, making them stronger and better able to share in the defense of the free world. The US can then reserve our armed forces for more significant threats to our own national security (DISAM, 1992:6).

In addition to preserving the national security, FMS also boosts the US economy:

> ...each $1 billion spent on new procurement in the United States for foreign military sales, whether FMS or foreign national funds, directly creates or preserves over 20,000 man years of employment. This $1 billion generates in excess of $1.8 billion of income as well as significant exports to help balance US trade with foreign nations. That $1.8 billion of income, in turn, produces over $400 million of tax revenue for the US Government. (DISAM, 1992:6)

In January of 1993, US industry made a profit of $1.2 billion from the sale of 47 F-16 aircraft to Egypt alone. Follow-on support for that one sale generated $1.7 billion (Noonan, 1993:unnumbered). In boosting the economy of the US in this way, FMS contributes to the "well-being of the United States" (DISAM, 1992:6).

The US has a reciprocal responsibility to our FMS customers. When weapon systems are sold, the US is responsible for ensuring that our "customers plan for and obtain all necessary support items, training, and services required to *introduce* and *operate* major systems/equipment" (DISAM, 1992:325). The US must support the weapon system throughout its entire expected service life (DISAM, 1992:325). Two phases are considered in the planning of this support -- initial support and follow-on support.

"Initial support is provided to the purchaser before or at the same time the system or major item is delivered" (DISAM, 1992:325). Initial support provides the spare parts required to support the weapon system during its initial period of service, the period between delivery of the system and the beginning of follow-on support (DISAM, 1992:326). "Follow-on support is normally defined as that support provided on a day-to-day basis subsequent to the initial support period and prior to removal of the end item from the inventory" (DISAM, 1992:325). In order to best support the weapon systems we sell, the US must consider both of these phases. However, the inventory requirements for initial support establish a foundation for follow-on support so that the determination of the level of initial support is crucial to the lifetime support of a weapon system.

The initial support period usually lasts for a 12 to 24 month period (DISAM, 1992:326). The level of support during this period varies from weapon system to weapon system. "A driving force in determining the amount of initial support to be provided for a particular weapon system for a customer country is often the amount of money that the country is willing to invest" (DISAM, 1992:325). Another concept that must be considered in determining the level of support is reliability. "The selection of parts must be aimed at reducing downtime in order that the weapon system can perform its designated mission in the most cost-effective manner." (DISAM, 1992:326). The US has the responsibility, then, of providing countries with an economical and efficient inventory purchase.

Currently there are several reparable sparing models available for use in determining inventory requirements for the initial support period in FMS. The computational foundation for these models is Air Force Logistics Command Regulation (AFLCR) 57-27. The calculations within this regulation result in the buying of large amounts of spare parts to support various weapon systems. The parts bought are often not the ones needed, resulting in additional part purchases. The calculations within AFLCR 57-27 and the models that are based on these calculations do not provide for an efficient and economical inventory purchase.

The Air Force, as well as the other DoD Components, have been directed to compute inventory requirements using models that relate inventory to the operational availability of the weapon system. "The models should be capable of: (1) Optimizing support to achieve weapon system readiness goals for the least cost; [or] (2) Maximizing weapon system readiness for a specified level of funding" (Department of Defense, 1993:3-1 to 3-2). A similar model that relates inventory stockage to system performance is needed for FMS reparable sparing. The model should be efficient and economical in that it buys those parts that contribute the most to the operational availability of the weapon system within a specified cost constraint.

"Availability is defined as the probability that a system is operating satisfactorily at any point in time" (Kapur and Lamberson, 1977:225). Aircraft availability is the probability that an aircraft is capable of operating satisfactorily at any point in time or that the aircraft has all of its essential parts and is capable of performing its mission (Niklas, 1992:3). For the purposes of this thesis, operational availability of the weapon system is referred to as aircraft availability.

Statement of the Problem

The purpose of this research is to determine if an inventory model exists that can be used in Foreign Military Sales (FMS) reparable sparing to provide the greatest possible aircraft availability from a given inventory investment.

Research Questions

In order to fulfill the purpose of this research, the following questions will be answered:

1. What computational methods for initial support requirements of an FMS customer have been used in the past?

2. What mathematical models have been used in the past to obtain the most aircraft availability possible from a given inventory investment?

3. Which one of these available models is appropriate for use in FMS reparable sparing?

4. How does the chosen model compare to the current method for FMS reparable sparing?

   a. Does it spend less providing a better mix of parts for the investment?

   b. Does it use aircraft availability as a primary measure of effectiveness?

Scope and Limitations

Even though both the initial support and follow-on support phases are important in the lifetime support of a weapon system, this thesis focuses on the initial support phase and particularly on the determination of an appropriate model to use in FMS reparable sparing during this phase. Comparisons are made between the models currently being used and existing availability based models. A model is selected based on these comparisons. The model selected must: be convenient to use, provide performance measures, ensure an efficient inventory investment, and maximize aircraft availability subject to a cost constraint.

Although the data used by the various models may be questionable, it is not the focus of this thesis to investigate the data. The application of the thesis results may thus be limited by the accuracy of the input data.

Definitions

The models to be discussed are mathematical (analytical) models that represent a foreign Air Force's reparable item inventory system. A reparable, or recoverable, item is one that is designed to be repaired when broken and then reused.

The models are multi-indenture as well as multi-echelon. They are multi-indenture in that they consider at least two levels, or indentures, of components. The components considered are line replaceable units (LRUs) and shop replaceable units (SRUs). An LRU is "a component typically removed from the aircraft at the flight line, rather than in a back shop" (Isaacson and others, 1988:xv). An SRU is "a subcomponent of an LRU, typically removed from the LRU in the shop" (Isaacson and others, 1988:xvi).

The models are multi-echelon in that they consider logistics activities (supply, maintenance, and transportation) within a three-level, hierarchical logistics structure: flight lines, local base repair shops, and depots (Isaacson and others, 1988:5).

> Reparable components essentially move upward in this hierarchy. Reparable parts are removed from the aircraft at the flight line and are serviced at base level. If not reparable there....they are sent on to the depot...Stocks of serviceable spare parts may be held at any level, and over time these spares are sent down the hierarchy to replace the reparable ones that have been sent up. (Isaacson and others, 1988:5)

The models compute the number of LRUs and SRUs that flow through logistics resupply pipelines over time. A pipeline is:

> a network of repair and transportation processes through which reparable and serviceable parts flow as they are removed from their higher assemblies, repaired, and requisitioned from other points of supply. (Isaacson and others, 1988:xv)

Overview

This chapter presented the management issue that prompted this thesis -- an economical and efficient FMS reparable sparing method. The current FMS reparable sparing methods are inefficient and do not directly relate stockage to aircraft availability.

Several mathematical models exist that maximize aircraft availability for a given inventory investment. This thesis determines which (if any) of these existing models are appropriate for use in FMS reparable sparing. The literature on these mathematical models of reparable item inventory systems is reviewed in the following chapter. The computational methods that have been used in the past to determine the initial support requirements of an FMS customer are also reviewed.

An explanation of the approach used in this thesis is provided in Chapter III. The approach includes evaluating and selecting an availability-based model for use in FMS reparable sparing, collecting data, developing the application of the model, and validating the model through comparing the results of the chosen model with the results of the current method for FMS reparable sparing.

In Chapter IV, the inventory model is validated. Comparisons are made between current models being used and the chosen availability-based model. An evaluation of how the chosen model compares to the current sparing method is made.

The result of this thesis is an inventory model that can be used in FMS reparable sparing to provide a more efficient and economical inventory purchase. The implications of this result are explained in Chapter V.

II. Literature Review

Overview

Now that the need for an availability-based inventory model to be used in FMS reparable sparing has been established, the literature on current methods used to compute initial support requirements of an FMS customer and on existing availability-based models is reviewed. The review addresses: the computational foundation and current models used for FMS reparable sparing, the theoretical and mathematical foundations of reparable item inventory models, and the development of inventory models based on the Multi-Echelon Technique for Recoverable Item Control (METRIC).

FMS Reparable Sparing Models

Two current models being used in FMS reparable sparing are: the International Weapon Item Projection System (IWIPS) and the International Data System (IDS). These models use similar methodologies in computing a spares quantity. The methodologies are based on Air Force Logistics Command Regulation (AFLCR) 57-27.

Computational Foundation for Current Models (AFLCR 57-27). AFLCR 57-27 provides policy and procedures for determining "initial spare and repair parts requirements to support Air Force weapon systems and end articles" (Department of the Air Force, 1991:3). There are four basic pipeline computations used in calculating the total initial spares requirement for a part. The four pipeline segments include the base repair pipeline, the base order and ship time (OST) quantity, the depot repair pipeline, and the base level and depot level condemnation quantity (Department of the Air Force, 1991:28-29). The formulas used in the computation of these pipeline segments are presented in Appendix A.

International Weapon Item Projection System (IWIPS). The IWIPS is a database that contains information on "parts and equipment required to support a weapon system activation and (that) projects initial support requirements of a given weapon system sale under FMS concepts and requirements" (Department of the Air Force, 1983:1-1). IWIPS was developed in the 1970s as a minicomputer-based system at San Antonio ALC, TX.

The initial spares computations within the IWIPS are based on the computations within AFLCR 57-27 (Mueller, 1992:unnumbered). These IWIPS computations are presented in Appendix A.

International Data System (IDS). The "IDS is a computer data base, containing information on spare parts, for specified FMS programs" (Mueller, 1992:unnumbered). The IDS is used to compute initial spares quantities for various FMS programs such as the F-16 aircraft. The initial spares computations within the IDS are identical to those within the IWIPS except that the IDS does not compute a safety stock level (Peterson, 1992:unnumbered).

Intermediate Conclusions. Current FMS reparable sparing models use the "item approach" (Sherbrooke, 1992:3). "Traditional inventory theory uses the item approach, where the spares for an item are determined by simple formulas that balance the costs of holding inventory, ordering, and stockout" (Sherbrooke, 1992:3). The item approach projects the number of spare parts needed for an item without considering the other items on the system. The consideration of only one item at a time may lead to a very low system availability or a funding requirement for all parts that exceeds the overall budget (Sherbrooke, 1992:3). Thus the item approach is not very efficient or economical; "the availability and total investment in the system of items are uncontrolled outputs of the item decisions " (Sherbrooke, 1992:3).

According to Sherbrooke, a preferred alternative for reparable item inventory management is the "system approach" (Sherbrooke, 1992:2).

> The system approach presents the manager with an availability-cost curve of efficient system alternatives....Any points below the curve are 'inefficient' in that it is possible to find solutions on the curve with more availability or less cost; points above the curve are unobtainable. The manager chooses the point on the curve that meets the availability requirements within budget limitations. (Sherbrooke, 1992:3)

In providing for the most availability possible from a given inventory investment, the system approach provides the optimal number of spare parts to buy for each item:

> The mismatch between item-level decisions and system resources, such as money, or system performance requirements does not exist when the system approach is used. Each point on the optimal system cost-effectiveness curve corresponds to a set of stockage policies - a stock level for every item. (Sherbrooke, 1992:4)

The system approach then provides for an efficient and economical inventory purchase such as is required in FMS reparable sparing. The METRIC-based models to be discussed use this system approach.

Foundations of Systems-Based Reparable Item Inventory Models

There are several principles, processes, and theorems that form the theoretical and mathematical foundations of reparable item inventory models. These principles, processes, and theorems include (S-1,S) ordering policies, Poisson processes, Palm's Theorem, and the nature of demands (whether stationary or dynamic). Understanding such concepts assists in understanding reparable item inventory models. In understanding how well a reparable item inventory system performs, it is important to understand the measurement criteria used in assessing the system's performance.

(S-1,S) Ordering Policies. The theory of one-for-one (S-1,S) ordering policies is the foundation for the reparable item inventory models reviewed. In order to understand this policy, the normal supply process must be understood. Parts break. If possible, they are repaired at the base; if not, they are shipped to the depot. The base will provide a spare to the customer if available. If no spares are available at the base, the customer must wait for a spare from the depot or for a repair at the base (Nahmias, 1981:254).

The inventory position at the base, then, is defined as the total number of units on hand plus units due in from base and depot repair minus backorders. The base maintains its inventory position at a fixed stockage objective, S, and follows an (S-1,S) ordering policy. Whenever one or more units is demanded, the inventory position falls below S (at least to S-1). To restore S, an order is placed for an equal number of units that have been demanded. Net inventory, which is on hand minus backorders, becomes negative whenever backorders exist (Nahmias, 1981:254).

Poisson Processes. Poisson processes "closely approximate real-world arrival processes" (Crawford, 1981:1). An arrival process is a counting process - "some group of entities (people, aircraft, etc.), each of which may give rise to some event of interest (make a telephone call, have a radio failure, etc.) in each time interval" (Crawford, 1981:10) Assume the entities are numbered successively (1, 2, 3, ..., n) and associated with each is a random variable, x(i), that is set to one if the entity caused an event or zero if the entity did not. The total number of events or number of arrivals, y, in some fixed time interval is the sum of all x(i) (Crawford, 1981:10).

> Suppose that Pr{x(i) = 1} = p(i). If the entities act independently and all the p(i) are equal to some value p, y has a binomial distribution. If n is fairly large and p is small, the Poisson distribution with mean np provides a very good approximation to the distribution of y. (Crawford, 1981:10)

Because the number of intervals during which a demand can occur is very large (each interval being short, lasting only a day or less), the number of demands in each interval is independent of the demands occurring in any other interval, and the probability of a demand in each interval is some small number, Poisson distributions are used to describe the demand process within reparable item inventory models:

> the Poisson distribution is a good approximation to an arrival process generated by a collection of entities acting independently of one another, each with a small probability of generating an event in a given short time interval. (Crawford, 1981:10)

Poisson Distribution. A counting process, $\{N(t), t \geq 0\}$, is said to be a Poisson process with mean rate λ if the following assumptions are true:

1. $\{N(t), t \geq 0\}$ has stationary independent increments;
2. for any times s and t such that s<t, the N(t) - N(s) counts in the interval (s,t) is Poisson-distributed, with mean $\lambda(t-s)$. That is, (Sherbrooke, 1966:2)

$$P[N(t) - N(s) = k] = e^{-\lambda(t-s)}\lambda(t-s)^k/k! \qquad k=0,1,2,... \qquad (1)$$

The distribution of time between arrivals, or demands, is exponential (Feeney and Sherbrooke, 1966:4-5)

Compound Poisson Processes. A generalization of the simple Poisson is the compound Poisson. The compound Poisson involves batches of demand rather than single demands (Feeney and Sherbrooke, 1966:4-5). The compound Poisson represents "a series of customers with Poisson arrivals who demand an amount which has an independent discrete distribution" (Feeney and Sherbrooke, 1966:5).

The compound Poisson has three properties:

1. Any compound Poisson distribution with a positive, discrete compounding distribution has a variance that equals or exceeds its mean.
2. The compound Poisson distributions are the most general class of 'memoryless' discrete distributions.
3. The summation of N independent compound Poisson processes with mean customer arrival rates $\lambda_1, \lambda_2, ..., \lambda_N$ yields a compound Poisson process with mean customer arrival rate λ = the sum over all N of λ_i. (Sherbrooke, 1966:7)

The negative binomial distribution is an example of a compound Poisson. Several distributions, such as the logarithmic and geometric, can be combined with the Poisson to obtain the negative binomial distribution (Hadley and Whitin, 1963:90):

$$p(x) = \binom{x + n - 1}{n - 1} p^n (1 - p)^x \qquad 0 < p < 1, \quad x = 0,1,2,... \qquad (2)$$

The mean, M, of the negative binomial is $n(1-p)/p$. The variance, V, of the negative binomial is $n(1-p)/p^2$ (Hadley and Whitin, 1963:100). The variance-to-mean ratio, then, is V/M or 1/p.

Palm's Theorem. Another theorem that plays an important role in reparable item inventory models is Palm's Theorem. There are two forms of this theorem, the classical form and the generalized form.

The classical form of Palm's Theorem addresses steady state, or stationary, arrival processes; if

1. Demands are Poisson with arrival rate, λ, and
2. The resupply time is an arbitrary probability distribution with mean T (Feeney and Sherbrooke, 1966:3)
3. The resupply times are independent of each other and of the demand process. (Crawford, 1981:5)

The number of assets in resupply is Poisson with mean, λT. The steady state probability that x units are in resupply is $(\lambda T)^x e^{-\lambda T} / x!$ (Feeney and Sherbrooke, 1966:5). Palm's Theorem requires an infinite server queuing system. Within reparable item inventory models, this translates to the availability of unlimited repair resources.

The above form of Palm's theorem incorporates a simple Poisson. This can be modified to incorporate a compound Poisson distribution.

The classical form of Palm's Theorem provides the basis for the generalized, or dynamic, form of the theorem. The generalized form addresses dynamic, or non-stationary, arrival processes.

Nature of Demands. All the reparable inventory models reviewed assume that demands for parts are independent. The breaking of one part does not influence the breaking of another part. Earlier METRIC-based models assume that "the distribution of demand over some future period of interest, such as six months, is stationary" (Sherbrooke, 1968:129). Later models, such as Dyna-METRIC, address dynamic demands due to changing operational tempos during wartime (Isaacson and Others, 1988:7). Isaacson describes Hillestad and Carrillo's 1980 efforts:

> Hillestad and Carrillo (1980) demonstrated that Palm's result could be extended to the dynamic wartime situation. In their formulation, the time-dependent component removals due to operational demands (e.g., daily demands over some time interval) are combined with the time-dependent repair or transportation capability (e.g., the probability that an item entering the pipeline segment at time s will still be in the pipeline segment at time t) to estimate the expected pipeline quantity size over time. They also extended Palm's original result to show that the pipeline distribution would be Poisson--

even under conditions of time-varying demands and repair. (Isaacson and others, 1988:8)

Measurement Criteria. In assessing the performance of a reparable item inventory system, one of three measurement criteria has typically been used. The three criteria are fill rate, backorders, and aircraft availability rate.

Fill Rate. Fill rate is the probability that at least one spare item is available on the warehouse shelf when a demand for an item occurs; it is the probability that the number of demands during the resupply time are strictly less than the spare stock level. A pure or compound Poisson can be used in calculating the fill rate. Because $p(x \mid \lambda T)$ here represents the steady-state probability of x items in resupply, a pure Poisson is used:

$$\sum_{x=0}^{S-1} p(x \mid \lambda T) \tag{3}$$

where

S = spare stock level
λT = expected number of broken items
(expected pipeline quantity)
λ = average daily demands
T = average resupply time
(Forshaw and others, 1986:8)

Backorders. Backorders are unfilled demands. They are the number of "holes" in an aircraft, or the number of missing items on an aircraft. Again, a pure or compound Poisson can be used in calculating the expected backorders. Using a pure Poisson, the expected backorders are computed as follows:

$$\sum_{x=S+1}^{\infty} (x - S)p(x \mid \lambda T) \tag{4}$$

Aircraft Availability. Aircraft availability rate is the percentage of aircraft which are available, or fully mission capable. If an aircraft is not missing a reparable component, it is considered available (O'Malley, 1983:1-1). The computation of aircraft availability is discussed in a subsequent section.

Typically, the objectives associated with each measurement criteria are to maximize fill rate, minimize expected backorders, and maximize aircraft availability. The objectives associated with METRIC-based models are to either minimize expected backorders or maximize aircraft availability.

Development of METRIC-Based Models

Figure 2-1 represents the development of reparable item inventory models. METRIC is the basis for the development of Mod-METRIC, the Aircraft Availability Model (AAM), Vari-METRIC, Dyna-METRIC, and the Aircraft Sustainability Model (ASM). All of these models assume independent demands as discussed in the previous section. Stationary demand reparable inventory models are examined first.

Stationary Demand, Multi-Echelon, Single Indenture.

METRIC. Sherbrooke describes METRIC as:

> ...a mathematical model translated into a computer program, capable of determining base and depot stock levels for a group of recoverable items; its governing purpose is to optimize system performance for specified levels of system investment. METRIC is designed for application at the weapon-system level, where a particular line item may be demanded at several bases and the bases are supported by one central depot. (Sherbrooke, 1968:123)

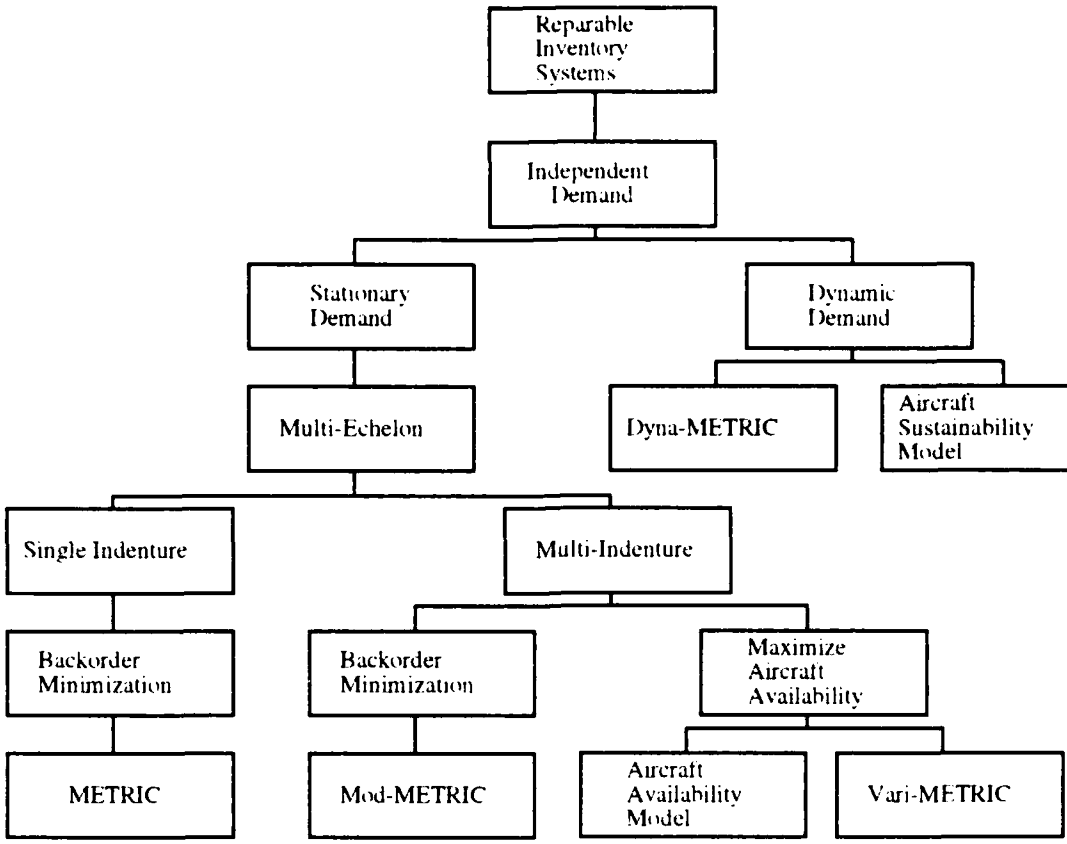

Figure 2-1. Development of Reparable Item Inventory Models (Peterson, 1989:unnumbered)

Assumptions. The mathematical assumptions of the model are:

1) the objective is to minimize the sum of expected backorders on all recoverable items at all bases for a specific weapon system: a backorder is defined as "a recoverable item missing on an aircraft" (Sherbrooke, 1968:125)

2) compound Poisson demand: each item has a logarithmic Poisson demand process. This is obtained by considering "batches of demand where the number of batches follows a Poisson process and the number of demands per batch has a logarithmic distribution" (Sherbrooke, 1968:128). The logarithmic distribution is represented by $f(m) = (1-p)^m/(\lambda m)$ where λ is the natural logarithm of $(1/p)$ and p is between 0 and 1 (Feller, 1968:291). The negative binomial distribution (Equation 2) is used to represent a logarithmic Poisson process.

3) stationary demand

4) complexity of repair, only, determines where a part will be repaired (base or depot)

5) lateral resupply between bases is not modeled

6) conservative system (there are no asset condemnations)

7) depot repair begins as soon as the part arrives from a base

8) recoverable items have equal essentialities, that is, the relative backorder cost for all items is the same

9) demand from different bases can be pooled (Sherbrooke, 1968:126-131).

Demand Computational Process. In order to understand the computations within the METRIC solution process, certain fundamental computations need to be understood. Throughout the explanation of the computations performed within METRIC, the following data elements with notation appear: i = item, I = total number of items, j = base, and J = total number of bases.

When a customer arrives at a base with one or more demands, he turns in a similar amount of reparable items. An assumption of METRIC is that with probability r_{ij} all of items of type i can be repaired at the base and with probability $(1 - r_{ij})$ all of these items must be repaired at the depot. The mean customer arrival rate at the depot from any base j is $(1 - r_{ij})$ times the mean customer arrival rate at the base, λ_{ij}. The mean customer arrival rate at the depot for item i, λ_i, is the sum over all bases of $\lambda_{ij}(1 - r_{ij})$. The mean demand per customer at the base is f_{ij}, so that the mean demand for item i at base j is $\lambda_{ij} f_{ij} = \theta_{ij}$. Incorporating the mean demand for item i at base j, θ_{ij}, the mean depot demand rate then is:

$$\sum_{j=1}^{J} \lambda_{ij} f_{ij}(1 - r_{ij}) = \sum_{j=1}^{J} \theta_{ij}(1 - r_{ij}) \qquad (5)$$

This equation represents the proportion of total demands placed on the bases that are sent to the depot (Sherbrooke, 1968:131).

Like the base, the depot demand process is compound Poisson. The compounding distribution, or distribution of demands placed by a customer, is a composite of the base compounding distributions. These distributions are logarithmic Poisson. METRIC assumes that the demand for each item at each base has the same variance to mean ratio (all $f_{ij} = f_i$), even though the means are different. By assuming this, a logarithmic Poisson process at the depot with that variance to mean ratio is obtained (Sherbrooke, 1968:132).

Formulation. Because the objective of METRIC is to minimize the sum of backorders across bases, the expected backorder calculation is very important. This calculation is used to compute the expected number of backorders, B(S), at a random point in time given a particular spare stock level, S. The mean resupply (repair) time, T, is drawn from an arbitrary distribution and is applicable to all demands placed by the customer (Sherbrooke, 1968:132). Demands are compound Poisson, $p(x \mid \lambda T, VTMR)$, with the parameters being the mean customer rate, λT, and a variance-to-mean ratio, VTMR. The VTMR varies by part and is approximated by $\alpha(\lambda T)^{\beta}$ where α is 1.132477 and β is .3407513 (Department of the Air Force, 1991:404). The expected number of backorders at a random point in time then is:

$$B(S) = \sum_{x=S+1}^{\infty} (x - S)p(x \mid \lambda T, VTMR) \qquad (6)$$

Solution Process. The METRIC solution process consists of five stages. In the first stage the average time between a base request for a resupply from the depot and base receipt of the item is computed. The average time between request and receipt is a function of the depot spare stock, S_{j0}. If the depot has infinite spare stock, the time is the average order and ship time, O_{ij}. If the depot has zero spare stock, the time is $O_{ij} + D_j$, where D_j is the average depot repair time. Because there is not always a serviceable item at the depot when a resupply request is received, the delay at the depot must be between zero and D_i (Sherbrooke, 1968:132).

To compute the delay at the depot, the depot spare stock, S_{i0}, must be considered. If the number of units sent for depot repair, x, is less than or equal to S_{i0}, no resupply is being delayed. If the number of units sent for depot repair is greater than S_{i0}, the resupply on x - S_{i0} units is being delayed. Using this, the expected number of units which are delayed at the depot at a random point in time is (Sherbrooke, 1968:133):

$$B(S_{i0} \mid \lambda_i D_i) = \sum_{x=S_{i0}+1}^{\infty} (x - S_{i0}) p(x \mid \lambda_i D_i, VTMR_i) \quad (7)$$

where

λ_i = mean customer arrival rate at the depot (from above)
D_i = average depot repair time

The total expected system delay is the expected number of units which are delayed at the depot at a random point in time multiplied by the length of the depot repair time. METRIC is concerned with the average delay per demand. To obtain this, divide the total expected system delay by the expected number of demands on the depot. The average delay per demand is (Sherbrooke, 1968:133):

$$\sum_{x=S_{i0}+1}^{\infty} (x - S_{i0}) p(x \mid \lambda_i D_i, VTMR_i)/\lambda_i f_i = \delta(S_{i0}) D_i \quad (8)$$

where

$\lambda_i f_i$ = expected number of demands on the depot per day for item i

$$\delta(S_{i0}) = \sum_{x=S_{i0}+1}^{\infty} (x - S_{i0}) p(x \mid \lambda_i D_i, VTMR_i)/\lambda_i D_i f_i$$

In stage two of the METRIC solution process, the expected backorders, as a function of the base stock, S_{ij}, are computed for each level of depot stock, S_{i0}, and each base. This is done by using Equation 6 where $S = S_{ij}$, $\lambda = \lambda_{ij}$, and $T = r_{ij}A_{ij} + (1 - r_{ij})[O_{ij} + \delta(S_{i0})D_i]$ (A_{ij} = average base repair time) (Sherbrooke, 1968:133). The resupply time, T, then, considers the time it takes to repair items at the base and the time it takes to repair items at the depot, based on the fraction of items going to the base (r_{ij}) for repair and the fraction of items going to the depot ($1 - r_{ij}$) for repair.

A marginal analysis is performed within the third stage of the METRIC solution process. The marginal analysis is used to optimally allocate the [first, second,...] units of depot stock to the several bases in order to minimize the sum of expected backorders at all bases. This marginal allocation procedure is performed for each level of depot stock, S_{i0}. At each step of the procedure, the next unit of stock is given to the base where the greatest decrease in expected backorders will be realized (Sherbrooke, 1968:133).

Within stage four a table is constructed showing the expected backorders by item given depot stock, S_{i0}, and the total stock across bases, S_i under optimal allocation. The (southwest to northeast) diagonals of this table represent constant total system stock for an item, $S_{i0} + \sum_{j=1}^{J} S_i$. For each of these alternative system-wide stock levels, the minimum expected system backorders is identified and the corresponding stock allocations recorded (Sherbrooke, 1968:133).

Stage five considers all items. Another marginal analysis is performed within this stage. Using the backorders computed in stage four, the next investment is allocated to that item which provides the greatest benefit-to-cost ratio (decrease in expected backorders divided by unit cost, c_i). This item is the most efficient purchase alternative. After each allocation of funding, the system investment and system backorders are computed. The allocation procedure ends whenever the investment constraint is just exceeded or the expected backorders are just less than a specified target value (Sherbrooke, 1968:134).

The result of METRIC is a "shopping list" of what items should be purchased. This list also gives the optimal allocation of the items among bases and depot.

As stated in assumption five, lateral resupply between bases is ignored in METRIC. If a serviceable item is not available at the depot to resupply a base, the base must wait until an item returns from depot repair. Sherbrooke states that this is appropriate, because the number of lateral shipments that would be required is "typically small" (Sherbrooke, 1968:129). By ignoring lateral resupply, transportation costs and special costs of expediting can be avoided (Sherbrooke, 1968:129).

Summary. METRIC was the first multi-item, multi-echelon, reparable inventory model "ever proposed for implementation" (Sherbrooke, 1968:123). Sherbrooke describes its advantages over existent USAF inventory models in 1968:

> Compared to current Air Force policy our technique has the advantage that unit cost is considered in the calculation. But even more important in our view is the system approach, which displays a range of optimal cost-effectiveness alternatives to management. Instead of computing stock levels on the basis of artificial estimates of holding cost rate and backorder cost, this approach focuses management attention on the entire weapon system so that an appropriate combination of system effectiveness and system cost can be selected. (Sherbrooke, 1968:123)

Stationary Demand, Multi-Echelon, Multi-Indenture.

Mod-METRIC. Mod-METRIC models a multi-item, multi-echelon, multi-indenture inventory system. The model, like METRIC, is multi-echelon in that it considers two echelons of repair and supply, bases and a depot. Unlike METRIC, the model is multi-indenture. It "permits the explicit consideration of a hierarchical parts structure" (Muckstadt, 1973:472). This "hierarchical parts structure" consists of two levels of indenture--an LRU ("major assembly") made up of SRUs ("components") (Muckstadt, 1973:472).

The first objective of Mod-METRIC is to describe the logistics relationship between an LRU and its SRUs. Considering this logistics relationship, the second objective is to compute spare stock levels for both echelons and both indentures. To determine the spare stock levels, Mod-METRIC minimizes the total expected base backorders for the LRU subject to an investment constraint on the total system (bases and depot, LRU and SRU) stock (Muckstadt, 1973:472).

Assumptions. The assumptions of Mod-METRIC are identical to those of METRIC except for the following: items may have different essentialities (Muckstadt, 1973:474). METRIC assumes that the relative backorder cost of all items is the same. Mod-METRIC assumes that the backorder cost of an LRU is different than that of an SRU. An LRU backorder grounds an aircraft. An SRU backorder only delays the repair of an LRU (Muckstadt, 1973:475). Mod-METRIC is primarily concerned with minimizing the LRU backorders at minimal cost. It determines the most cost effective inventory mix that reduces LRU backorders.

Demand Computational Process. In order to compute how effective the supply system is in meeting the demands for LRUs, the system's relationship between LRUs and SRUs must be described. This relationship is expressed in the equation which represents the average LRU resupply time (Muckstadt, 1973:475).

Throughout the following discussion of the computations performed within Mod-METRIC, i refers to LRU, j refers to base, and k refers to SRU (I = total number of LRUs, J = total number of bases, and K = total number of SRUs on LRU i).

The average LRU resupply time for item i at base j, T_{ij}, depends on the resupply time at the base and the resupply time at the depot, considering that an item can be repaired at a base or the depot. If an item is repaired at a base, the resupply time is the time it takes to move through the base maintenance system. If an item is repaired at the depot, the resupply time is the time it takes to submit an order for a serviceable item to the depot and to receive the item from the depot. This assumes that the depot has a serviceable item. If the depot has no serviceable item, an expected delay is included in the resupply time. This delay is a function of the depot LRU stock level (Muckstadt, 1973:475).

The average resupply time, if the LRU is to be repaired at the depot, is the sum of the average order and ship time, O_{ij}, and the average delay at the depot due to the lack of a serviceable item. The computation of this average depot resupply time within Mod-METRIC is identical to the computation within METRIC (refer to the first stage of the "Solution Process" within the "METRIC" discussion). The expected number of items incurring a delay at the depot at a random point in time is computed using Equation 7 except that the $VTMR_i$ is different. The VTMR within Mod-METRIC varies by part but is typically between 1.5 and 2.0 (Niklas, 1994:unnumbered). Equation 8 is then used to compute the average delay at the depot per demand of an LRU, $\delta(S_{i0})D_i$. The sum of the average order and ship time, O_{ij}, and this delay is the average resupply time for an LRU given that it is to be repaired at the depot (Muckstadt, 1973:476).

If the LRU is to be repaired at the base, the average resupply time is B_{ij}. B_{ij} is the sum of the average repair time, A_{ij}, given that the SRU needed to repair the LRU is available, and the expected delay in the base LRU repair due to the lack of a serviceable SRU, d_{ij}. Then, $B_{ij} = A_{ij} + d_{ij}$ (Muckstadt, 1973:476).

There are two assumptions in this calculation. The first assumption is that only one SRU breaks an LRU. The second assumption is that if the LRU is repaired at the base, the failure of the LRU is due to the failure of one of its SRUs (Muckstadt, 1973:476).

The expected delay in the base LRU repair due to the lack of serviceable SRU k is represented by d_{ijk} (Muckstadt, 1973:476):

$$d_{ijk} = \sum_{x_{ijk}=S_{ijk}+1}^{\infty} (x_{ijk} - S_{ijk})p(x_{ijk} \mid \lambda_{ijk}T_{ijk}, VTMR_{ijk}) / \lambda_{ijk} \qquad (9)$$

where

λ_{ijk} = average daily demands of SRU k on LRU i at base j
S_{ijk} = stock level of SRU k on LRU i at base j
T_{ijk} = average resupply time for SRU k on LRU i at base j

The average SRU resupply time, T_{ijk}, is (Muckstadt, 1973:476):

$$T_{ijk} = r_{ijk}B_{ijk} + (1 - r_{ijk})(O_{ijk} + \delta_k D_k) \qquad (10)$$

where

r_{ijk} = the probability that a failure of SRU k will be repaired at the base

B_{ijk} = average base repair time for SRU k at base j

O_{ijk} = average order and ship time for SRU k at base j

D_k = average depot repair time for SRU k

The expected depot delay per demand of SRU k, $\delta_k D_k$, is computed in the same manner as the expected depot delay per demand of an LRU. The expected number of items of SRU k on which a delay will be incurred at the depot is divided by the expected depot demands for SRU k (Muckstadt, 1973:476):

$$\delta_k D_k = \sum_{x=S_{0k}+1}^{\infty} (x - S_{0k}) p(x \mid \theta_k D_k, VTMR_k) / \theta_k \tag{11}$$

where

S_{0k} = stock level of SRU k at the depot

θ_k = expected daily depot demands for SRU k = $\sum_{j=1}^{J} \lambda_{ijk}(1-r_{ijk})$

The expected delay of LRU i's repair at base j, then, due to the lack of an available SRU at base j is (Muckstadt, 1973:476):

$$d_{ij} = (1 / r_{ij}\lambda_{ij}) \sum_{k=1}^{K} \lambda_{ijk} d_{ijk} \tag{12}$$

where

$\sum_{k=1}^{K} \lambda_{ijk} d_{ijk}$ = total expected delay due to all SRUs on the LRU

$r_{ij}\lambda_{ij}$ = number of daily LRU demands at the base

Thus, the average resupply time for LRU i, T_{ij}, is the sum of the base resupply time and the depot resupply time weighted by the probability that the item can be repaired at the base or at the depot (Muckstadt, 1973:477):

$$T_{ij} = r_{ij}(A_{ij} + d_{ij}) + (1 - r_{ij})(O_{ij} + \delta(S_{i0})D_i) \tag{13}$$

The difference between METRIC and Mod-METRIC is within this calculation. The incorporation of the average delay in base LRU repair due to the lack of a serviceable SRU, d_{ij}, is new in Mod-METRIC. A similar delay in depot LRU repair due to the lack of a serviceable SRU does not appear to be incorporated within $\delta(S_{i0})D_i$. It is assumed that D_i, the average depot repair time, includes a delay for the unavailability of SRUs (Niklas, 1991:unnumbered). Repair at the depot involves the repair of an entire LRU. The time to repair an entire LRU incorporates the time to repair any SRUs that may be unserviceable. Thus, the depot repair time for an LRU represents the total time required to repair that LRU, which includes the delay required for the repair of associated SRUs.

Formulation. The problem to be solved by Mod-METRIC is the minimization of total expected base LRU backorders subject to an investment constraint on the total system (bases and depot, LRUs and SRUs) stock (Muckstadt, 1973:481). The solution of this problem results in the optimal allocation of spare stock for both LRUs and SRUs among the depot and several bases (Muckstadt, 1973:477):

$$\min \sum_{j=1}^{J} \sum_{x_{ij}=S_{ij}+1}^{\infty} (x_{ij} - S_{ij}) p(x_{ij} \mid \lambda_{ij} T_{ij}, VTMR_{ij})$$

s.t.

$$\sum_{i=1}^{I} \{ \sum_{j=1}^{J} [c_i S_{ij} + \sum_{k=1}^{K} c_k S_{ijk}] + \sum_{k=1}^{K} c_k S_{i0k} + c_i S_{i0} \} <= C \qquad (14)$$

where

S_{ij} = stock level of spare LRU i at base j
c_i = unit cost of LRU i
c_k = unit cost of SRU k
C = dollar budget limit

Solution Process. In order to obtain optimal spare stock levels for several LRUs and SRUs, this problem is solved for each LRU and its associated SRUs. Then, a marginal analysis, using each individual LRU performance/cost function, is performed.

The result is an optimal allocation of spare stock among the several LRUs and their associated SRUs and among the depot and several bases (Muckstadt, 1973:481).

Summary. In 1973, the Air Force implemented Mod-METRIC as the method for computing recoverable spare stock levels for the F-15 weapon system (Muckstadt, 1973:481). Currently, Mod-METRIC is used to compute spare stock levels for engines and their associated modules.

Aircraft Availability Model. Minimizing expected backorders, alone, as in METRIC and Mod-METRIC, is not a particularly useful performance measure. A more appropriate measure of performance would be the number of available aircraft, which takes into account the number of backorders. Recall from chapter I, an available aircraft is one that has all of its essential parts and is capable of performing its mission. An available aircraft has no broken parts, or in other words, no backorders outstanding. A backorder, then, can cause an aircraft to be unavailable to perform its mission. The Aircraft Availability Model (AAM), as its name implies, computes aircraft availability rates as they relate to various funding constraints.

The AAM models a multi-item, multi-echelon, multi-indenture inventory system. Like Mod-METRIC, it considers two echelons of repair and supply, a depot and several bases. Unlike Mod-METRIC, it can simultaneously consider 40 types of aircraft with 250 subtypes and 92,000 total components with commonality; that is, a proportion of the items can be on two or more types, or subtypes, of aircraft (O'Malley, 1983:3-8).

The objective of the AAM is to maximize the aircraft availability rate for a particular aircraft type, Mission Design (MD), subject to an investment constraint on total system stock. The purpose of the model is to answer the following question for each MD: "With a given amount of money, what spare items should be procured to achieve the highest possible availability rate?" (O'Malley, 1983:3-1).

Assumptions. The assumptions of the AAM are identical to those of METRIC except that the objective of the AAM is to achieve a target availability rate at a minimum cost. It is not to minimize the sum of expected backorders only as in METRIC and Mod-METRIC. The AAM also allows for asset condemnations and models all recoverable LRUs as having equal essentialities. In addition, the AAM assumes that all bases modeled are identical, there are unlimited repair resources, and the removal and replacement of an LRU is instantaneous (Rexroad, 1992:unnumbered).

Computational Process. In calculating the aircraft availability rate, the AAM takes into consideration the number of LRU backorders upon an aircraft. In fact, an available aircraft is defined as "one with no LRU backorders outstanding" (O'Malley, 1983:2-1). The availability rate then is the percentage of aircraft available over a certain period of time (O'Malley, 1983:1-1). The expected number of backorders do not explain the effects of a backorder upon an aircraft. The availability rate represents the probable effect of backorders upon support of the aircraft (O'Malley, 1983:2-1).

Given an inventory of spare stock, the AAM computes the availability rate in two steps. First, the expected number of backorders for each LRU on the aircraft are computed. Second, the probability of one or more of the expected backorders occurring on the aircraft is computed (O'Malley, 1983:2-1).

In computing the expected number of backorders for each LRU on the aircraft, the AAM uses the expected backorder calculations derived from METRIC and Mod-METRIC (O'Malley, 1983:2-1).

> For a given component, the model computes the total worldwide EBO for many different total worldwide asset levels. For each worldwide asset level, the model considers every possible way to distribute those assets between base and depot and selects the distribution with the lowest total EBO. (O'Malley, 1983:B-3)

The probability that an aircraft is not waiting for a spare, the aircraft availability rate, is computed using the calculated number of expected backorders, EBO_i, for LRU_i. The basic aircraft availability calculation does not consider either commonality or levels of indenture. The application percentage, or percentage of the aircraft that contain LRU_i, is also assumed to be one; all of the aircraft of a certain MD contain LRU_i.

Formulation. The total number of LRU_i installed on an aircraft type, or the total number of LRU_i which should be functioning for a particular MD, is the number of aircraft, AC, multiplied by the quantity per application on the aircraft type, Q_i. For a given level of spare units, n, of LRU_i, the probability that LRU_i is backordered is $EBO_{i,n}/(AC \times Q_i)$. The assumption is that backorders are uniformly distributed among the number of required LRU_i on the aircraft. A backorder of LRU_i is as likely to occur on one aircraft as it is to occur on another. The probability that the aircraft is not waiting for one spare of LRU_i ($Q_i = 1$) is $1 - [EBO_{i,n}/AC]$. For an aircraft requiring Q_i of LRU_i, the probability that the aircraft is not waiting for a spare of LRU_i ($Q_i > 1$) is $(1 - [EBO_{i,n}/(AC \cdot Q_i)])^{Q_i}$ (O'Malley, 1983:2-3). Assuming independence of backorders among all LRUs on an aircraft, the probability that a random aircraft of type MD is not missing any of its reparable LRUs is the product of all the individual LRU probabilities. The aircraft availability rate is then (O'Malley, 1983:2-6):

$$AA = \prod_{i=1}^{I} (1 - [EBO_i / (AC \times Q_i)])^{Q_i} \tag{15}$$

Solution Process. O'Malley explains the technique used by the AAM to tie aircraft availability to funding constraints:

> The AAM uses a marginal analysis technique, i.e., it ranks the candidates for procurement and repair in decreasing order of benefit per cost to form an ordered 'shopping list.' Buying and repairing from this list in the order indicated assures that items which give the greater increase in availability rate per dollar (of procurement cost or repair cost, as appropriate) will be acquired earlier. Thus, the AAM optimizes aircraft availability for any funding constraint and produces optimum shopping lists and optimum repair strategies, by component, for each funding level. (O'Malley, 1983:v)

The AAM uses a "sort value" in order to sort candidate units for procurement (Rexroad, 1992:17). The sort value is computed using the aircraft availability rate calculation.

Equation 16 represents the availability rate of a certain type of aircraft before procurement of the first additional unit and can be written as (Rexroad, 1992:15-16)

$$AA = \prod_{i=1}^{I} q_{h,i,n(i)}$$

$$= [\prod_{i \neq j} q_{h,i,n(i)}]\, q_{h,j,n(j)} \qquad (16)$$

where

$q_{h,i,n(i)}$ = the probability that an aircraft of Mission Design Series (MDS) h is not missing a unit of component i with n spare units of component i in the system (Rexroad, 1992:10)

After procurement of the first additional unit of component j, the availability rate calculation is (Rexroad, 1992:16):

$$AA' = [\prod_{i \neq j} q_{h,i,n(i)}]\, q_{h,j,n(j)+1} \qquad (17)$$

The ratio of the new to the old availability rates is:

$$AA' / AA = q_{h,j,n(j)+1} / q_{h,j,n(j)} \qquad (18)$$

This ratio is dependent on the spares level of component j only and is referred to as the "improvement factor due to unit n(j) + 1 of component j" (Rexroad, 1992:16). This improvement factor is written as (Rexroad, 1992:16)

$$I_{h,i,n} = q_{h,i,n} / q_{h,i,n-1} \qquad (19)$$

The sort value of the n^{th} unit of component i is then (Rexroad, 1992:16-17):

$$S_{h,i,n} = \ln (I_{h,i,n}) / C_i$$

$$= \ln (q_{h,i,n} / q_{h,i,n-1}) / C_i \qquad (20)$$

where

C_i = cost of component i

"The sort value is the measure of benefit per cost that is used to sort the candidate units for procurement" (Rexroad, 1992:17). The natural logarithm function is used to simplify the calculation. Without using the natural logarithm function, the calculation of the sort value would involve multiplication and division of very small increments (the improvement factors, mentioned above). Using the natural logarithm function allows for addition of the increments, simplifying the calculation of the sort value while providing equivalent results (Rexroad, 1992:17).

Using this sort value calculation, a "shopping list", identifying what spare items to buy in order to achieve a target availability rate at a minimum cost, is developed (Rexroad, 1992:15). The "'starting availability rate', AA_S" for each type of aircraft is calculated using Equation 16 (Rexroad, 1992:17). AA_S provides a baseline availability rate. "The first unit on the shopping list will be that with the highest sort value, say unit n(j) + 1 of component j" (Rexroad, 1992:18). After this unit is bought, the availability rate is calculated by (Rexroad, 1992:18)

$$
\begin{aligned}
AA &= AA_S \cdot \left(q_{h,j,n(j)+1} / q_{h,j,n(j)} \right) \\
&= \left[\prod_{i=1}^{I} q_{h,i,n(i)} \right] \cdot \left(q_{h,j,n(j)+1} / q_{h,j,n(j)} \right) \\
&= \left[\prod_{i \neq j} q_{h,i,n(i)} \right] \cdot q_{h,j,n(j)} \cdot \left(q_{h,j,n(j)+1} / q_{h,j,n(j)} \right) \\
&= \left[\prod_{i \neq j} q_{h,i,n(i)} \right] \cdot q_{h,j,n(j)+1} \qquad (21)
\end{aligned}
$$

This product of the item availabilities incorporates the new spares levels. Items are added to the shopping list in decreasing order of sort value; the one with the second highest sort value is added, then the one with the third highest sort value, etc. Equation 21 is used to calculate the availability rate after each subsequent unit is added to the shopping list (Rexroad, 1992:18). Items are added to the shopping list until the desired availability rate is achieved. "This shopping list contains only optimal solutions. For any desired availability rate, buying in order from this list until the rate is attained minimizes the funds required" (Rexroad, 1992:19).

Summary. The AAM has been implemented into D041, the Recoverable Consumption Items Requirements System:

> In D041, the AAM is computing the Air Force worldwide peacetime requirement for reparable spare parts. It permits the Air Force to set availability goals by aircraft type and compute a worldwide requirement for reparable parts which will satisfy these goals at a minimum cost. (Rexroad, 1992:1)

Vari-METRIC. Vari-METRIC was developed to improve upon the estimation of expected backorders within METRIC and other, METRIC-based, multi-indenture, models. Sherbrooke explains the problem:

> Multi-indenture models for (s-1, s) inventory policies, such as Mod-METRIC and the Logistics Management Institute (LMI) Aircraft Availability Model, understate the delay in the repair of a higher indenture item caused by backorders on the item's lower indenture components. These models also understate the multi-echelon delay in the resupply of a base from a depot that has backorders. Consequently, the models tend to understate expected backorders and overstate expected availability of repair items. (Sherbrooke, 1986:311)

Items due-in at the base can either be on their way (in the process of being shipped from the depot) or waiting at the depot for a lower indenture item that is backordered at the depot (Slay, 1993:unnumbered). Vari-METRIC, unlike METRIC and other METRIC-based models, considers these two situations and models them producing a more accurate estimate of the expected backorders.

Assumptions. Although the assumptions of Vari-METRIC are identical to those of METRIC, Vari-METRIC differs from METRIC in its computation of the variance. The incorporation of this variance computation within Vari-METRIC "produces an estimate of backorders that exceeds that of METRIC in all cases except when stock levels are zero (when the two models agree)" (Sherbrooke, 1986:318). Sherbrooke explains:

> In multi-indenture cases, and in multi-indenture, multi-echelon cases, we have shown a few examples indicating that the Vari-METRIC estimate of expected backorders can be much larger than METRIC. Furthermore, the Vari-METRIC estimate of backorders is close to the 'true' value obtained by simulation. We have shown that Vari-METRIC might lead to a different allocation in such cases, and in these cases the Vari-METRIC solution is better. (Sherbrooke, 1986:318)

Computational Process. Recall the multi-indenture, multi-echelon repair process. When an LRU breaks, it is brought into base repair. If base supply has a spare LRU, the LRU is replaced. If not, the base incurs an LRU backorder. The broken LRU has a probability of being repaired at the base; if it cannot be repaired at the base, it is sent to the depot for repair and a resupply request for the LRU is placed on the depot (Sherbrooke, 1986:315).

Assume, as in Mod-METRIC, that if the LRU is repaired at the base, the failure of the LRU is due to the failure of one, and only one, of its SRUs (Muckstadt, 1973:476). If base supply has a spare SRU, it is put on the LRU, and the LRU is repaired. If not, the broken SRU has a probability of being repaired at the base; if it cannot be repaired at the base, the SRU is sent to the depot for repair and a resupply request for the SRU is placed on the depot (Sherbrooke, 1986:315)

"If the LRU is not repaired at the base, a similar process for SRU repair occurs at the depot" (Sherbrooke, 1986:315). An assumption is that all SRUs can be repaired at the depot (Sherbrooke, 1986:315).

As in the discussion of the computations performed within Mod-METRIC, j refers to base (0 = depot), and k refers to SRU (J = total number of bases and K = total number of SRU's). The discussion to follow on the computations performed within Vari-METRIC concentrates on a single item group (one LRU and its associated SRUs). Thus, k = 0 refers to the LRU.

The essence of Vari-METRIC is in the enhancement of the calculation of the expected base LRU backorders. Before discussing this calculation, an equation for the demand rate for the kth SRU at the depot must be developed (Sherbrooke, 1986:316).

The mean demand rate (arrival rate) at the depot for the LRU, λ_{00}, is "the sum of LRU demands at the bases that result in resupply of LRUs from the depot" (Sherbrooke, 1986:316). Mathematically, λ_{00} is the sum over all bases of $\lambda_{j0}(1 - r_{j0})$ where λ_{j0} is the base LRU demand rates for $j > 0$, r_{j0} is the probability that a failure at base j can be repaired at the base and $(1 - r_{j0})$ is the probability that the failure must be repaired at the depot (Sherbrooke, 1986:316).

The demand rate at base j for SRU k is that portion of the LRU demands that can be repaired at the base which result in a demand for the kth SRU: $\lambda_{jk} = \lambda_{j0} r_{j0} q_{jk}$, $J,K > 0$, where q_{jk} is the conditional probability that an LRU repaired at base j will be due to SRU k which is broken and results in a demand for SRU k (Sherbrooke, 1986:316).

Within Vari-METRIC, the demand rate for the kth SRU at the depot is comprised of two terms, "the resupply demand rate from each base plus the SRU demand rate resulting from LRU repairs at the depot" (Sherbrooke, 1986:316). The resupply demand rate from each base is the number of demands at the base for the kth SRU that are not repairable at the base and must be sent to the depot. The SRU demand rate resulting from LRU repairs at the depot is that portion of the LRU demands at the depot that are due to SRU k. (Mod-METRIC does not include this second source of SRU demand.) The demand rate for the kth SRU at the depot, then, is (Sherbrooke, 1986:316):

$$\lambda_{0k} = \sum_{j=1}^{J} \lambda_{jk}(1 - r_{jk}) + \lambda_{00} q_{0k} \qquad k>0 \qquad (22)$$

This equation is essential to the calculation of the expected base LRU backorders that follows. This calculation requires a three-step procedure for any item group with given stock levels.

<u>Mean and Variance for the Number of LRUs in Depot Repair (Sherbrooke, 1986:316)</u>. The portion of the demands for SRU k at the depot that is due to LRU repairs is (Sherbrooke, 1986:316):

$$f_{0k} = \lambda_{00} q_{0k} / \lambda_{0k} \qquad k>0 \qquad (23)$$

The number of LRUs in depot repair consists of two parts: the number of LRUs that are actually being repaired within D_{jk}, the average depot repair time, and the number of LRUs that are waiting for an SRU which is backordered (Sherbrooke, 1986:316). These two parts are independent because an awaiting LRU at a random point in time, t, is due to an LRU demand prior to t - D_{jk} (Sherbrooke, 1986:313). In other words, an LRU cannot be awaiting an SRU and be in actual repair at the same time. The total expected number of LRUs in depot repair, then, is (Sherbrooke, 1986:316):

$$E(x_{00}) = \lambda_{00} D_{00} + \sum_{k=1}^{K} f_{0k} E[B(s_{0k} \mid \lambda_{0k} D_{0k})] \qquad (24)$$

where

s_{0k} = stock level at the depot for the kth SRU

The expected number of LRUs that are actually being repaired (the first term in equation 24) is Poisson with mean, $\lambda_{00} D_{00}$. The expected number of SRU backorders at the depot (the second term in equation 24) is binomially distributed with parameters $p = f_{0k}$ and $n = B(s_{0k})$. The variance of the expected number of LRUs in depot repair, then, is (Sherbrooke, 1986:316):

$$Var(x_{00}) = \lambda_{00} D_{00} + \sum_{k=1}^{K} f_{0k}(1 - f_{0k}) E[B(s_{0k} \mid \lambda_{0k} D_{0k})] +$$

$$\sum_{k=1}^{K} f_{0k}^2 Var[B(s_{0k} \mid \lambda_{0k} D_{0k})] \qquad (25)$$

<u>Mean and Variance for the Number of SRUs in Base Repair/Resupply (Sherbrooke, 1986:316)</u>. The portion of the demands for SRU k at the depot that is being resupplied to base j is (Sherbrooke, 1986:316):

$$f_{jk} = \lambda_{jk}(1 - r_{jk}) / \lambda_{0k} \qquad j,k>0 \qquad (26)$$

The number of SRUs in repair/resupply consists of three parts: the number of SRUs that are being resupplied from the depot if the depot has stock on hand, the number of SRUs that are being repaired at the base when repair parts are on hand, and the number of depot SRU backorders that are delaying SRU resupply. The expected number of SRUs that are being resupplied from the depot and repaired at the base (the first term in equation 27) is Poisson with mean, $\lambda_{jk}[(1 - r_{jk})O_{jk} + r_{jk}A_{jk}]$. The expected number of SRU backorders at the depot (the second term in equation 27) is binomially distributed with parameters $p = f_{jk}$ and $n = B(s_{0k})$. The expected number and variance of SRUs in base repair/resupply, then, are (Sherbrooke, 1986:316):

$$E(x_{jk}) = \lambda_{jk}[(1 - r_{jk})O_{jk} + r_{jk}A_{jk}] + f_{jk}E[B(s_{0k} | \lambda_{0k}D_{0k})] \qquad j,k>0 \qquad (27)$$

$$Var(x_{jk}) = \lambda_{jk}[(1 - r_{jk})O_{jk} + r_{jk}A_{jk}] + f_{jk}(1 - f_{jk})E[B(s_{0k} | \lambda_{0k}D_{0k}] + f_{jk}^2 Var[B(s_{0k} | \lambda_{0k}D_{0k})] \qquad j,k>0 \qquad (28)$$

where

O_{jk} = average order and ship time from the depot to any base, j, of the kth SRU
A_{jk} = average base repair time at base j for the kth SRU

Mean and Variance for the Number of LRUs in Base Repair/Resupply (Sherbrooke, 1986:316). The portion of the LRU demand at the depot that came from base j is (Sherbrooke, 1986:316):

$$f_{0j} = \lambda_{0j}(1 - r_{0j})/\lambda_{00} \qquad j>0 \qquad (29)$$

The number of LRUs in base repair/resupply consists of three parts: (1) the number of LRUs that are in repair/resupply when the base and depot have stock on hand; (2) the number of LRUs that are waiting at the depot for an SRU which is backordered (this delays LRU resupply since there is a shortage of LRUs at the depot); and, (3) the number of depot SRU backorders that are delaying SRU resupply (this delays base LRU repair because there is a shortage of SRUs at the base) (Sherbrooke, 1986:316-317). As stated previously, each LRU failure is assumed to be due to the failure of only one SRU. Thus, the expected number and variance of LRUs delayed in base repair (the third part above) is just the sum of the means and variances for the SRUs backordered at the depot; each SRU backorder at the depot equals an LRU delayed in base repair. The mean and variance for LRUs in repair/resupply at base j, then, are (Sherbrooke, 1986:317):

$$E(x_{j0}) = \lambda_{j0}[(1 - r_{j0})O_{j0} + r_{j0}A_{j0}] + f_{j0}E[B(s_{00} \mid E(x_{00}), Var(x_{00}))] + \sum_{k=1}^{K} E[B(s_{jk} \mid E(x_{jk}), Var(x_{jk}))] \qquad j>0 \qquad (30)$$

$$Var(x_{j0}) = \lambda_{j0}[(1 - r_{j0})O_{j0} + r_{j0}A_{j0}] + f_{j0}(1-f_{j0})E[B(s_{00} \mid E(x_{00}), Var(x_{00}))] + f_{j0}^2 Var[B(s_{00} \mid E(x_{00}), Var(x_{00}))] + \sum_{k=1}^{K} Var[B(s_{jk} \mid E(x_{jk}), Var(x_{jk}))] \qquad j>0 \qquad (31)$$

Within Vari-METRIC, then, the expected base LRU backorders are computed using the expected backorder calculation from the AAM. Equations 30 and the quotient of Equation 31/Equation 30 are used to estimate the negative binomial parameters, mean and VTMR, respectively.

Formulation and Solution. The formulation and solution processes of Vari-METRIC are very similar to that of the AAM previously discussed. Vari-METRIC calculates an availability by computing the expected backorders just as in AAM. The essential difference is in the calculation of the expected LRU backorders as defined above.

Summary. Vari-METRIC was developed for incorporation into existing models such as Mod-METRIC, the AAM, and the Aircraft Sustainability Model (ASM).

The Vari-METRIC theory is not used in the AAM (Rexroad, 1994:unnumbered), but it is used in the ASM, to be discussed later. According to Sherbrooke:

> Vari-METRIC theory is used by a number of manufacturers in the United States, particularly those involved with aircraft and related systems. In most cases the application is initial stockage lists, but it is hard to know the full range of model usage. (Sherbrooke, 1992:201)

Dynamic Demand, Multi-Echelon, Multi-Indenture.

Dyna-METRIC. Dyna-METRIC models the Air Force reparable item inventory system. It is multi-indenture as well as multi-echelon. It is multi-indenture in that it considers three levels of components, LRUs, SRUs, and subSRUs. SubSRUs are "subcomponents of an SRU, including bits and pieces that are often consumed during repair of the SRU" (Isaacson and others, 1988:xv-xvi). Dyna-METRIC is multi-echelon in that it considers logistics activities (supply, maintenance, and transportation) within a five level hierarchical structure: flight lines, local base repair shops, centralized intermediate repair facilities (CIRFs), depots, and various suppliers of components (Isaacson and others, 1988:5).

Dyna-METRIC builds upon previous METRIC-based models. It uses the expected backorder calculation from METRIC and Mod-METRIC and calculates aircraft availability as in the AAM. Dyna-METRIC, though, offers several improvements over previous METRIC-based models. The major improvement of Dyna-METRIC is that it considers "time-varying demands" (Isaacson and others, 1988:8). This is essential in modeling a dynamic wartime scenario. Dyna-METRIC was developed to provide the kinds of information logisticians need "to improve wartime logistics support within a single theater." (Isaacson and others, 1988:1). The kinds of new information that Dyna-METRIC provides are:

1. operational performance measures
2. effects of wartime dynamics
3. effects of repair capacity and priority repair
4. problem detection and diagnosis
5. spares requirements (Isaacson and others, 1988:1)

Dyna-METRIC is applied, then, in three major areas: capability assessments, problem parts identification, and spares requirements computations (Niklas, 1992:unnumbered).

Assumptions. This thesis focuses directly on Dyna-METRIC's ability to assess a unit's performance. Critical to the assessment of a unit's performance is the calculation of the aircraft availability rate for that unit. The aircraft availability rate can be computed in two ways -- under a no cannibalization policy (as with the AAM) and under a full cannibalization policy. Cannibalization is:

> the practice of transferring a serviceable component from one aircraft to repair another. The [donor] aircraft must already be unserviceable because of another component failure, and the needed serviceable component cannot be obtained from local supplies. (Isaacson and others, 1988:xv)

Under a full cannibalization policy, all LRUs can be cannibalized, while under a no cannibalization policy, no LRUs can be cannibalized. In computing the aircraft availability under full cannibalization, three assumptions are made. The first is that all aircraft at a base are identical. The second is that cannibalization is always 100% successful, and the third is that "cannibalization can be done instantly and without consuming resources" (Isaacson and others, 1988:95). These assumptions are inherent in Dyna-METRIC's aircraft availability calculations.

Other assumptions of Dyna-METRIC are that demands for spare parts are driven by flying hours; there are always sufficient personnel and facilities to perform repair; and repair and resupply are based on a First In, First Out (FIFO) policy. Simulated war exercises, such as Coronet Warrior I, II, and III and Bull Rider, as well as Desert Storm have validated these assumptions (Niklas, 1992:unnumbered).

Computational Process. The average daily demand rate, θ, within previous METRIC-based models is based on a stationary probability distribution. It is calculated using averages -- the average number of aircraft and the average number of sorties per day per aircraft. Within Dyna-METRIC the daily demand rate is a function of time. It is based on variables that may change over time:

> For example, the number of aircraft can change in time according to the time sequence of deployment or because of aircraft attrition. The number of sorties per day per aircraft changes as a result of programmed changes in flying rates, and the flying hours per sortie change as missions change. (Hillestad, 1982:9)

The repair time used in Dyna-METRIC is not a constant average repair time, T, as it is in previous METRIC-based models. Dyna-METRIC uses "the probability that a component entering repair at time s is still in repair at time t. This probability function, F(t,s) is called the repair function." (Hillestad, 1982:9).

The repair function is defined by (Hillestad, 1982:9):

$$\begin{aligned} F(t,s) &= \text{Prob}\,\{\text{Component entering at } s \text{ is } \underline{\text{still}} \text{ in repair at } t\} \\ &= \text{Prob}\,\{\text{Repair time} > t\text{-}s \text{ when started at } s\} \end{aligned}$$

This refinement is important since the repair capability can now vary over time. The following examples demonstrate how this function is obtained for most instances in component repair (Hillestad, 1982:9):

i. Deterministic (constant or fixed) repair time, T. This is typical of METRIC, Mod-METRIC, and AAM

$$F(t,s) = \begin{cases} 1 & \text{if } t-s < T \\ 0 & \text{if } t-s \geq T \end{cases}$$

ii. Exponentially distributed repair time with average T.

$$F(t,s) = e^{-(t-s)/T}$$

iii. No repair capability until time, τ, with exponentially distributed repair time after τ.

$$F(t,s) = \begin{cases} 1 & \text{if } t < \tau \\ e^{-(t-\tau)/T} & \text{if } s \leq \tau \leq t \\ e^{-(t-s)/T} & \text{if } \tau < s \leq t \end{cases}$$

iv. Fixed transportation lag, S, with exponentially distributed repair time after transportation occurs.

$$F(t,s) = \begin{cases} 1 & \text{if } t-s < S \\ e^{-(t-(s+S))/T} & \text{if } t-s \geq S \end{cases}$$

Each of these repair functions is independent of the demand function. Other repair functions could be modeled provided they too are independent of the demand function (Hillestad, 1982:11).

"Dyna-METRIC combines the repair and demand functions to determine the average number of parts in the pipeline" (Hillestad, 1982:11). Looking at the interval of time, Δs, centered at time s, the expected number of assets in the repair pipeline at time t is (Hillestad, 1982:11):

$$\Delta\lambda(t,s) = \theta(s) \cdot F(t,s) \cdot \Delta s \tag{32}$$

where

$\Delta\lambda(t,s)$ = expected number of components in the repair pipeline at time t that arrived during the interval around s
$\theta(s)$ = daily demand rate at time s
$F(t,s)$ = probability of component not out of repair by time t
Δs = interval of time centered at s

If we assume that the number of failures arriving in the interval Δs is independent of the number of failures arriving in similar intervals centered at other times other than s and that the repair probability function is independent of the probability distribution generating the demand rate, we can sum the contributions of all intervals to obtain (Hillestad, 1982:11)

$$\lambda(t) = \sum_{s \leq t} \Delta\lambda(t,s)$$

$$= \sum_{s \leq t} \theta(s) \cdot F(t,s)\Delta s \tag{33}$$

Making the time interval, Δs, arbitrarily small (Hillestad, 1982:12)

$$\lambda(t) = \int_0^t \theta(s)F(t,s)ds \tag{34}$$

Equation 34 represents the average number of components in the repair pipeline at time t (Hillestad, 1982:12) and is the dynamic analog of λT in the METRIC, Mod-METRIC, and AAM models.

Assuming "that the component failure probability distribution is Poisson, $\lambda(t)$ is the mean of a nonhomogeneous (time varying) Poisson process. That is, the probability of k components in repair at time t is" (Hillestad, 1982:12)

$$P(k) = \lambda(t)^k e^{-\lambda(t)} / k! \tag{35}$$

where Equation 34 is used to compute $\lambda(t)$ (Hillestad, 1982:12).

Dyna-METRIC uses the generalized, or dynamic, form of Palm's Theorem to compute the expected contents of the pipeline. This theorem states that if parts are demanded according to a non-homogeneous Poisson process and if the repair function is independent of the demand function, then the average number of parts in the pipeline at time t has a Poisson distribution with mean equal to $\lambda(t)$ (Isaacson and others, 1988:78).

Formulation. As mentioned previously, Dyna-METRIC is used to assess a unit's performance. To do this, it calculates the aircraft availability rate for that unit. The aircraft availability rate can be computed in three ways -- under a policy of no cannibalization, full cannibalization, or partial cannibalization (Niklas, 1991:unnumbered).

In computing the aircraft availability under no cannibalization, the calculation is identical to that within the AAM (Equation 16). The EBO_i, though, are calculated according to Equation 4 with Equation 34 replacing λT (Niklas, 1991:unnumbered).

In computing the aircraft availability under full cannibalization, the Expected Not Mission Capable Supply (ENMCS) aircraft is first calculated. ENMCS aircraft are aircraft that are unable to perform their mission due to the need for spare parts that the supply system is unable to provide (Niklas, 1991:unnumbered).

With full cannibalization, the maximum number of a particular part, i, that can be broken and yet not create more than Z NMCS aircraft (where Z=0,1,...,AC) is:

$S_i + Q_iZ$. The number of part i available for cannibalization is represented by Q_iZ. This is the total number of part i on the broken aircraft and are considered as additional spare stock. $P(x \mid \lambda(t)_i, VTMR_i)$ is the probability that exactly x parts are broken and is represented by any discrete probability function (Poisson, binomial, or negative binomial) with mean, $\lambda(t)_i$, and $VTMR_i$ greater than 0. The VTMR is one when using a Poisson, between zero and one when using a binomial, and greater than one when using a negative binomial. The probability of less than Z aircraft being NMCS due to part i, then is (Niklas, 1991:unnumbered)

$$P(\leq Z \text{ NMCS}) = \sum_{x=0}^{S_i + Q_iZ} P(x \mid \lambda(t)_i, VTMR_i) \tag{36}$$

To obtain the $P(\leq Z$ NMCS) due to all parts, I, the $P(\leq Z$ NMCS) due to each part (Equation 36) must be multiplied together. This is because the parts are independent (in most cases the breaking of one part does not impact the breaking of another part) (Niklas, 1991:unnumbered):

$$\prod_{i=1}^{I} \sum_{x=0}^{S_i + Q_iZ} P(x \mid \lambda(t)_i, VTMR_i) \tag{37}$$

This product represents the $P(\leq Z$ NMCS) due to all parts. The quantity $1 - P(\leq Z$ NMCS) is the $P(> Z$ NMCS). Summing the probability, $P(> Z$ NMCS), for Z=0,1,....,AC-1 would give the ENMCS (Niklas, 1991:unnumbered):

$$\text{ENMCS} = \sum_{Z=0}^{AC-1} \left(1 - \prod_{i=1}^{I} \sum_{x=0}^{S_i + Q_iZ} P(x \mid \lambda(t)_i, VTMR_i) \right) \tag{38}$$

Since this is the expected number of not mission capable aircraft, or unavailable aircraft, the number of available aircraft would be AC - ENMCS. Using this number, the aircraft availability rate under full cannibalization would then be (Niklas, 1991:unnumbered)

$$\text{Full-Cann AA} = (AC - \text{ENMCS}) / AC \tag{39}$$

Solution Process. Dyna-METRIC can be run to provide one of two types of information -- spares assessment performance reports (resulting in problem parts identification) or spares requirements. The solution process within the performance mode involves computing pipelines, expected backorders, and the aircraft availability rates as discussed in the Computational Process and Formulation sections above. The solution process within the requirements mode is very similar to that within the AAM except that Dyna-METRIC does not compute a sorted list of candidate units to purchase. It computes the marginal improvement in the aircraft availability rate per unit cost due to incrementing each part's stock level and then increments the stock for that item that provides the maximum improvement per cost. With this new stock level for the chosen item, the system aircraft availability is computed. The process ends when the system aircraft availability is greater than or equal to a specified target system aircraft availability (Niklas, 1991:unnumbered).

Summary. Dyna-METRIC is the accepted Air Force capability assessment model. Units are rated on their war-fighting capability based on the assessments provided by this model. Dyna-METRIC is also used within the Air Force Materiel Command to evaluate Readiness Spares Package (RSP) requirements (Niklas, 1992:unnumbered).

Aircraft Sustainability Model (ASM). The ASM is derived from the AAM. The AAM is a "peacetime readiness model" (Slay and King, 1987:1-2); the ASM is an extension of the AAM that evaluates wartime sustainability (Slay and King, 1987:1,3). The ASM is a

> model of wartime sustainability that relates resources to fighting ability over a period of time. Specifically, it relates funding by weapon system to the probability - day by day - of being able to attain the flying levels specified in the Air Force War and Mobilization Plan (WMP). (Slay and King, 1987:iii)

The ASM is a "two-indenture, two-echelon requirements model for a single weapon system." (Slay and King, 1987:2-2). It is not only an assessment model but also a requirements model. It projects the aircraft availability rates given the asset positions (stock levels) for the parts being modeled, as well as computes the stock levels "needed to fly the WMP, with a specified level of confidence, over a given period of time." (Slay and King, 1987:1-3). The user is allowed to specify the desired goal, such as an expected availability goal or a funding constraint (Sherbrooke, 1992:184). The ASM then provides a "shopping list" (as discussed in the AAM "Solution Process"), identifying what spare items to buy in order to achieve a target availability rate at a minimum cost (Rexroad, 1992:15).

The ASM computes the relationship between funding and sustainability in such a way that planners can easily develop and evaluate various budgets for War Reserve Materiel (WRM) spares (Slay and King, 1987:iii).

Assumptions. The assumptions of the ASM are similar to those of other, previously discussed, METRIC-based models. An aircraft is down (not available) upon failure of an LRU for which no spare is available. If a part cannot be repaired at the base, it is shipped to the depot for possible repair. A replenishment from the depot is requested immediately. Both the base and depot operate under an (s-1,s) inventory policy. At either the base or the depot, repair of the LRU consists of replacing a failed SRU. A failed SRU delays LRU repair; a failed LRU causes an aircraft to be unavailable. Like AAM, the bases are assumed to be uniform with respect to demands, resupply times, and repair capabilities. All failures occur at the base. At the depot, the part may be repaired or condemned. If a part is condemned, a replenishment from an outside source of supply is requested (Slay and King, 1987:2-2). Unlike AAM, the ASM incorporates the effects of cannibalization (as described within the "Assumptions" of the Dyna-METRIC model). Each part can be flagged as either cannibalizable or not cannibalizable (Slay, 1994:unnumbered).

Computational Process. It is difficult to model war because it is difficult to quantify sustainability (Slay and King, 1987:1-1). Because war is dynamic in nature, performance over time cannot be represented with just one number. Related to this is the problem of "computing, in a dynamic environment, the number of units in the various logistics resupply pipelines." (Slay and King, 1987:1-1). The term pipeline "denotes the mean value of the number of items in a specific resupply process" (King, 1985:2-1). The most significant difference between AAM and ASM lies in the computation of these dynamic pipelines (Slay and King, 1987:2-1).

ASM uses the Dyna-METRIC approach to derive these dynamic pipeline quantities (refer to the "Computational Process" within the "Dyna-METRIC" section). For example, the number of LRUs that are in repair/resupply at the base and depot are computed using the dynamic pipeline computation from Dyna-METRIC (King, 1985:2-6). Resupply pipelines within the ASM are then computed by applying Vari-METRIC theory to the dynamic environment. Both the mean and the variance of the number of units in the resupply pipelines are computed as a function of time (Slay and King, 1987:1-1). Applying Vari-METRIC theory to the dynamic environment, Equations 30 and 31 for computing the mean and variance for the number of LRUs in base repair/resupply become (King, 1985:4-6)

$$E(x_{j0}) = \int_{t-O_{j0}}^{t} \lambda_{j0}(u)(1 - r_{j0})\,du + \int_{t-A_{j0}}^{t} \lambda_{j0}(u) r_{j0}\,du + f_{j0} E[B(s_{00} \mid E(x_{00}), Var(x_{00}))] + \sum_{k=1}^{K} E[B(s_{jk} \mid E(x_{jk}), Var(x_{jk}))] \qquad j>0 \qquad (40)$$

$$
\begin{aligned}
Var(x_{j0}) = & \int_{t-O_{j0}}^{t} \lambda_{j0}(u)(1 - r_{j0})\, du + \int_{t-A_{j0}}^{t} \lambda_{j0}(u) r_{j0}\, du \; + \\
& f_{j0}(1-f_{j0}) E[B(s_{00} \mid E(x_{00}), Var(x_{00}))] \; + \\
& f_{j0}^{2} Var[B(s_{00} \mid E(x_{00}), Var(x_{00}))] \; + \\
& \sum_{k=1}^{K} Var[B(s_{jk} \mid E(x_{jk}), Var(x_{jk}))] \qquad j>0 \qquad (41)
\end{aligned}
$$

The expected backorder calculation within ASM uses a negative binomial distribution. The parameters for the negative binomial distribution are the mean and the variance-to-mean ratio(VTMR) -- mean=$E(x_{j0})$ (Equation 40) and VTMR=$Var(x_{j0})/E(x_{j0})$ (Equation 41/Equation 40), respectively.

Formulation and Solution Process. The formulation and solution processes of ASM are very similar to that of the AAM previously discussed. The essential difference is in the objective of each model. The objective of the AAM is to maximize the aircraft availability rate for a particular weapon system, subject to an investment constraint on total system stock. The objective of the ASM is to minimize the Expected Not Mission Capable Supply (ENMCS) aircraft for a particular weapon system, subject to an investment constraint. This is essentially the same objective since the ENMCS aircraft can be used to obtain the aircraft availability rate (Equation 39). When cannibalization is not considered, the objective functions are very similar (refer to Equation 15 which gives the probability that a randomly chosen plane is not NMCS for any part). When cannibalization is considered, the objective function within ASM is to minimize the ENMCS as computed by Equation 38 (Slay, 1994:unnumbered). The objective function within the ASM becomes more complicated than that within the AAM when cannibalization is considered.

Summary. The ASM has been incorporated into the Weapon System Management Information System (WSMIS). It is the "heart" of the

Requirements/Execution Availability Logistics Module (REALM) Mobility Readiness Spares Package (MRSP)/In-place Readiness Spares Package (IRSP) computation system. The ASM not only performs MRSP/IRSP requirements computations but also performs the budget allocation function (DRC, 1992:2-7). The ASM is also embedded in another subsystem of WSMIS, the Major Command Dyna-METRIC Microcomputer Analysis System (MAJCOM DMAS). The ASM is used within the MAJCOM DMAS to perform requirements computations of spares requirements for unit deployments (DRC, 1993:2-4).

Summary

The METRIC-based models (METRIC, Mod-METRIC, AAM, Vari-METRIC, Dyna-METRIC, and ASM) use the system approach to project the number of spare parts to buy for an item. The system approach provides the optimal number of spare parts to buy for each item to achieve a desired aircraft availability within a budgetary constraint.

METRIC and Mod-METRIC do not provide an actual aircraft availability rate, such as the others, but they do provide the optimal spares levels for minimizing the expected backorders within a budgetary constraint. This is still more efficient and economical than the spares levels provided by current FMS reparable sparing models.

Current FMS sparing models follow an item approach. Because the item approach considers only one part at a time, it can provide for spares levels that result in a very low system availability or a funding requirement that exceeds the overall budget. A model that uses the system approach is needed for use in FMS reparable sparing to provide adequate aircraft availability without spending more than a given dollar amount.

III. Methodology

Overview

The purpose of this research is to determine if an inventory model exists that can be used in Foreign Military Sales (FMS) reparable sparing to provide the most aircraft availability possible from a given inventory investment. As shown in chapter II, several models exist that maximize availability for a given investment level. Table 3-1 provides a comparison of all the METRIC-based models presented in chapter II.

Table 3-1. Comparison of METRIC-Based Models

	METRIC	Mod-METRIC	AAM	Vari-METRIC	Dyna-METRIC	ASM
Objective Function & Constraint	Minimize Expected Backorders subject to Budget		Maximize Aircraft Availability subject to Budget			Minimize ENMCS subject to Budget
Performance Measures	Expected LRU Backorders		Expected Backorders by Part, Aircraft Availability Rate			
Uses	Compute Reqmt for Parts; currently not used	Compute spare stock for engine modules	Compute Air Force Worldwide Reqmt for Parts	Compute Reqmt for Parts; not currently used as stand-alone model	Perform Air Force Capability Assessments	Compute MRSP & IRSP Reqmts
Convenience	N/A	Easily run on micro-computer	Runs on mainframe computer; not easily distributed	N/A	Easily run on micro-computer	Easily run on micro-computer; easily distributed

Referring to Table 3-1, the AAM, Vari-METRIC model, Dyna-METRIC model, and ASM provide an aircraft availability measure. The AAM, Vari-METRIC model, and

ASM actually provide an ordered shopping list of parts to buy to maximize availability for a given investment. The Dyna-METRIC model can compute stock level requirements but is primarily used for assessing the capability of pre-determined stock levels. Even though the Vari-METRIC model could be used as a stand-alone model, in practice, it is not; however, the logic has been incorporated into other models, such as the ASM. There are actually only two METRIC-based models, then, that could be most readily used in FMS reparable sparing. They are AAM and ASM.

The criteria for selecting a model, as defined within chapter I, "Scope and Limitations", were that the model is convenient to use, provides performance measures (i.e. expected backorders, aircraft availability rate), ensures an efficient inventory investment, and maximizes aircraft availability subject to a cost constraint. Both the AAM and the ASM fulfill the last three criteria, but the ASM is more convenient to use. The AAM is computationally demanding and runs only on a mainframe computer; the ASM can run very quickly on both a mainframe and a micro-computer. The ASM is easily distributed to multiple users; the AAM is currently run by only one user within the Air Force. Not only is the ASM more convenient to use, but it also provides more features by incorporating the Vari-METRIC logic and by allowing for cannibalization of parts. For these reasons, the ASM was chosen as the model to be used in FMS reparable sparing.

The remaining tasks are adaptation of the ASM to the FMS environment and validation of the ASM for use in FMS reparable sparing. The results of the ASM are compared to the current FMS sparing models in terms of dollars spent, mix of spare parts, and aircraft availability. The comparison involves the following steps: data collection, model development, model validation, and model use. This research demonstrates that the ASM can be used in FMS reparable sparing to provide the most efficient and economical inventory purchase.

Data Collection

Data collection involves gathering the data from two different FMS systems, analyzing the data, and converting the data for use in the ASM.

Data Gathering. Mr Gary Bingham, Ogden Air Logistics Center (ALC), provided a "Spares Negotiation Listing for FMS" from the International Data System (IDS) for a subset of F16 parts (177 parts) recently sold to a foreign country. Mr Tony Castillo, San Antonio ALC, provided a "Spares Negotiation Listing for FMS" from the International Weapon Item Projection System (IWIPS) for a subset of F5 parts (88 parts). The "Spares Negotiation Listing for FMS" contains part data, program data, and actual recommended quantities calculated by the FMS system, IDS and IWIPS, respectively.

The spares negotiation listings provide the necessary input data for the ASM, as well as the actual stock levels (by part) computed by the FMS systems. The part data includes: National Stock Number (NSN), cost, quantity per end item, application fraction, next higher assembly NSN, NRTS, and condemnation rate. The program data includes: procurement lead time, total number of aircraft, flying hours per month, base repair days, and depot repair days. The base repair days and depot repair days are the same across all parts in the listing. The actual stock levels computed by the FMS systems are compared to the stock levels computed by the ASM.

Data Analysis Plan. The data provided by the centers is used as provided. The ASM has built-in screening and range checking capability. This capability is relied upon to ensure the correctness of the data. If any questionable data elements are encountered, the model flags the situation by putting out a warning. Under certain conditions, the model defaults to appropriate values. Two different representative data files, IDS and IWIPS, were provided. Multiple data sets ensure that the model does not accommodate only one situation.

Data Conversion. Although the negotiation listing provides the required data for the ASM, the listing is not in the correct format for the ASM. A conversion program was written to put the FMS data into the ASM format. The program determines indenture relationships among the parts, computes pipeline quantities according to both the appropriate FMS system and the ASM, computes a maximum stock level for each part, and builds the ASM input files. The computation of the pipeline quantities and a maximum stock level for each part will be discussed within "Model Validation".

A user interface was also developed for the convenience of the FMS program manager. The interface manages data, runs the ASM, and provides the capability to view and/or print output reports. The interface in managing data provides the capability to: convert existing FMS data to the ASM format, load existing data files to be rerun, input new FMS data to run through the ASM, and edit and save existing data. A database structure is used to manage the data. The data to be used by the ASM is entered and maintained in a format familiar to the FMS customer.

Model Development

Model development involves making assumptions, designing an approach, and summarizing the results. Several assumptions are made in running the ASM to compute stock level requirements for the FMS data. These assumptions are made to provide a comparable technique to that used within the FMS systems. The ASM not only computes the FMS stock levels but also assesses both the IDS/IWIPS computed stock levels and the ASM computed stock levels. Summaries of the resulting stock levels and associated cost figures and aircraft availabilities are provided.

Assumptions. The assumptions made in running the ASM to compute FMS requirements are:

1. There is only one base and no depot. Modeling the entire supply system as if at one base accounts for all demand (base, depot, and condemnations) but provides a "worldwide" stock level for each part, or the total requirement by part for the particular

customer country. The current FMS sparing models also provide a total requirement by part: the requirement is not separated into a base portion and a depot portion.

2. The FMS requirements computation represents a peacetime computation. The Air Force currently uses ASM to compute wartime requirements, but it also can be used to compute peacetime requirements.

3. The probability distribution of the pipeline quantity is modeled as a pure Poisson. Thus, the Vari-METRIC feature is not used in computing the FMS requirements.

4. As mentioned in chapter I, the models discussed within this thesis are reparable sparing models. Requirements for consumable items, items that cannot be repaired and are consumed in use, are not computed using METRIC-based models. For this reason, consumable items are not included in the requirements computations.

5. The FMS spares negotiation listings do not identify items as LRUs and SRUs. The ASM relies upon indenture relationships in performing its computations. The following strategy is used to distinguish LRUs from SRUs: if a part appears on the listing as a next higher assembly NSN for another part, the part is an LRU. The part having a next higher assembly NSN located in the listing is an SRU. If the next higher assembly for a part can not be found in the listing, that part is an LRU. If a part appears more than once in the listing with identical data elements, the additional occurrences of the part are removed from the listing. If a part appears more than once in the listing without identical data elements, the additional parts are given an extension ("F" for first, "S" for second, "T" for third, "O" for fourth, etc.). The extension ensures that each part on the listing has a unique NSN. This is required by the ASM.

6. Cannibalization is not considered when running the ASM. This is consistent with the current FMS sparing process.

7. The FMS spares negotiation listing does not provide a demand rate for each part. The listing does provide a condemnation rate, a NRTS rate, and a RTS rate (base processing rate). Because the demand rate is used in computing these rates, the demand

rate for each part is determined by setting the equation for each of the above rates equal to the value provided in the listing and then solving for the demand rate. This results in identical pipeline quantities between the ASM and the current FMS models.

8. The repair times used in the FMS requirements computation are fixed (deterministic), allowing for no variability. Thus, the same fixed times are used in the ASM.

9. The order and ship time (OST) is assumed to be 14 days based on discussions with system program managers. The OST is included in the depot repair time (DRT) in current FMS sparing models. For the ASM requirements computation, the DRT is the difference between the given FMS DRT and a 14 day OST.

10. To ensure that the ASM does not spend more than the current FMS models, the cost of the requirements computed by the FMS sparing model (either IDS or IWIPS) is used as the desired cost target. The objective of the ASM run is to minimize the Expected Not Mission Capable Supply (ENMCS) aircraft (maximize aircraft availability) subject to this cost constraint.

Approach. The overall approach demonstrating that the ASM model is preferable to current FMS reparable sparing techniques involves the comparison of stock levels, cost figures, and aircraft availabilities of the current FMS sparing models (IDS and IWIPS) with those of the ASM. A comparison of the current models and the ASM displays the benefits of using the system approach as opposed to the item approach. The following procedure is used to make this comparison.

After obtaining the spares negotiation listings from the FMS system managers, the first step is to verify the pipeline quantities and thus, the FMS requirements. Using the equations presented in Appendix A for computing IDS and IWIPS pipeline quantities and the data from the FMS listings, pipeline quantities are computed. This is done for two reasons. First, the IDS spares negotiation listing does not provide the actual pipeline quantity but only a requirement. The actual pipeline quantity is required for comparison with the ASM pipeline quantity; the two should be the same. This will be discussed in "Model Validation". Second, the IWIPS pipeline quantities incorporate the Quantity Per Configuration (QPC). The QPC is not a data element on the listing but rather a factor used by the equipment specialists to adjust the Quantity Per Application (QPA). The QPC factor is determined by recalculating the pipeline quantity. The QPA is then factored by the QPC so that the correct QPA is input to the ASM.

The next step is to run the ASM in requirements mode to compute the stock level requirements for the FMS data. Two runs are made--one using the IDS data and one using the IWIPS data. The first run computes requirements for the parts on the IDS spares negotiation listing using the total cost of the requirements on the IDS listing as the investment constraint. The second run computes requirements for the parts on the IWIPS spares negotiation listing using the total cost of the requirements on the IWIPS listing as the investment constraint. The previously discussed assumptions are incorporated into the ASM input files to ensure consistent modeling of the FMS pipelines. The results of each requirements computation are presented in Chapter IV.

The final step is to run the ASM in assessment mode to evaluate the various computed stock levels. Four assessments are run. The first is an assessment of the stock levels computed using the ASM with the IDS data. The second is an assessment of the stock levels computed using the IDS system. The third is an assessment of the stock levels computed using the ASM with the IWIPS data, and the final assessment is of the stock levels computed using the IWIPS system. The results of the assessments are performance measures (i.e. expected backorders, aircraft availability rate) and cost figures to be used in evaluating and comparing the ASM with the FMS systems. These results are presented in Chapter IV.

Representation of Results. The ASM and the current FMS models are compared with respect to the computed stock levels (actual number of parts (depth) as well as the number of parts with an actual requirement (range)), the resulting cost figures, and the associated aircraft availabilities. The comparisons are made by evaluating the absolute differences between the values. Two reports represent the results. The first report is a "Computations Summary": the second report is a "Performance/Cost Summary".

The "Computations Summary" presents the stock level comparison. For each part (NSN) it displays the pipeline, the requirement and expected backorders for both the ASM computation and the FMS computation, the cost, and the stockage cap. The pipeline is the same under both models, the ASM and the FMS (IDS or IWIPS). The expected backorder figure represents the number of backorders expected given the specified stock level (requirement).

The "Performance/Cost Summary" presents the cost and aircraft availability comparison. This report is simple in that it only displays the cost and aircraft availability associated with each model - the readiness based sparing (RBS) model (ASM) and the FMS model.

Model Validation

The result of this study is a model that can be used in FMS reparable sparing to provide the greatest aircraft availability possible from a given inventory investment. In order to show that the model provides the most efficient and the most economical inventory purchase, the model is validated. In validating the readiness based sparing technique, system approach, of the ASM, the following four components of Sargent's "validation program" (Sargent, 1988:33) are addressed:

1. conceptual model validation
2. computerized model verification
3. operational validation
4. input data validation

"Input data validity" (Sargent, 1988:34) was addressed in "Data Analysis Plan".

Conceptual Model Validation. Conceptual model validation is determining that the underlying assumptions and theories are correct and that the model logic and mathematical foundation is sound (Sargent, 1988:35). The validation techniques that are used in the conceptual model validation are mathematical proof (the correctness of the mathematical foundation of the model has been documented in the literature; refer to Chapter II) and "face validity" (Sargent, 1988:34). Face validity involves having experts in the area of readiness based sparing review the FMS application of the ASM model and its assumptions and explain whether or not it appears "reasonable" (Sargent, 1988:34).

Computerized Model Verification. Computerized model verification is determining the correctness of the computer program and incorporation of the conceptual model (Sargent, 1988:35). The validation techniques that are used in the computerized model verification are "walking through" (Sargent, 1988:35) the code and "extreme-condition tests" (Sargent, 1988:33).

Walking through the code involves stepping through the computation of the pipeline quantities. The ASM pipeline computation is very similar to that of the FMS models (both the IDS and the IWIPS). For this reason, the ASM pipeline quantities should equal the FMS pipeline quantities. If the two quantities differ, the correctness of the data conversion program, discussed in "Data Conversion", is verified. If the data conversion program is not correct, the results of the ASM runs are not correct.

Extreme-condition tests involve structuring the model to be robust in handling extreme conditions and "restricting behavior outside of normal operating ranges" (Sargent, 1988:33). The built-in range checking capability of the ASM is relied upon heavily. If any extreme conditions occur, the model flags the situation and under certain conditions defaults to appropriate values. If the condition does not prevent the model from running, the situation is marked so that the user can investigate. The model may abnormally terminate, but it provides explanatory warning messages.

Operational Validation. Operational validation is determining that the model's output is accurate and useful (Sargent, 1988:35). The technique that is used in the operational validation is "comparisons to other models" (Sargent, 1988:33-34).

If in computing the FMS requirements the ASM computes identical pipeline quantities to that provided in the spares negotiation listings, the accuracy of the model is demonstrated. If in assessing the FMS requirements the ASM computes an identical cost (the model recomputes the associated cost) to that provided in the spares negotiation listings, the accuracy of the model is again demonstrated.

The usefulness of the model is demonstrated if the ASM provides reasonable stock levels, spends no more than the current FMS models, and provides better aircraft availability. Reasonable stock levels are those that are not too different in range and depth from the current models. The ASM can be run allowing for a maximum stock level (stockage cap) for each part. The stockage caps provide a more stable, robust computation, especially when the accuracy of the data is a concern. These caps ensure that the marginal analysis process does not compute extremely high safety stock quantities for low cost items. This helps reduce excess inventory and warehouse requirements. Stockage caps are not applied, but the cap is computed for review. Reviewing the stockage cap reveals if the stockage cap could be applied to ensure reasonable stock levels.

Model Use

After the ASM is validated as the model to use in FMS reparable sparing, authorization for incorporating the model into the current FMS systems (IDS and IWIPS) must be obtained. Once authorization is obtained, the model can be used by the FMS program managers to provide customer countries with the most aircraft availability possible from a given inventory investment. The equipment specialists at San Antonio ALC, specifically Mr Tony Castillo (mentioned in "Data Gathering" as the source of the IWIPS data), are currently looking into using the ASM with the data conversion program and user interface developed in this research effort. They are very interested in incorporating readiness based sparing into the IWIPS.

Summary

This research seeks to demonstrate that the ASM is superior to current FMS reparable sparing models in providing the most efficient and economical inventory purchase. Data used in the analysis was collected from system program managers at Ogden ALC and San Antonio ALC. This data is analyzed and converted into the proper format for the ASM. After making several assumptions, pipeline computations are verified, a cost target is chosen, and the ASM is run to not only compute the FMS stock levels but also to assess both the IDS/IWIPS computed stock levels and the ASM computed stock levels. The resulting stock levels and associated cost figures and aircraft availabilities are compared to validate the model. If the ASM computes reasonable stock levels and provides better aircraft availability for a given level of expenditure than the current FMS models, then it is validated. The model can then be used by FMS program managers to provide better support to customer countries.

IV. Results and Analysis

Overview

The approach used to demonstrate that the ASM is preferable to current FMS reparable sparing techniques is outlined in chapter III. The first step in the approach is to verify pipeline quantities. Pipeline quantities are computed in the data conversion program using both the appropriate FMS equations (IDS and IWIPS) and the ASM equations. The next step in the approach is to run the ASM twice in requirements mode. The first run computes the stock level requirements using the IDS input data. The second run computes the stock level requirements using the IWIPS input data. Running the ASM in assessment mode to evaluate the various computed stock levels is the final step in the approach. Four assessments are run (refer to chapter III, "Approach").

The results of the data conversion program and the various ASM runs are now presented. There are two sets of results: the IDS as compared to the ASM and the IWIPS as compared to the ASM. Both sets of results are presented and then analyzed. An evaluation of the analysis is also provided.

In following the approach, three modifications are made. The first modification involves the investment constraint used in the ASM requirements computation. The original investment constraint was the total cost of the requirements computed by the FMS sparing model (IDS or IWIPS, as appropriate). The actual investment constraint is the FMS total cost less the unit cost of the most expensive part in the input data file. Using this modified investment constraint ensures that ASM does not spend more than the FMS sparing model.

The second modification involves the stockage cap calculation. As mentioned in chapter III, the stockage caps are not applied in this research, but they are computed for review of applicability. The standard IWIPS safety stock computation, $\sqrt{3 \cdot \text{pipeline}}$, (refer to Appendix A), is not used. A slight modification is made to this computation so that the stockage cap is the pipeline plus $\sqrt{4 \cdot \text{pipeline}}$. The minimum value of the stockage cap is two so that if the pipeline for a part is very small the maximum stock level for that part is at least two. The modified stockage cap computation provides basically the same results as the standard IWIPS computation. The differences are that when the pipeline for a part is very small the minimum stockage cap of two is applied and when the pipeline for a part is large the modified stockage cap allows for larger amounts of stock. In either case, the modified stockage cap allows for only a slightly greater amount of stock but still provides the extra that may be needed with larger pipelines.

The third modification involves the addition of another "Performance/Cost Summary" report. The additional report provides more details on the range and depth of parts and the average and maximum expected backorders. It is used with the performance/cost summary described in chapter III.

IDS versus ASM

Data Conversion Results. The data conversion program produces five files--the ASM input files (four files) and an intermediate part file containing pipeline quantities (IDS and ASM computed quantities) and the stockage cap for each part.

The ASM input files include a parameters file, a scenario file, an LRU component data file, and an SRU component data file. The parameters file contains all the processing options for the ASM run. The assumptions discussed in chapter III are represented in this file.

The scenario file contains the flying program in hours per day for the ASM run. The IDS run is for 50 aircraft flying an average of 13 hours per aircraft per month so that the flying hours per day equal 21.67 assuming 30 days in a month ($50 \cdot 13 / 30 = 21.67$).

The LRU component data file and the SRU component data file contain all the part data as provided on the spares negotiation listing described in chapter III, "Data

Gathering". The data conversion program uses the strategy described in chapter III, assumption 5, to determine whether a part is an LRU or an SRU. Based on this strategy, the IDS data contains 95 LRUs and 82 SRUs.

The ASM uses the indenture relationships to determine the stock level requirements as explained in chapter II. Current FMS techniques do not distinguish between LRUs and SRUs. Because of this, all parts in the output reports are listed together without distinguishing between LRUs and SRUs.

Reviewing the intermediate part file confirms that the IDS pipeline quantities equal the ASM pipeline quantities. This verifies the accuracy of the data conversion program and the accuracy of assumption 7 (chapter III) which explains the determination of demand rates. The pipeline quantity as well as the computed stockage cap for each part are presented in Appendix B, Table B-1, "Computations Summary for the ASM/IDS Comparison".

Model Results. The ASM is run once in requirements mode to compute the required stock levels using the IDS input data and then twice in assessment mode to evaluate both the ASM computed requirements and the IDS computed requirements. The results of the requirements run are presented in Appendix B, Table B-1. The results of the assessment run are presented in Table 4-1, "Performance/Cost Summary for the ASM/IDS Comparison".

All data in Table B-1 is presented by part, "NSN". The third column of Table B-1, "RBS Computation Reqmt", represents the requirement computed using the ASM. The fifth column, "FMS Computation Reqmt", represents the requirement computed using the IDS system. Columns four and six represent the number of expected backorders, "EBOs", associated with the RBS (ASM) requirements and the FMS (IDS) requirements, respectively. The pipeline quantity, "Pipeline", is presented in column two. The unit cost, "Cost", is presented in column seven, and the stockage cap, "Stock Cap", is presented in the last column.

A preliminary look at Table B-1 demonstrates that the ASM computes a larger requirement than the IDS for 168 out of the 177 parts. Of the nine remaining parts, four parts have very small pipelines indicating a very low demand for these parts and the other five parts are five of the most expensive parts. Because the five expensive parts have relatively low pipelines, the marginal analysis technique of the ASM accommodates the need for a cheaper part with a larger pipeline, or greater demand.

Table 4-1. Performance/Cost Summary for the ASM/IDS Comparison

PERFORMANCE/COST SUMMARY
Cost of RBS: $11,846,728.00
Aircraft Availability associated with this cost: 66%
Cost of FMS Sparing: $12,112,378.00
Aircraft Availability associated with this cost: 21%

Table 4-1 presents the total cost and the aircraft availability associated with the cost for both the RBS (ASM) and the FMS (IDS) computations. The total cost of the ASM computed requirements is $11,846,728.00. The aircraft availability associated with this cost is 66%; that is, of the 50 total aircraft 33 aircraft would be operational given the ASM computed stock levels from Table B-1 are maintained. The total cost of the IDS computed requirements is $12,112,378.00. The aircraft availability associated with this cost is 21%; of the 50 total aircraft approximately 11 aircraft would be operational given the IDS computed stock levels.

IWIPS versus ASM

Data Conversion Results. The results of the data conversion program using the IWIPS input data are very similar to the results using the IDS input data. Five files are produced --the ASM input files (four files) and an intermediate part file containing pipeline quantities (IWIPS and ASM computed quantities) and the stockage cap for each part.

The parameters file is identical to that used in the IDS and ASM comparison, except for weapon system name and number of aircraft.

The IWIPS run is for 20 aircraft flying an average of 10 hours per aircraft per month, so that the scenario file contains 6.67 flying hours per day (20 · 10 / 30 = 6.67).

Based on the strategy described in chapter III, assumption 5, for distinguishing LRUs from SRUs, the IWIPS data contains 87 LRUs and no SRUs. An SRU component data file is produced, but contains no data. The LRU component data file contains all the part data as provided on the spares negotiation listing described in chapter III, "Data Gathering".

Reviewing the intermediate part file confirms that the IWIPS pipeline quantities equal the ASM pipeline quantities. This again verifies the accuracy of the data conversion program and the accuracy of assumption 7 (chapter III). The pipeline quantity as well as the computed stockage cap for each part are presented in Appendix C, Table C-1, "Computations Summary for the ASM/IWIPS Comparison".

Model Results. The ASM is run once in requirements mode to compute the required stock levels using the IWIPS input data and then twice in assessment mode to evaluate both the ASM computed requirements and the IWIPS computed requirements. The results of the requirements run are presented in Appendix C, Table C-1. The results of the assessment run are presented in Table 4-2, "Performance/Cost Summary for the ASM/IWIPS Comparison".

Table C-1 is identical to Table B-1, except that the fifth column, "FMS Computation Reqmt", represents the requirement computed using the IWIPS system. Column six also represents the number of expected backorders associated with the IWIPS requirements.

The data in Table C-1 shows that the ASM computes a larger requirement than the IWIPS for 82 out of the 87 parts. The five remaining parts are the five most expensive parts. Like the IDS comparison, the five most expensive parts have relatively low pipelines so that the ASM recognizes the need for more cheaper parts with larger pipelines.

Table 4-2. Performance/Cost Summary for the ASM/IWIPS Comparison

PERFORMANCE/COST SUMMARY
Cost of RBS: $1,229,314.00
Aircraft Availability associated with this cost: 53%
Cost of FMS Sparing: $1,273,282.00
Aircraft Availability associated with this cost: 4%

Table 4-2 presents the total cost and the aircraft availability associated with the cost for both the RBS (ASM) and the FMS (IWIPS) computations. The total cost of the ASM computed requirements is $1,229,314.00. The aircraft *availability* associated with this cost is 53%. Of the 20 total aircraft approximately 11 aircraft would be operational given the ASM computed stock levels from Table C-1 are maintained. The total cost of the IWIPS computed requirements is $1,273,282.00. The aircraft availability associated with this cost is 4%. Of the 20 total aircraft approximately 1 aircraft would be operational given the IWIPS computed stock levels.

Analysis of the ASM/FMS Model Comparisons

Although two sets of results have been presented, the more significant comparison is between the ASM and the current FMS techniques. The two sets of results presented verify that the ASM is preferable to current FMS reparable sparing techniques in the computation of stock level requirements.

Expert Opinion. The Division of Management Sciences, Headquarters, Air Force Materiel Command, (HQ AFMC/XPS), is the technical office of primary responsibility (OPR) for several of the METRIC-based models --Mod-METRIC, the AAM, and Dyna-METRIC. Analysts within HQ AFMC/XPS are considered experts by the Air Force logistics community with regard to these models and readiness based sparing. The FMS application of the ASM has been reviewed by several of the analysts within HQ AFMC/XPS. These analysts approve of this application of readiness based sparing to the FMS situation, finding it reasonable as well as long overdue.

The true experts in FMS reparable sparing are the actual equipment specialists, such as Mr Tony Castillo, San Antonio ALC. Mr Castillo provided the IWIPS data used in the ASM/IWIPS comparison. In reviewing the results, he is very impressed with the fact that the ASM computed a larger requirement for most parts while spending less and providing a higher aircraft availability. He is also impressed that his data could easily and accurately be converted to the ASM format. Mr Castillo is very interested in actually using the FMS application of the ASM.

Walking Through Pipeline Computations. Pipeline quantities are computed in the data conversion program using both the appropriate FMS equations (IDS and IWIPS) and the ASM equations. The computed FMS pipeline quantities equal the computed ASM pipeline quantities in both situations.

As added verification of the computed pipeline quantities and the accuracy of the input data to the ASM, the actual pipeline quantities computed by the ASM are compared to those computed in the data conversion program. All pipeline quantities are identical. The FMS quantities equal the preliminary ASM quantities which equal the actual quantities computed by the ASM. Because the actual ASM pipeline quantities are the same as those from the FMS models, the ASM is considered to accurately represent the current FMS reparable sparing environment.

Stock Level Comparisons. In comparing stock levels between the ASM and the current FMS models, looking at the quantities by part, as presented in "Model Results" for both the IDS and the IWIPS comparisons, is not enough. Looking at the depth and range of parts is also important. The ASM provides reasonable stock levels if the computed stock level requirements are not too different in depth and range from the current FMS models. Reviewing the stockage caps will reveal if the stockage cap could be applied to control the depth and range ensuring reasonable stock levels.

The depth is the total number of parts required. The ASM as demonstrated in "Model Results" computes a larger requirement for most of the parts. This results in a larger number of available spares. If the cost target is not exceeded this is good. The depth of parts with the ASM should be larger than that with the current FMS models.

The range is the number of parts with an actual requirement. Storing spare parts requires warehouse space. Requiring new parts that previously have not been required can increase warehouse requirements. For this reason, the range of parts with the ASM should be no greater than that with the current FMS models.

Table 4-3 presents the "Detailed Performance/Cost Summary for the ASM/IDS Comparison"; Table 4-4 presents the "Detailed Performance/Cost Summary for the ASM/IWIPS Comparison".

From Table 4-3, the depth of parts with the ASM is 3673 while the depth of parts with the IDS is 2743 --a difference of 930 parts. The range of parts with the ASM is 170 while the range of parts with the IDS is 177 --a difference of seven parts. The ASM provides a larger total number of parts while requiring no new parts. The ASM stock level requirements, then, are reasonable.

Table 4-3. Detailed Performance/Cost Summary for the ASM/IDS Comparison

	ASM	IDS
Cost of Spares	$11,846,756.00	$12,112,412.00
Number of Spares (Depth)	3673	2743
Number of Items with Requirement > 0 (Range)	170	177
Average EBOs	0.17	1.07
Maximum EBOs	3.14	10.89
Aircraft Availability	66%	21%

Table 4-4. Detailed Performance/Cost Summary for the ASM/IWIPS Comparison

	ASM	IWIPS
Cost of Spares	$1,229,353.88	$1,273,321.63
Number of Spares (Depth)	1235	842
Number of Items with Requirement > 0 (Range)	83	80
Average EBOs	0.15	0.75
Maximum EBOs	1.53	7.07
Aircraft Availability	53%	4%

From Table 4-4, the depth of parts with the ASM is 1235 while the depth of parts with the IWIPS is 842 --a difference of 393 parts. The range of parts with the ASM is 83 while the range of parts with the IWIPS is 80 --the ASM requires 3 additional parts. The

ASM, then, provides a larger total number of parts while requiring 3 additional parts. At first this does not appear reasonable, but the following analysis demonstrates that the ASM stock levels are not unreasonable.

Referring to Table C-1, the ASM computes a requirement for seven parts for which the IWIPS does not compute a requirement. The total cost of the requirements for these seven parts is $37,294.00. The IWIPS computes a requirement for four parts for which the ASM does not compute a requirement. The total cost of the requirements for these four parts is $439,245.11. In computing a requirement for 3 additional parts, the ASM is still spending $401,951.11 less on these parts. The ASM stock level requirements, then, appear to be reasonable.

The marginal analysis process of the ASM may compute large stock level requirements for low cost items. To ensure that stock level requirements do not become too unreasonable, stockage caps can be applied to provide maximum stock levels. Table B-1 contains the stockage caps for the IDS data, and Table C-1 contains the stockage caps for the IWIPS data.

Reviewing these caps indicates that the ASM is providing stock levels that are very close to these caps for both sets of FMS data. If the cap is exceeded, it is not by much. It is exceeded because the parts are cheaper than other parts.

Applying the stockage caps does not appear to be necessary. The depth of parts would not be significantly affected. The depth of parts would only decrease by 188 parts with the IDS data and 134 parts with the IWIPS data. The range would also not be affected. The stockage cap controls the requirement from becoming too large. If a part has no requirement, the cap would not affect this. Stockage caps, then, are not needed in the ASM/FMS comparison. The ASM not only provides larger stock levels than the current FMS models, but it also provides reasonable stock levels.

Performance/Cost Comparisons. The ASM spends less and provides better aircraft availability than both of the current FMS models (IDS and IWIPS).

Referring to Table 4-1, the ASM spends $265,650 less than the IDS model and provides three times the availability (33 aircraft, as compared to 11 aircraft). From Table 4-2, the ASM spends $43,968 less than the IWIPS model and provides over 10 times the availability (11 aircraft, as compared to 1 aircraft).

The accuracy of the ASM is demonstrated in the recalculation of the FMS cost. The actual cost of the IDS requirements is $12,112,412 (Table 4-3). In assessing the IDS requirements, the ASM computes a total IDS cost of $12,112,378 (Table 4-1). The difference of $34 is due to rounding; the ASM does not round the costs associated with individual parts while the IDS model does.

The actual cost of the IWIPS requirements is $1,273,321.63 (Table 4-4). The ASM computes a total IWIPS cost of $1,273,282.00 (Table 4-2). Again, the difference of $39.63 is due to rounding.

The improved aircraft availability provided by the ASM is also demonstrated through review of the expected backorders (EBOs) resulting from the ASM and the FMS stock level requirements. The average EBOs across all parts of the ASM using the IDS data is 0.17; the average EBOs across all parts of the IDS model is 1.07. The maximum EBOs for any part of the ASM is 3.14; the maximum EBOs for any part of the IDS model is 10.89 (refer to Table 4-3).

The average EBOs across all parts of the ASM using the IWIPS data is 0.15; the average EBOs across all parts of the IWIPS model is 0.75. The maximum EBOs for any part of the ASM is 1.53; the maximum EBOs for any part of the IWIPS model is 7.07 (refer to Table 4-4).

Compared to both the IDS and the IWIPS, the ASM stock levels result in less expected backorders, or less unfilled demands. Thus, the ASM provides better aircraft availability than the current FMS models.

Evaluation of Analysis

The FMS application of the ASM has been validated. The underlying assumptions, theories, and mathematical foundation of the application of the ASM are correct and sound. The logic and the output of the model are accurate and useful. Readiness based sparing techniques can and should be applied to the FMS environment. This has been shown. Because of this, the analysis is meaningful.

The analysis is also as expected. Readiness based sparing is known for providing the most aircraft availability possible for a given investment. The system approach of the ASM, as opposed to the item approach of current FMS reparable sparing models, provides a more efficient and economical inventory purchase.

The analysis has application. Customer countries can be assured that their investment level will be maintained while they obtain an optimal mix of spare parts. By entering the investment level as a cost target, the country is assured that the ASM will spend no more than the investment level.

The analysis will have an impact. The use of the ASM in FMS reparable sparing will provide better support to our customer countries.

Summary

The results of the ASM/FMS comparison demonstrate that the ASM provides reasonable stock levels, spends no more than the current FMS models, and provides better aircraft availability. The research is a success. The ASM can be used in FMS reparable sparing to provide the most aircraft availability possible from a given inventory investment.

V. Summary, Conclusions and Recommendations

Summary of Research Effort

Current FMS reparable sparing models use the item approach. The number of spare parts for an item are determined without considering the other items on the system. By considering only one item at a time, the current FMS models may provide stock levels that result in a very low system availability or a funding requirement that exceeds the overall budget. An inventory model is needed that can be used in FMS reparable sparing to provide the most aircraft availability possible from a given inventory investment. The ASM is such a model. It uses the system approach, which provides the most aircraft availability possible from a given inventory investment by computing the optimal number of spare parts to buy for each item.

FMS data was obtained from two sources: the IDS and the IWIPS. Both the IDS and the IWIPS are currently used in FMS reparable sparing to provide stock level requirements to customer countries. The IDS is used at Ogden Air Logistics Center, and the IWIPS is used at San Antonio Air Logistics Center. The data obtained from these FMS systems included part data, program data, and actual recommended stock level quantities calculated by the respective FMS systems.

The ASM was run twice in requirements mode to compute stock level requirements using the part and program data from each FMS system. The stock levels recommended by the IDS and IWIPS and the stock levels from the two ASM requirements runs were then evaluated using the ASM in assessment mode. The ASM and the current FMS models were compared with respect to the computed stock levels, the resulting cost figures, and the associated aircraft availabilities. The two sets of results verified that the ASM is preferable to current FMS reparable sparing techniques in the computation of stock level requirements.

Conclusions

The current FMS models, both the IDS and the IWIPS, recommended stock levels that resulted in much lower aircraft availability estimates than the ASM. To obtain a higher aircraft availability with the mix of parts specified by the IDS and the IWIPS, a larger investment level (greater than the budget provided) would be required. These results demonstrate the drawbacks of the item approach.

The stock levels computed by the ASM provided a greater depth of parts than the current FMS models while not varying much in range. The stock levels also resulted in a much higher aircraft availability and a slightly smaller investment. Two conclusions can be made from the results presented in chapter IV. The first conclusion is the ASM is superior to current FMS reparable sparing models in providing the most efficient and economical inventory purchase. The second conclusion is that the ASM provides more features than the current FMS models, such as the choice of using a cost or aircraft availability target, the application of stockage caps and the cannibalization of parts.

The objective of the ASM is to minimize the Expected Not Mission Capable due to Supply (ENMCS) aircraft subject to an investment constraint. To achieve this objective, a cost target as well as an aircraft availability target can be applied. The cost target was used in this research effort. The aircraft availability target can be used when a particular ENMCS level is desired. Using the desired ENMCS level (aircraft availability target), the ASM will compute the stock levels required to achieve this target at the least level of investment. The ASM can then be run to achieve the maximum aircraft availability for a given investment level (cost target) or to achieve a given aircraft availability at the minimum investment level (aircraft availability target).

The ASM allows for the application of stockage caps. Stockage caps can be applied [illegible] parts as well as on only selected parts. The application of stockage caps [illegible] stable stock level requirements that are not exceptionally high or

The ASM can compute stock level requirements considering cannibalization. The cannibalization of parts can improve aircraft availability. If spare parts are not available from supply, a serviceable part (one that is not broken) can be taken from an aircraft that is already unavailable because of the failure of a different part. This serviceable part can then be used in the repair of another aircraft that is waiting on a part from supply. The cannibalization of a serviceable part from an already unavailable aircraft makes another aircraft available. Without cannibalization, both aircraft would have been unavailable. Thus, cannibalization can improve aircraft availability and should therefore be considered in a realistic model.

This research has demonstrated that the system approach can be applied to FMS reparable sparing and that it can be applied through the use of the ASM. The ASM was demonstrated to be efficient in that it buys those parts that contribute the most to aircraft availability. The ASM was also demonstrated to be economical in that it does not spend more than a given dollar amount. The results of this research have demonstrated that when compared with current techniques, the ASM is the inventory model to use in FMS reparable sparing.

Recommendations

The equipment specialists, specifically Mr Tony Castillo, at San Antonio Air Logistics Center, F5 Technical Support, are currently looking into developing a new system, similar to IWIPS, that incorporates readiness based sparing. It is this author's recommendation that the equipment specialists use the ASM with the data conversion program and user interface developed in this research effort. The data conversion program simplifies the transfer of data from the IWIPS to the ASM, and the user interface allows for convenient use of the data conversion program and the ASM. The ASM would provide customer countries with recommended stock quantities that can be purchased within their budget constraints and with an assessment of how the stock quantities would affect their performance (aircraft availability).

Recommendations for follow-on work include: determining a more efficient and economical technique for computing requirements of consumable parts, incorporating readiness based sparing into the Security Assistance Management Information System (SAMIS), and developing a better forecast of the demands for parts.

The FMS data includes many consumable parts. This research effort excluded consumable parts, primarily because readiness based sparing is not currently applied to consumables. Consumable parts are usually very cheap parts that are bought in large quantities at a specified reorder point. The complexity involved in computing optimal stock level requirements for consumable items requires a different technique than the marginal analysis technique of readiness based sparing models such as the ASM. Further research should be conducted into how the US Air Force computes its consumable requirements and how this computation compares with the current readiness based sparing models.

SAMIS is the primary data system containing FMS data. The data maintained by SAMIS includes requisition data (past and present), country data, part data, and weapon system data. The data is for all countries, all parts, and all weapons systems involved in US foreign military sales. The various FMS systems at the air logistics centers, such as the IWIPS, are linked to SAMIS. SAMIS receives and maintains data from the various FMS systems and also passes required data to other US Air Force systems, such as D041, the Recoverable Consumption Items Requirements System (refer to chapter II, "Aircraft Availability Model"). The stock level requirements from systems such as IWIPS are passed to D041 and then used in the computation of the overall US Air Force requirements. If the stock level requirements passed through SAMIS are not accurate, the requirements computed by D041 will not be accurate. Further research into the requirements being passed through SAMIS would indicate if the application of readiness based sparing within SAMIS would be appropriate for ensuring the accuracy of all stock level computations. Stock levels could be computed for all parts within SAMIS and then passed onto the FMS systems at the centers, such as IWIPS, and the other US Air Force systems, such as D041.

The demand rates used in this research were approximated using the part data that was given (refer to Chapter III, assumption 7). Demand data is essential to the calculations performed within the ASM, so having accurate demand data is very important. Since SAMIS maintains requisition data (past and present) for all FMS parts, further research into the SAMIS requisition data could provide information on the demands for parts. The requisition data may be of use in forecasting demands, providing more accurate demand rates.

Appendix A: Computations of Current FMS Reparable Sparing Models

Computational Foundation for Current Models (AFLCR 57-27)

There are four pipeline computations used in the calculation of the total initial spares requirement for a part within AFLCR 57-27. The four pipeline segments include the base repair pipeline, the base order and ship time (OST) quantity, the depot repair pipeline, and the base level and depot level condemnation quantity (Department of the Air Force, 1991:28-29).

The average number of parts in the base repair pipeline is the base repair cycle quantity. The base repair cycle

> is the average time (in days) required to repair an item at base level, exclusive of days awaiting parts (AWP). In essence, a standard base repair cycle consists of minimum shop flow time and not more than 1 day for moving the reparable from point of generation to point of repair. (Department of the Air Force, 1991:530)

The base repair cycle quantity, then, represents the total number of parts at base level. These parts are either repaired, or condemned, at base level:

$$\text{Base repair cycle quantity} = BRC \cdot \text{Peak FH} \cdot Q \cdot APPL \cdot DR \cdot (1 - NRTS) / 30 \qquad (1)$$

where

BRC =	base repair cycle (in days)
Peak FH =	peak monthly aircraft inventory · average operating hours per month
Q =	quantity per end item
APPL =	application percent
DR =	demand rate = total organization and intermediate demand rate
=	estimated failures per 100 flying hours
NRTS =	1 - base processing rate = percent of reparable generations occurring at the base that are repaired at the depot
1 - NRTS =	base processing rate = percent of reparable generations occurring at the base that are repaired at the base

The base OST quantity is the average number of parts that have been requisitioned from the depot. These parts are either in-transit or awaiting transportation from the depot to the base.

$$\text{Base OST quantity} = OST \cdot \text{Peak FH} \cdot Q \cdot APPL \cdot DR \cdot NRTS / 30 \qquad (2)$$

where

$$OST = \text{base order and ship time (in days)}$$

The average number of parts in the depot repair pipeline is the depot repair cycle quantity. The depot repair cycle "is the calendar time in days from date a reparable item is removed to the date the item is made serviceable by a depot level repair activity, less dead storage and AWP item at base or depot" (Department of the Air Force, 1991:530). The depot repair cycle quantity, then, represents the number of broken parts that will be repaired at the depot:

$$\text{Depot repair cycle quantity} = DRC \cdot \text{Average FH} \cdot Q \cdot APPL \cdot DR \cdot NRTS / 30 \qquad (3)$$

where

$$DRC = \text{depot repair cycle (in days)}$$
$$\text{Average FH} = \text{average monthly aircraft inventory} \cdot \text{average operating hours per month}$$

The base level and depot level condemnation quantity is the average number of parts that will be condemned at the base and the depot. The number of parts condemned at the base is the percentage of parts that, even though the base has the capability to repair, are damaged beyond repair. The number of parts condemned at the depot is the percentage of parts sent to the depot for repair that are damaged beyond repair. Once a part is condemned at the depot a replacement is ordered from an outside supplier (Issacson and others, 1988:7). It takes time for replacements to arrive; this time is included in the calculation of the total (base level and depot level) condemnation quantity:

$$\text{Base level and depot level condemnation quantity} = (3 + PCLT) \cdot Q \cdot APPL \cdot DR \cdot \text{Average FH} \cdot [(1 - NRTS) \cdot Bcond + (NRTS) \cdot Dcond] \qquad (4)$$

where

$$PCLT = \text{procurement lead time} = \text{the sum of administrative lead time and production lead time}$$
$$Bcond = \text{base condemnation rate}$$
$$Dcond = \text{depot condemnation rate}$$

The total initial spares requirement for a part is the sum of equations one through four (Department of the Air Force, 1991:32). Note, this total initial spares requirement provides for the item's procurement lead time and incorporates a three month safety level (3 + PCLT).

<u>International Weapon Item Projection System (IWIPS)</u>

The initial spares computations within the IWIPS are based on the computations within AFLCR 57-27 (Mueller, 1992:unnumbered). These IWIPS computations are as follows.

The calculation of the base pipeline quantity within the IWIPS is very similar to the base pipeline calculation within AFLCR 57-27 except that the base pipeline calculation within IWIPS represents only those parts actually repaired at the base. It excludes those parts condemned at the base. The application percent (APPL), also, is assumed to be one:

$$\text{Base pipeline quantity} = \text{Average FH} \cdot \text{BRC} / 30 \cdot (1 - (\text{NRTS} + \text{Bcond})) \cdot \text{DR} \cdot \text{Q} \qquad (5)$$

The average FH is the product of the average operating hours per month for one end article and the total number of aircraft. This number is then divided by 100 "to factor out program units in 100s of hours" (Peterson, 1992:unnumbered).

The depot pipeline quantity within the IWIPS is identical to that within AFLCR 57-27 assuming an application percent of one:

$$\text{Depot pipeline quantity} = \text{Average FH} \cdot \text{DRC} / 30 \cdot \text{NRTS} \cdot \text{DR} \cdot \text{Q} \qquad (6)$$

The calculation of the condemnation pipeline quantity within the IWIPS is similar to the calculation of the condemnation quantity within AFLCR 57-27 except for a difference in the calculation of base condemnations. The base condemnation rate within IWIPS is a percentage of all broken parts that are beyond repair at base level. The base condemnation rate within AFLCR 57-27 is the percentage of those broken parts at the base that are beyond repair. Assuming an application percent of one:

$$\text{Condemnation pipeline quantity} = \text{Average FH} \cdot \text{PGM MO} \cdot \text{Q} \cdot (\text{Dcond} \cdot \text{NRTS} + \text{Bcond}) \cdot \text{DR}$$

The PGM MO is "the number of months support that are projected for during the spares buy" (Peterson, 1992:unnumbered). Generally, the PGM MO is 24 months.

The total initial spares requirement is the sum of equations five through seven and a safety stock level (Mueller, 1992:unnumbered). The safety stock level is:

$$\sqrt{3 \cdot \text{basic pipeline quantity}} \tag{8}$$

where

basic pipeline quantity = base pipeline quantity + depot pipeline quantity + condemnation pipeline quantity (Peterson, 1992:unnumbered)

The total initial spares requirement then is the sum of the basic pipeline quantity and the safety stock level.

Appendix B: Computations Summary for the ASM/IDS Computation

Table B-1. Computations Summary for the ASM/IDS Computation

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
2840011465636JF	0.35	3	0.00	1	0.00	258.67	2
2840011465637JF	0.35	3	0.00	1	0.00	226.72	2
2840011465651JF	2.75	7	0.01	3	0.51	3398.18	6
2840011465652JF	0.73	3	0.01	1	0.56	3279.78	2
2840011465656JF	0.51	3	0.00	1	0.12	1169.09	2
2840011465657JF	0.75	4	0.00	1	0.20	1355.48	2
2840011465735JF	1.05	1	0.39	1	0.39	7734.09	3
2840011467481JF	0.46	3	0.00	1	0.10	679.80	2
2840011469387JF	0.82	4	0.00	1	0.28	850.84	3
2840011469390PR	0.00	0	0.00	1	0.00	7630.24	2
2840011469391JF	1.08	5	0.00	1	0.45	296.11	3
2840011470468JF	0.70	4	0.00	1	0.00	704.00	2
2840011470474JF	0.70	4	0.00	1	0.00	214.49	2
2840011474566JF	16.38	28	0.01	16	2.04	230.68	24
2840011610494JF	3.90	10	0.00	4	0.75	607.40	8
2840011712515JF	2.15	8	0.00	2	0.63	256.47	5
2840011712720JF	0.55	2	0.03	1	0.14	504.70	2
2840011735492JF	0.54	2	0.02	1	0.12	9290.87	2
2840011906881PR	0.38	2	0.01	1	0.06	13043.85	2
2840011906882PR	0.04	0	0.04	1	0.00	43745.13	2
2840011906884PR	9.06	18	0.00	9	1.10	1093.26	15
2840011906909PR	0.25	1	0.03	1	0.03	6579.64	2
2840011906910PR	0.25	2	0.00	1	0.03	4966.43	2
2840011909262PR	1.35	5	0.00	1	0.59	2789.37	4
2840011920855PR	86.11	114	0.00	85	3.85	132.87	105
2840011920874PR	1.07	1	0.41	1	0.41	7302.54	3
2840011987361PR	0.87	4	0.00	1	0.28	2275.25	3
2840011987362PR	0.87	4	0.00	1	0.28	1726.19	3
2840011989210JF	2.54	5	0.07	3	0.43	745.91	6
2840011990545PR	1.41	5	0.00	1	0.61	770.96	4
2840011997453PR	3.16	10	0.00	3	0.85	306.74	7
2840012000032PR	0.62	2	0.03	1	0.17	8624.74	2
2840012005337PR	1.41	5	0.00	1	0.61	1514.01	4
2840012005339PR	1.56	5	0.01	2	0.31	1460.15	4
2840012005345PR	1.13	5	0.00	1	0.48	990.29	3
2840012005347PR	9.36	19	0.00	9	1.39	286.16	15
2840012010562PR	2.10	6	0.01	2	0.62	1849.74	5
2840012011633PR	1.66	4	0.04	2	0.35	3681.96	4

Table B-1. Computations Summary for the ASM/IDS Computation (continued)

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
2840012105099PR	2.10	6	0.01	2	0.62	2584.20	5
2840012153604PR	0.45	3	0.00	1	0.06	2434.74	2
2840012153607PR	0.43	2	0.01	1	0.08	2829.28	2
2840012218303JF	2.73	6	0.03	3	0.55	13200.00	6
2840012218304JF	1.56	3	0.10	2	0.29	10300.00	4
2840012269004PR	0.86	3	0.01	1	0.28	3633.51	3
2840012506871XN	0.52	1	0.12	1	0.12	28503.71	2
2840012665905PR	0.66	0	0.68	1	0.19	44105.67	2
2840012823686PR	30.43	44	0.02	30	2.48	3042.00	41
2840013076359PR	3.01	4	0.33	3	0.69	15848.00	6
2840013079562PR	1.26	1	0.53	1	0.53	25100.00	3
2840013079563PR	3.01	4	0.33	3	0.69	71390.37	6
2840013079564PR	19.89	29	0.05	20	1.71	320.00	29
2840013080815PR	2.15	4	0.10	2	0.63	17269.00	5
2840013080841PR	0.62	2	0.03	1	0.16	3565.00	2
2840013085469PR	1.56	4	0.03	2	0.31	3287.00	4
2840013085480PR	1.26	3	0.05	1	0.55	15693.00	4
2840013085481PR	2.86	4	0.27	3	0.60	52243.00	6
2840013085484PR	2.12	4	0.17	2	1.33	47522.00	5
2840013085486PR	8.42	17	0.01	8	1.54	1400.00	14
2840013085487PR	2.34	2	1.03	2	2.30	152776.00	5
2840013085488PR	7.88	16	0.01	8	1.04	325.82	13
2840013085489PR	4.80	12	0.00	5	0.75	237.00	9
2840013085490PR	33.25	49	0.01	33	2.49	304.00	45
2840013085491PR	0.44	2	0.11	1	1.68	31661.14	2
2840013086147PR	3.12	7	0.02	3	0.74	5000.00	7
2840013086169PR	7.04	13	0.02	7	1.06	513.84	12
2840013086170PR	3.52	9	0.00	3	1.00	422.10	7
2840013087037PR	0.43	1	0.08	1	0.08	25940.00	2
2840013087038PR	1.54	3	0.10	2	0.31	24961.00	4
2840013087046PR	0.43	1	0.08	1	0.08	31930.00	2
2840013087605PR	1.55	3	0.10	2	0.31	35000.00	4
2840013088506PR	7.04	14	0.01	7	1.06	293.56	12
2840013088507PR	28.16	40	0.04	28	2.18	248.85	39
2840013091193PR	2.86	0	2.91	3	1.26	245563.00	6
2840013098395PR	3.09	11	0.00	3	1.08	248.85	7
2840013104076PR	2.64	4	0.21	3	0.49	34261.00	6
2840013113804PR	97.18	118	0.06	96	4.11	1007.00	117
2840013113805PR	90.62	117	0.01	90	3.36	199.00	110
2840013113806PR	212.59	240	0.14	210	6.24	1210.00	242
2840013113807PR	2.94	8	0.00	3	0.61	1339.00	6

Table B-1. Computations Summary for the ASM/IDS Computation (continued)

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
2840013114795PR	25.73	39	0.01	25	2.44	1770.51	36
2840013114797PR	28.68	43	0.01	28	2.39	422.34	39
2840013117417PR	16.69	28	0.01	16	2.03	304.00	25
2840013119046PR	1.03	1	0.37	1	0.37	51950.00	3
2840013119976PR	2.15	4	0.10	2	0.63	20160.00	5
2840013123481PR	25.74	35	0.09	25	2.39	777.00	36
2840013126039PR	26.03	38	0.03	26	2.04	2914.00	36
2840013129285PR	439.92	489	0.07	440	8.16	299.00	482
2840013129286PR	505.44	549	0.23	505	8.99	609.00	550
2840013187654PR	4.29	10	0.01	4	0.95	1244.62	8
2840013193709PR	3.93	4	0.98	4	1.99	139701.25	8
2840013206433PR	3.09	2	1.35	3	1.45	174636.34	7
2840013206832PR	0.77	2	0.05	1	0.21	25735.00	3
2840013206833PR	0.76	2	0.06	1	0.26	37251.00	3
2840013225347PR	1.54	3	0.10	2	0.30	11017.35	4
2840013225348PR	79.47	87	1.22	79	4.26	4461.50	97
2840013225354PR	4.42	9	0.02	4	1.00	475.43	9
2840013225357PR	2.00	3	0.21	2	0.53	41454.32	5
2840013226203PR	1.56	3	0.10	2	0.31	14090.65	4
2840013226271PR	0.18	1	0.01	1	0.01	58303.94	2
2840013226274PR	28.16	39	0.06	28	2.18	267.00	39
2840013226275PR	28.16	40	0.04	28	2.18	259.00	39
2840013226276PR	24.64	35	0.05	24	2.30	255.00	35
2840013234299PR	390.92	437	0.08	386	10.89	299.00	430
2840013372542PR	0.82	1	0.26	1	0.26	111039.60	3
2840013392176PR	2.30	8	0.00	2	0.68	175.34	5
2840013392177PR	4.74	13	0.00	5	0.84	179.65	9
2840013392178PR	1.58	7	0.00	2	0.35	180.37	4
2840013392179PR	1.58	7	0.00	2	0.35	183.24	4
2840013396139PR	1.66	0	1.67	2	0.36	237163.75	4
2840013432465PR	1.68	1	0.88	2	0.37	139071.25	4
2840013470818PR	3.74	6	0.15	4	0.67	13784.52	8
2840013470819PR	3.74	6	0.14	4	0.62	13806.08	8
2840013470837PR	1.63	2	0.35	2	0.35	101744.13	4
2840013472190PR	17.89	19	1.20	18	1.62	10913.18	26
2840013472191PR	1.66	2	0.77	2	1.41	168478.69	4
2840013472207PR	1.68	2	0.58	2	0.65	136861.30	4
2840013472228PR	3.09	0	3.14	3	1.25	327372.75	7
2840013476527PR	0.91	1	0.31	1	0.60	96129.29	3
2840013476595PR	1.56	5	0.01	2	0.31	4102.85	4
2840013499023PR	5.71	10	0.06	6	0.82	13282.70	10

Table B-1. Computations Summary for the ASM/IDS Computation (continued)

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
2840013511591PR	2.70	6	0.03	3	0.52	6661.09	6
2840013513397PR	3.03	3	0.70	3	0.70	79354.09	7
2840013513398PR	2.61	3	1.01	3	1.49	150467.66	6
2840013574300PR	0.83	0	1.08	1	1.50	264527.94	3
2840013607971PR	1.52	4	0.02	1	0.72	13864.00	4
2915011909267PR	4.18	11	0.00	4	0.85	329.95	8
2915011920847PR	3.72	8	0.02	4	0.63	4186.01	8
2915012665925PR	12.00	23	0.00	12	1.26	194.62	19
2915013102142PR	12.64	22	0.01	12	1.60	737.00	20
2915013102881PR	9.60	15	0.07	9	1.53	14389.00	16
2915013102883PR	7.41	15	0.01	7	1.28	591.00	13
2915013102884PR	0.62	4	0.00	1	0.16	589.00	2
2915013102888PR	10.68	17	0.05	10	1.65	9781.00	17
2915013102891PR	3.72	6	0.14	4	0.63	43431.00	8
2915013105595PR	7.80	16	0.00	8	1.01	591.00	13
2915013432931PR	4.68	9	0.04	5	0.71	10554.51	9
2915013470854PR	3.43	9	0.00	3	0.94	1459.03	7
2915013548333PR	3.72	7	0.06	4	0.63	15622.85	8
2915013576591PR	4.05	4	0.80	4	0.80	126107.09	8
2915013581344PR	0.68	3	0.01	1	0.19	2317.00	2
2925011909213PR	3.42	7	0.04	3	0.94	7293.01	7
2925013086220PR	1.72	5	0.01	2	0.38	2765.00	4
2925013093075PR	0.86	4	0.00	1	0.28	1571.00	3
2935013195010	3.86	8	0.03	4	0.69	8345.90	8
2995013072945PR	3.86	10	0.00	4	0.69	1532.00	8
2995013130342PR	3.86	7	0.07	4	0.69	17802.56	8
2995013386479PR	3.86	9	0.01	4	0.69	3799.45	8
2995013568687PR	5.00	5	1.13	5	4.45	136535.89	9
3010013079073PR	2.22	5	0.04	2	0.67	13132.88	5
3010013079079PR	13.07	21	0.03	13	1.49	5632.00	20
3040011997382PR	1.54	5	0.00	2	0.26	4471.25	4
3110	2.96	8	0.01	3	0.68	2875.36	6
3110011469312JF	7.64	17	0.00	8	0.95	540.31	13
3110011470338PR	8.78	20	0.00	9	1.04	201.62	15
3110011474486PR	8.19	16	0.01	8	1.22	1692.88	14
3110011474488PR	6.86	15	0.00	7	0.97	902.28	12
3110011474490JF	1.35	5	0.00	1	0.65	2875.36	4
3110011474491PR	8.10	16	0.01	8	1.43	1942.38	14
3110013100711PR	7.30	15	0.01	7	1.18	1954.[illegible]	13
4320013088876PR	6.35	11	0.05	6	1.16	8104.[illegible]	[illegible]
4320013306395PR	6.35	10	0.11	6	1.16	[illegible]	[illegible]

Table B-1. Computations Summary for the ASM/IDS Computation (continued)

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
4710013093158PR	1.56	6	0.00	2	0.31	319.00	4
5930012154689PR	1.56	6	0.00	2	0.29	627.16	4
5998013487546PR	6.28	11	0.05	6	1.12	5561.27	11
5998013490589PR	6.28	11	0.05	6	1.12	5561.27	11
5998013496077PR	6.28	11	0.05	6	1.12	5561.27	11
5998013496078PR	6.28	11	0.05	6	1.12	5561.27	11
5998013497545PR	6.28	11	0.05	6	1.12	5561.27	11
5998013537280PR	6.28	11	0.05	6	1.12	5561.27	11
5998013540550PR	6.28	11	0.05	6	1.12	5561.27	11
5998013540551PR	6.28	11	0.05	6	1.12	5561.27	11
5998013568819PR	6.28	11	0.05	6	1.12	7028.78	11
6130013542835PR	6.28	12	0.02	6	1.12	2000.00	11
6685011388075JF	1.36	5	0.00	1	0.59	3150.00	4
6685013080858PR	2.34	5	0.05	2	0.76	9419.00	5
6685013105587PR	5.85	12	0.01	6	0.88	3091.00	11
6695013633031PR	2.17	6	0.01	2	0.65	4242.00	5

Appendix C: Computations Summary for the ASM/IWIPS Computation

Table C-1. Computations Summary for the ASM/IWIPS Computation

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
2840000110704RX	0.78	2	0.05	1	0.24	3590.67	3
2840001053844RX	1.56	4	0.03	2	0.31	1677.70	4
2840001067641RX	1.15	2	0.15	1	0.47	6087.43	3
2840001106672RX	0.78	2	0.05	1	0.24	4926.87	3
2840001601685RX	0.78	2	0.05	1	0.24	4868.30	3
2840004934441RX	0.78	0	0.78	1	0.24	62469.99	3
2840005628039RX	0.66	1	0.18	1	0.18	23896.16	2
2840007803486RX	1.89	2	0.48	2	0.48	16443.40	5
2840007951507RX	2.88	15	0.00	3	0.60	0.01	6
2840007951513RX	0.78	2	0.05	1	0.24	5069.98	3
2840008323313RX	0.39	1	0.07	0	0.39	15639.09	2
2840008635157RX	1.32	2	0.21	1	0.59	9755.24	4
2840008691830RX	1.32	2	0.21	1	0.59	10949.59	4
2840009084520RX	0.78	2	0.05	1	0.24	7707.93	3
2840009119484RX	1.32	1	0.59	1	0.59	33142.12	4
2840009315747RX	1.56	4	0.03	2	0.31	1733.08	4
2840009874040	345.60	409	0.00	346	7.07	21.38	383
2840010043187RX	0.78	2	0.05	1	0.24	4424.88	3
2840010048911RX	0.78	2	0.05	1	0.24	2969.46	3
2840010053050RX	1.32	1	0.59	1	0.59	37331.42	4
2840010074233RX	1.32	1	0.59	1	0.59	20448.80	4
2840010352030RX	0.78	1	0.24	1	0.24	9961.88	3
2840010389105RX	1.32	3	0.06	1	0.59	6278.08	4
2840010404257RX	0.78	2	0.05	1	0.24	6133.09	3
2840010770702RX	1.32	3	0.06	1	0.59	4467.86	4
2840010770702SX	1.32	3	0.06	1	0.59	4467.86	4
2840011150305RX	2.30	5	0.04	2	0.73	2316.65	5
2840011151441RX	2.30	5	0.04	2	0.73	1997.03	5
2840011183603RX	1.32	2	0.21	1	0.59	14436.33	4
2840011327297RX	1.32	0	1.32	1	0.59	134792.00	4
2840011327297SX	1.20	0	1.20	1	0.50	134792.00	3
2840011385659RX	5.64	7	0.44	6	0.77	14436.33	10
2840012311048RX	3.85	5	0.36	4	0.70	14578.22	8
2840FX	0.48	7	0.00	0	0.48	0.01	2
2840OX	0.48	7	0.00	0	0.48	0.01	2
2840SX	0.48	7	0.00	0	0.48	0.01	2
2840TX	0.48	7	0.00	0	0.48	0.01	2
2840VX	172.80	238	0.00	173	5.07	0.01	[illegible]

Table C-1. Computations Summary for the ASM/IWIPS Computation (continued)

		RBS Computation		FMS Computation			Stock
NSN	Pipeline	Reqmt	EBOs	Reqmt	EBOs	Cost	Cap
2915001065464RX	46.18	62	0.03	46	2.79	603.15	60
2915001436107RX	0.94	3	0.02	1	0.33	2440.65	3
2915001436107S	0.38	2	0.01	0	0.38	2263.39	2
2915001679145RX	1.32	3	0.06	1	0.59	2714.02	4
2915004834282RX	1.32	3	0.06	1	0.59	3571.15	4
2915007821759RX	9.22	18	0.01	9	1.31	200.91	15
2915008710942RX	58.80	81	0.01	59	2.94	146.09	74
2915008960173RX	1.89	5	0.02	2	0.48	1654.02	5
2915009092305RX	0.94	3	0.02	1	0.33	1390.20	3
2915009099119RX	30.21	45	0.01	30	2.29	232.99	41
2915010139243RX	1.54	0	1.53	2	0.30	53595.56	4
2915010996143RX	0.77	1	0.23	1	0.23	25850.85	3
2915011114882RX	1.54	1	0.75	2	0.30	38156.71	4
2925009970633RX	1.89	3	0.18	2	0.48	10175.98	5
2935008573659RX	1.32	3	0.06	1	0.59	4623.86	4
2995004750698RX	1.32	2	0.21	1	0.59	17127.85	4
2995009114336RX	1.32	3	0.06	1	0.59	6101.75	4
2995009114336SX	1.32	3	0.06	1	0.59	6101.75	4
2995010074738RX	3.96	6	0.19	4	0.76	5894.43	8
2995011382303RX	0.48	1	0.10	0	0.48	17127.85	2
3110001807307RX	7.20	13	0.03	7	1.15	1126.07	13
3110004004409RX	1.32	5	0.00	1	0.59	478.54	4
3110004360215RX	1.22	4	0.01	1	0.52	524.78	3
3110006181388RX	1.15	5	0.00	1	0.47	185.87	3
3110006181388SX	6.91	15	0.00	7	0.99	185.87	12
3110006185880RX	2.30	7	0.00	2	0.73	307.77	5
3110008254869RX	1.32	5	0.00	1	0.59	149.94	4
3110008256048RX	1.32	5	0.00	1	0.59	204.32	4
3110008256048SX	1.32	5	0.00	1	0.59	220.27	4
3110008265078RX	1.32	5	0.00	1	0.59	191.47	4
3110008265078SX	1.32	5	0.00	1	0.59	212.60	4
3110008265079RX	1.32	5	0.00	1	0.59	243.34	4
3110008349616RX	1.32	5	0.00	1	0.59	165.70	4
3110008475136RX	1.32	5	0.00	1	0.59	337.54	4
3110008938233RX	1.32	5	0.00	1	0.59	373.14	4
3110009282285RX	1.56	6	0.00	2	0.30	268.53	4
3110009898932RX	1.32	5	0.00	1	0.59	243.34	4
3110009898932SX	1.32	5	0.00	1	0.59	243.34	4
4320007371397RX	1.89	4	0.06	2	0.48	3607.23	5
4320009170844RX	1.89	3	0.18	2	0.48	7334.61	5
4320009170844SX	0.77	2	0.05	1	0.23	7334.61	3

Table C-1. Computations Summary for the ASM/IWIPS Computation (continued)

NSN	Pipeline	RBS Computation Reqmt	RBS Computation EBOs	FMS Computation Reqmt	FMS Computation EBOs	Cost	Stock Cap
4320010423944RX	1.32	3	0.06	1	0.59	5068.26	4
4320010423944S	1.32	3	0.06	1	0.59	5068.26	4
4810008668132RX	2.30	4	0.13	2	0.73	5318.32	5
4820001689832RX	3.78	7	0.06	4	0.66	2084.90	8
4820007100849RX	1.56	5	0.01	2	0.31	720.43	4
4820007100978RX	1.56	5	0.01	2	0.31	757.10	4
5310008057553RX	62.21	77	0.11	62	3.22	1534.67	78
6620007852251	1.32	3	0.06	1	0.59	3315.09	4

Bibliography

Crawford, Gordon B. Palm's Theorem for Nonstationary Processes. Report R-2750-RC. Santa Monica, CA: The RAND Corporation, October 1981.

Defense Institute of Security Assistance Management (DISAM). The Management of Security Assistance (Twelfth Edition). Library of Congress Catalog Card No. 92-081208. Wright-Patterson AFB, Ohio, May 1992

Department of Defense. DoD Materiel Management Regulation. DoD 4140.1-R. Washington: Office of the Assistant Secretary of Defense, 25 January 1993.

Department of the Air Force. Recoverable Consumption Item Requirements System (D041). AFLCR Manual 57-4. Wright-Patterson AFB, Ohio: HQ AFLC, 1 August 1991.

Department of the Air Force. Initial Requirements Determination. AFLCR 57-27. Wright-Patterson AFB, Ohio: HQ AFLC, 15 May 1991.

Department of the Air Force. International Weapon Item Projection System (IWIPS) D219 Users Manual. AFLCM 400-62. Wright-Patterson AFB, Ohio: HQ AFLC, 31 October 1983.

Dynamics Research Corporation. MAJCOM DMAS End Users Manual. Report E-957U. Andover, Massachusetts, 1993.

Dynamics Research Corporation. REALM WRSK/BLSS Requirement Computation, Functional Description, Version 1.9. Report E-21768U. Andover, Massachusetts, 1992.

Feeney, George J. and Craig C. Sherbrooke. The (s-1,s) Inventory Policy Under Compound Poisson Demand: A Theory of Recoverable Item Stockage. Report RM-4176-1-PR. Santa Monica, CA: The RAND Corporation, March 1966.

Feller, William. An Introduction to Probability Theory and Its Applications. New York: John Wiley & Sons, Inc., 1968.

Forshaw, David A. and others. "Selected Air Force Terms and Acronyms." Report to the Directorate of Management Sciences. HQ AFLC, Wright-Patteson AFB, Ohio, August 1986.

Hadley, G. and T.M. Whitin. Analysis of Inventory Systems. Englewood Cliffs, NJ: Prentice-Hall, Inc., 1963.

Hillestad, R.J. Dyna-METRIC: Dynamic Multi-Echelon Technique for Recoverable Item Control. Contract F49620-82-C-0018. Report R-2785-AF. Santa Monica, CA: The RAND Corporation, July 1982.

Isaacson, Karen E. and others. Dyna-METRIC Version 4: Modeling Worldwide Logistics Support of Aircraft Components. Contract F49620-86-C-0008. Report R-3389-AF. Santa Monica, CA: The RAND Corporation, May 1988.

Kapur, K.C. and L.R. Lamberson. Reliability in Engineering Design. New York: John Wiley & Sons, Inc., 1977.

King, Randall M. Assessing Aircraft Spares Support in a Dynamic Environment. Contract No. MDA903-84-C-0139. Bethesda, MD: Logistics Management Institute, July 1985.

Muckstadt, John A. "A Model for a Multi-Item, Multi-Echelon, Multi-Indenture Inventory System." Management Science,20: 472-481 (December 1973).

Mueller, David. "IDS (International Data System): The F-16 FMS Spares Recommendation and Requisition System." OO-ALC/LAIM, Hill AFB, UT, May 1992.

Nahmias, Steven. "Managing Reparable Item Inventory Systems: A Review," TIMS Studies in the Management Sciences, 16: 253-277 (1981).

Niklas, Michael, Operations Research Analyst. Personal Interview. HQ AFMC, Wright-Patterson AFB, Ohio, 7 April 1994.

Niklas, Michael, Operations Research Analyst. Class Lecture in LOG 290, Combat Capability Assessment. School of Systems and Logistics, Air Force Institute of Technology, Wright-Patterson AFB, Ohio, 1992.

Niklas, Michael. "Readiness Based Initial Requirements Determination (RBIRD): System Specification." Report to HQ AFMC/XRI. HQ AFMC/XPS, Wright-Patterson AFB, Ohio, October 1992.

Niklas, Michael, Operations Research Analyst. Lecture on Dyna-METRIC. Directorate of Management Sciences, Wright-Patterson AFB, Ohio, 1991.

Niklas, Michael, Operations Research Analyst. Personal Interview. HQ AFLC, Wright-Patterson AFB, Ohio, 24 October 1991.

Noonan, Diane, Peace Vector III Case Manager. Telephone Interview. AFSAC/ECMM (Egyptian Acquisition Branch), Wright-Patterson AFB, Ohio, 21 January 1993.

O'Malley, T.J. The Aircraft Availability Model: Conceptual Framework and Mathematics. Contract No. MDA903-81-C-0166. Bethesda, MD: Logistics Management Institute, June 1983.

Peterson, Major David. "FMS Reparable Sparing Methods." Presented to Major General Habedank. International Logistics Center, Wright-Patterson AFB, Ohio, September 1992.

Peterson, Major David. Class handout distributed in LOGM 628, Inventory Management. School of Systems and Logistics, Air Force Institute of Technology (AU), Wright-Patterson AFB OH, March 1989.

Rexroad, Frederick H., Operations Research Analyst. Personal Interview. HQ AFMC, Wright-Patterson AFB, Ohio, 14 February 1994.

Rexroad, Frederick H., Operations Research Analyst. Lecture on the Aircraft Availability Model. Directorate of Management Sciences, Wright-Patterson AFB, Ohio, 1992.

Rexroad, Frederick H. "Aircraft Availability Research Model (AARM) Analyst's Manual." Report to HQ AFMC/XPS. Wright-Patterson AFB, Ohio, July 1992.

Sargent, Robert G. "A Tutorial on Validation and Verification of Simulation Models." Proceedings of the 1988 Winter Simulation Conference. 33-39. New York: edited by M. Abrams, P. Haigh, and J. Comfort, 1988.

Sherbrooke, Craig C. Optimal Inventory Modeling of Systems: Multi-Echelon Techniques. New York: John Wiley & Sons, Inc., 1992.

Sherbrooke, Craig C. "Vari-METRIC: Improved Approximations For Multi-Indenture, Multi-Echelon Availability Models," Operations Research, 34: 311-319 (March-April 1986).

Sherbrooke, Craig C. "METRIC: A Multi-Echelon Technique For Recoverable Item Control." Operations Research, 16: 122-141 (1968).

Sherbrooke, Craig C. Discrete Compound Poisson Processes and Tables of the Geometric Poisson Distribution. Report RM-4831-PR. Santa Monica, CA: The RAND Corporation, July 1966.

Slay, F. Michael and Randall M. King. Prototype Aircraft Sustainability Model. Contract MDA903-85-C-0139. Bethesda, MD: Logistics Management Institute, March 1987.

Slay, F. Michael, Operations Research Analyst. Telephone interview. Logistics Management Institute, Bethesda, MD, 15 March 1994.

Slay, F. Michael, Operations Research Analyst. Telephone interview. Logistics Management Institute, Bethesda, MD, 16 February 1994.

Slay, F. Michael, Operations Research Analyst. Telephone interview. Logistics Management Institute, Bethesda, MD, 28 September 1993.

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13 ABSTRACT (Maximum 200 words) Current Foreign Military Sales (FMS) models provide stock levels that result in a very low system availability or a funding requirement that exeeds the overall budget. The purpose of this research was to determine if an inventory model exists that can be used in FMS reparable sparing to provide a more efficient and economical inventory purchase. The Aircraft Sustainability Model (ASM) is such a model, providing the most aircraft availability possible from a given inventory investment by computing the optimal number of spare parts to buy for each item. FMS data was obtained from two sources - the International Data System (IDS) and the International Weapon Item Projection System (IWIPS). Both systems are currently used in FMS reparable sparing to provide stock level requirements to customer countries. The data obtained from these FMS systems included part data, program data, and actual recommended stock level quantities calculated by the respective FMS systems. The ASM when compared to the current FMS models computed reasonable stock levels and provided better aircraft availability for a given level of expenditure. The comparison verified that the ASM is preferable to current FMS reparable sparing techniques in the computation of stock level requirements.

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