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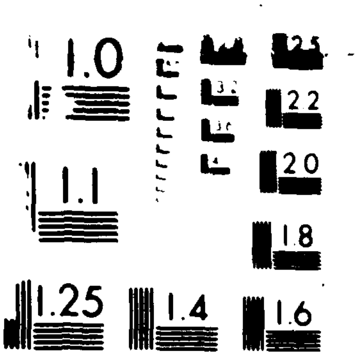
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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

REPAIRABLE ITEM INVENTORY MANAGEMENT FOR THE KOREAN AIR FORCE

by

Young Hong, Yoo

and

Il Suk, Kim

December 1986

Thesis Advisor F.R. Richards

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The Korean Air Force has determined that repairables management is one of the areas to which attention could be expected to lead to substantial improvement in the efficient management of defense resources and in maintaining adequate level of force effectiveness. This thesis reviews various inventory models for the management of repairable items. It discusses the characteristics of each model, and, identifies and explains the differences in each model with respect to assumptions, objectives, constraints, and optimization methods. Each model was compared to the existing system for managing repairables for the Korean Air Force to determine the most appropriate models.

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Repairable Item Inventory Management for The Korean Air Force

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ABSTRACT

The Korean Air Force has determined that repairables management is one of the areas to which attention could be expected to lead to substantial improvement in the efficient management of defense resources and in maintaining adequate level of force effectiveness. This thesis reviews various inventory models for the management of repairable items. It discusses the characteristics of each model, and, identifies and explains the differences in each model with respect to assumptions, objectives, constraints, and optimization methods. Each model was compared to the existing system for managing repairables for the Korean Air Force to determine the most appropriate models.

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I. INTRODUCTION

A. MOTIVATION

To ensure the desired high level of operational readiness, the Korean Air Force supply system must store sufficient stocks of replacement components and repair parts to support the maintenance of existing weapon systems and equipment. In the absence of a practical repairable inventory model, the Korean Air Force supply system tends to maintain relatively large stocks of repairable components and parts. This is done to avoid the risk of shortages which will eventually hurt operational readiness.

The repairable inventory system differs from that of the consumable inventory system in two ways. First, the repairable system contains two distinct inventories, one of which has items that are in a ready-for-issue (RFI) state and another which has items that are in a non-ready-for-issue (NRFI) state. The first inventory contains items which are usable and the second contains items that must be repaired before they can be used. Second, the RFI inventory is made up of a mixture of new items and items that have been used, failed, repaired, and are ready to be used again. This is one reason why the repairable inventory management is a complicated process.

Historically, most inventory models have been developed for the private sector where the profit motive is important. Hence, most such models attempt to minimize average total annual costs associated with the inventory. The three relevant costs in most inventory models are order placement costs, inventory holding costs, and stockout costs. The order placement cost originates from the expense of issuing a purchase order to an outsider supplier. The inventory holding cost includes capital cost, taxes, insurance, handling, shrinkage, obsolescence, and deterioration. The stockout cost originates from profit loss and good will erosion, or costs resulting from the delays that result.

However, inventory models derived using these cost parameters have less relevance to military inventories. In military supply systems, for example, it is very difficult to estimate the costs associated with stockouts. In the Air Force the cost of a stockout may be the inability of a fighter aircraft to be launched to accomplish a mission. Also, for most military organizations, cost is not the most important objective. Instead, such organizations are usually interested in having their forces ready to respond to the threat. The relevant objective is the maximization of force readiness with given resources.

B. THE SCOPE OF STUDY

The objective of this thesis will be the development of an inventory model for the management of repairable items at the wholesale level by the Korean Air Force. This will be accomplished by the review and comparative analysis of various models which have been developed and applied to the management of repairables items within the military services.

C. DEFINITION OF TERMS

1. Repairables

It has generally assumed that items are completely consumable. That is, once having satisfied demand, they leave the system forever. However, some items can be repaired faster and less expensively than they can be procured. These items are generally the high value items such as pumps, motors, circuit boards, engines, power suppliers and test equipment. These items are referred to as repairables.

2. Major System

This refers to an independent item which is at the highest level of the parts breakdown structure. Thus, this is the final assembly of all the modules and end items. Examples are aircrafts, ships, tanks, etc.

3. End Item

End item refers to the subsystem of a major system. In a weapon system like a fighter aircraft, there are various end items such as the engine, radar, avionics, etc. These end items are composed of several components which are also repairable.

4. Module

A module is the subcomponent of a major end item. The circuit boards of an avionics system would be an example.

D. OUTLINE

In Chapter II, we review the current Korean Air Force repairables management process. This review includes the description of the organizations involved, the general scheme of the system and mathematical approach to the problem.

In Chapter III, the various inventory models for repairables are introduced to reveal the mathematical approach to solving inventory problems.

In Chapter IV, an in-depth analysis and comparison of the major components of the inventory models, such as the demand process assumption, and the measure of effectiveness, is provided based on the findings from Chapters II and III. Finally, in Chapter V, the authors select that model which seems best for the Korean Air Force system. A brief summary of the selected model and its shortcomings will be given. Thus, these will be the recommended topics for future study.

II. OVERVIEW OF KOREAN AIR FORCE REPAIRABLES MANAGEMENT

A. INTRODUCTION

With military aid from the U.S.A., the Korean Air Force had no need for any kind of spare parts management models until the late 1960's. The inventory management initiatives by the Korean Air Force began in the beginning of the 1970's with the introduction of a model used by the U.S. Air Force in the early days of economic inventory models. The model adopted in the 1970's has never been reviewed or analyzed systematically since its adoption by the Korean Air Force. The performance of the model has declined as the weapon systems used in the Korean Air Force have become more complex and expensive than ever, and the overall size of the Korean Air Force has become larger. Thus, the study of new inventory management techniques is an imminent need for the Korean Air Force.

Noticing the fact that the annual budget for repairables takes 70% of the total annual stock fund budget of the Korean Air Force, the importance of repairables management cannot be overemphasized.

In this chapter, the repairables management system of the Korean Air Force will be briefly reviewed. The organizations, system parameters and mathematical models related to repairables management will be introduced and reviewed. This chapter will provide the basis for the analysis and suggested improvements to the Korean Air Force repairables inventory management system which will be described in Chapter IV.

B. THE LOGISTICS ORGANIZATIONS OF THE KOREAN AIR FORCE

The major logistics organizations are A-5 (logistics), Headquarters of the Korean Air Force, the Korean Air Force Logistics Command and its subordinate directorates, depots, and the supply maintenance squadrons at each airbase. Since the scope of this study does not deal with the overall Korean Air Force logistics policies, only the organizations within the Korean Air Force Logistics Command which have a direct effect upon repairables management will be introduced.

1. The Korean Air Force Logistics Command

The Korean Air Force Logistics Command is the intermediate echelon command which actually manages and allocates logistics resources among the tactical units of the Korean Air Force under the policies and directives of the Headquarters. This command is comprised of the Directorate of the Materials Management (DMM), the Depot of Maintenance and Ammunition (DMA), the Depot of Maintenance and Electronics and Communications (DMEC), the Depot of Maintenance and Equipment (DME) and the Depot of Supply and Transportation (DST). The specific functions and responsibilities of the directorate and each depot are described below.

2. DMM (Directorate of Materials Management)

The DMM is the focal point of material management for the Korean Air Force. Under the policies of the AFLC, it procures all materials according to its estimates of requirements, distributes the material to all of the tactical units and the supporting units within the Korean Air Force. Thus, the DMM is the equivalent of a wholesale level Inventory Control Point (ICP).

Currently, DMM manages approximately 180,000 items. These items are allocated among the hundreds of item managers at the DMM. The computer system which stores the integrated programs on demand forecasting, historical data on supply system performance, etc. is accessible to the item managers. Item managers place orders for procurement, repair, and issue stocks upon orders from each base. Finally, they update the system program files according to these transactions.

3. DST (Depot of Storage and Transportation)

This is the centralized warehouse for the Korean Air Force[1] where all procured and repaired materials including consumables, are stored. Even though the DMM manages all materials transactions and files historical data, the DST is the sole location where the materials are physically stored. The DMM exercises administrative control of materials management. Also, the DST disposes of the worn-out repairables from the DME.

4. DME (Depot of Maintenance and Equipment)

This is the unique in-house depot level maintenance organization for the Korean Air Force. It performs the maintenance of repairables which cannot be repaired at the base maintenance squadron. These items would be the major end items of an aircraft such as the engine, fuselage and the major supporting equipment for the operation of the aircraft, such as the automatic power unit (APU). However, the main function of the DME is the overhaul of the aircraft on a scheduled basis (preventive maintenance).

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[1] This is equivalent to the US Navy's NISTARS.

5. DMEC (Depot of Maintenance and Electronics and Communications) and DMA (Depot of Maintenance and Ammunition)

The maintenance of aircraft avionics is done at the DMEC and the DMA performs the maintenance of the repairables which is related to the armament of the aircraft.

C. THE REPAIRABLES MANAGEMENT SYSTEM

1. The General System

The current Korean Air Force repairable cycle is shown in Figure 2.1. For convenience, only the major components of the system are shown. As mentioned earlier, the DMM, DME and DST are directly involved in this process.

The Korean Air Force operates two kinds of maintenance operations for repairables: the base maintenance squadrons and the DME. The DME performs depot level maintenance and the base maintenance squadron performs base level maintenance. It should be noticed that all depot level repairables are not repaired at the Korean Air Force facilities. Because of the complexity, some repairs are done by commercial contractors in the United States through the United States Air Force Logistics Command (USAFLC) under Foreign Military Sales (FMS) agreements.

Thus, in Figure 2.1, three kinds of repairables flow are depicted. The first is the flow of carcasses to depot level maintenance. The second is the flow of carcasses to base level maintenance. The third is the flow of attrited carcasses from depot level maintenance. Note that the third flow implies the procurement of the new items from the USAFLC. The Korean Air Force procures all new items from the USAFLC.[2]

As depicted in Figure 2.1, when an aircraft experiences the failure of a subsystem, it is inspected to determine the cause of the failure. After isolation of the failure to a component or a major end item, that item is further inspected to determine if base level repair is possible. In case of the failure of a major end item, an RFI (Ready for Issue) item from the base supply is used to replace the failed item and the aircraft returns to operational status. Then, the failed unit is turned over to the base maintenance squadron to be repaired, if it can be repaired at the base level maintenance. After such a repair, it is sent to the base supply squadron as an RFI unit. [Ref. 1: p. 27]

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[2] The activities that coordinate with USAFLC for repair and procurement follow FMS procedures.

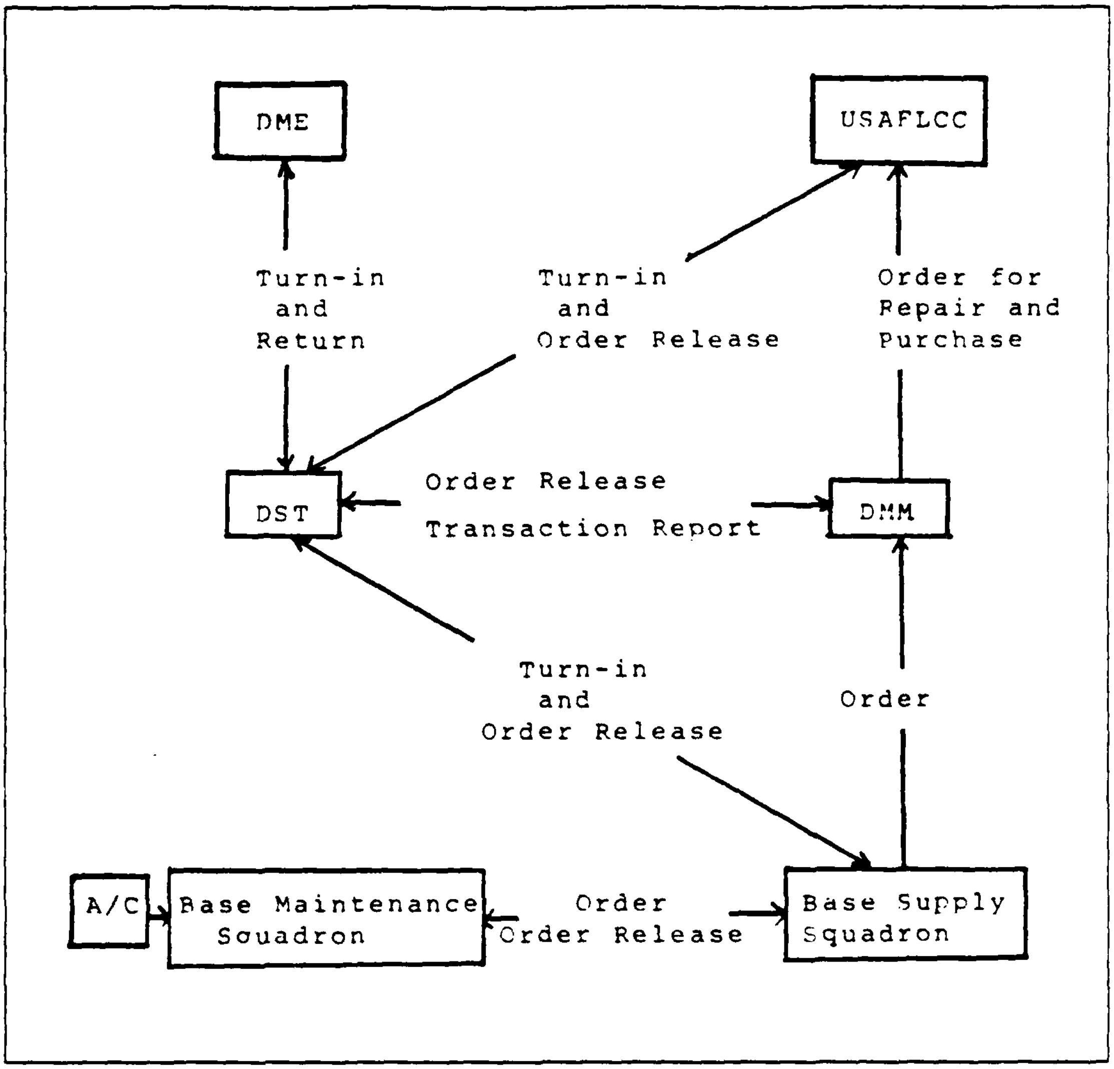

Figure 2.1 The Korean Air Force Repairables Cycle.

Actually, in the Korean Air Force, the determination of the maintenance level for major end items is controlled by a code associated with each item. Thus, the level of maintenance for each item is predetermined.

When base level repair is impossible, a serviceable unit is issued from the serviceable unit stock of the base supply squadron. The failed item is also turned in to the base supply squadron. Then, the base supply squadron sends the failed unit to the DST and places a procurement order for another serviceable unit to the DMM. All these transactions are reported and managed centrally by the DMM. Upon approval from the DMM, the DST issues a serviceable unit to the base.

The failed units from each base are stored in the DST facility waiting to be repaired. These carcasses are turned over to the DME in batches under the approval of the DMM. The batched repair is due to restricted capability of the DME and of the other depot level maintenance organizations.

2. The Operation of Base Supply and Maintenance

a. Base Supply Squadron

The base supply squadron acquires materials needed for base maintenance operations from the DMM. Using historical demand data, it maintains a level of stocks to satisfy the demands.

First, it categorizes all items by whether or not the demand is a recurring demand. A recurring demand is one in which demands have been placed more than once during the previous year. Otherwise items are categorized as non-recurring demand items. Base stockage items are confined to the recurring demand category.

The measure of effectiveness of the base supply squadron is the fill rate. This is the ratio of the number of demands satisfied immediately from the base stocks to the total number of demands placed upon the base supply squadron.

b. Base Maintenance Squadron

The base maintenance squadron performs base level preventive maintenance and base level corrective maintenance. Of note is the "benchstock" concept. This refers to the stockage of the spare parts needed for the repair of the repairables at the maintenance squadron. In the case of items with high demand, it would be convenient for the base maintenance squadron personnel to have direct access to the items needed instead of having to place orders whenever a part is needed. For items stocked at the base maintenance squadron, a stock level which is equivalent to three months demand is stored in the maintenance shop.

3. The Operation of Depot Level Maintenance

As mentioned earlier in this chapter, there are several depot maintenance organizations in the Korean Air Force. However, their concept of operation and relations to the DMM are identical to those of the DME. Thus, only the operation of the DME will be covered here.

The maintenance organizations of the Korean Air Force are restricted in terms of the capacity to process all incoming repairs and in terms of the level of technology to deal with the repair of complex systems. Thus, the MRS (Material Repair Schedule) and MRRL (Material Repair Return List) are established to manage these restrictions.

a. MRS (Material Repair Schedule)

The MRS is the repair schedule for the DME. In September of the fiscal year x - 1, item managers forecast the demand for each repairable for the next fiscal year and the total repair quantity. The integrated results for each item are provided to the DME. Usually, this results in forecasted maintenance requirements which exceed the capacity of the DME. Thus, the DME finally sets up the repair schedule (MRS) through coordination with the DMM. The maintenance requirements which are not considered in the MRS are turned over to the MRRL.

The repair quantity is set up on a quarterly basis. For the repair of the first quarter, the DMM places orders for the necessary spare parts in advance so that the repair process can proceed without interruption. Also, carcasses are issued from the DST according to the MRS. The MRS is updated as the repair operations take place during the year by monitoring the actual inductions.

b. MRRL (Material Repair Return List)

This is the list of repairables for which the Korean Air Force does not have depot level maintenance capability. These items are coded as a MRRL item. Sometimes, however, the non-MRRL items are repaired by MRRL procedures when the MRS is saturated.

In the case of an MRRL repair, the DST sends the carcass to the continental USAF facility. Upon the receipt of the carcass from the Korean Air Force, the USAF sends a serviceable unit to the DST. Serviceable units from both the DME and the USAF are integrated at the DST to make up the serviceable stocks which are available for the users.

c. The Measure of Effectiveness

Currently, the DMM uses two measures of effectiveness. The first one is fill rate. Fill rate is also used by each base as a measure of effectiveness. The second measure is supply response time. It measures the length of time elapsed for base backorders to be satisfied by the stock from the DST. That is, it is the length of time from the placement of orders to the receipt of the ordered item. But, notice that the DMM uses this more as a priority rule for issuing the stock than as a general measure of effectiveness for management of the repairable items. Currently, the Korean Air Force assumes that any backorders for spares result in Not Operationally Ready because of Supply (NORS). Thus, they developed codes which indicate the NORS condition. Each code provides the maximum supply response time requirement to fill backorders. When multiple demands for an item occur, the DMM would fill a demand with a shorter supply response time requirement. Table 1 summarizes the supply response time requirements for each demand with varying priority. Table 2 describes the meaning of each NORS code. [Ref. 1: p. 246]

TABLE 1

SUPPLY RESPONSE TIME REQUIREMENTS

Priority	Type of Order	Supply Response Time	Circumstances
03	Express	3 Days	G, A NORS
06	Semi-Express	14 Days	A, F NORS
13	Routine	30 Days	Routine Requisition

TABLE 2

DESCRIPTIONS OF NORS

NORS	Descriptions
G	Aircraft is totally not operational
K	Radar is malfunctioning
F	Aircraft is operational, but incapable of flying mission
A	NORS is anticipated associated with aircraft

D. DEFINITION OF SYSTEM PARAMETERS AND VARIABLES

Certain parameters and variables are officially defined and adopted within the Korean Air Force Logistics Command.

1. DDR (Daily Demand Rate)

This refers to the average number of demands per day and it is computed in the following manner.

$$\text{DDR} = \frac{\text{the sum of the recurring demands experienced per year}}{365}$$

2. DRP (Depot Repair Percentage)

From the past three years of historical data, it is computed in the following manner for each item.

$$\text{DRP} = \frac{\text{RTS}}{\text{RTS} + \text{NRTS} + \text{COND}}$$

where

RTS = repair this station
NRTS = non-repair this station
COND = condemned

RTS refers to the number of units repaired at the Air Force depots. Conversely, NRTS refers to the number of units repaired by the commercial contractors or by the foreign arrangements such as under a contract with the USAF. Non-Depot Repair Percentage (NDRP) is the complement of DRP.

3. SLQ (Safety Level Quantity)

This refers to the repairables stocked to meet the demands in case of delayed shipping, delays in maintenance or unexpected increase in demands.

for MRS items, $\text{SLQ} = \{3(\text{RCQ} + \text{OSTQ})\}^{1/2}$

for MRRL items, $\text{SLQ} = 3 \times \text{OSTQ}$

where

RCQ = Repair Cycle Quantity
OSTQ = Order and Shipping Time Quantity

RCQ and OSTQ will be defined later.

4. RCT (Repair Cycle Time)

Actually, there are two kinds of repair cycle times in the Korean Air Force. There is the repair cycle time of the base maintenance and that of the depot level maintenance. From the view of the ICP, items repaired at the base level would be considered as consumables. Thus, RCT refers to the time allowance for the depot level maintenance only.

In the DMM, RCT is constrained to be not less than 30 days and not more than 120 days.

5. RCQ (Repair Cycle Quantity)

This refers to the repairables stocked to meet demands during the repair cycle time. RCQ is applied to MRS items only and it is computed as follows.

$$RCQ = DDR \times RCT \times DRP$$

where

DDR = Daily Demand Rate
RCT = Repair Cycle Time
DRP = Depot Repair Percentage

6. OLQ (Operation Level Quantity)

This refers to the repairables stockage which is actually stored in maximum *quantity level for MRRL items. Its lowest limit is* 'SLQ+1'. Thus, item managers always should be aware of the OLQ stockage limit so that the backorders for the item can be minimized. RCQ is equivalent to OLQ in case of MRS items.

The Korean Air Force applies OLQ as 60 days of DDR so that:

$$OLQ = DDR \times 60$$

7. OST (Order and Shipping Time)

OST is defined as the time elapsed from the initiation of the procurement order or of the repair order, to the receipt of the item or a serviceable unit. In the case of procurement, the Korean Air Force constrains the OST to be not less than 120 days and not greater than 365 days. In case of repair, the OST is constrained to be not less than 220 days and not greater than 465 days. In both cases, the upper and lower bound are adopted to avoid extremes in the inventory position. The 100 days increment in the OST is due to the additional transportation time for MRRL items from Korea to the continental U.S.A. For the items for which historical data are not available, the upper bound OST is applied.

8. Order and Shipping Time Quantity (OSTQ)

OSTQ refers to the number of repairable items stock to meet the demands during the order and shipping time of the procured item or the repaired item. The formula for the OSTQ is given by:

for MRS items, OSTQ = DDR x NDRP x OST
for MRRL items, OSTQ = DDR x OST

E. MATHEMATICAL MODELS FOR REPAIRABLES

1. Requisition Objective Item Management

Practically, even with the assistance of the existing computer system, it is impossible for the item managers to manage 2,000 items that are assigned to them. Thus, the DMM designates items that have two or more requisitions per year as requisition objective items. Item managers monitor these items more closely. Among 180,000 items, about 30,000 items have been designated as requisition objective items, including about 5,000 repairables.

2. Periodic Review Model

The DMM applies a periodic review model which is based on a policy of reviewing and repairing at fixed regular intervals to bring inventory levels up to an optimal inventory requisition objective (RO). Each repair order is intended to bring the inventory up to a predetermined level, so that the actual quantity repaired may vary with each repair orders. Since repair orders are placed at predetermined intervals, the expected demand between intervals plus some allowance for the variability of demand must be considered. Thus, higher inventory levels are required under periodic review than under continuous review.

Currently, the DMM reviews the inventory position every two months.

3. The Determination of Requisition Objective

The requisition objective comprises three different types of inventories. These are the order and shipping time quantity (OSTQ), the repair cycle quantity (RCQ) and the safety level quantity (SLQ). The requisition objective is the sum of these three components.

As shown in the Figure 2.2, the repair order quantity is simply the difference between RO and the on hand inventory at the time of review. Since the system parameters such as OST, RCT, DDR, DRP and NDRP differ at each review period, the level of the RO may also vary every two months. Currently, the DMM computes RO as follows: [Ref. 1: p. 81] for MRS items, $RO = SLQ + RCQ + OSTQ$

where

$SLQ = \{3(RCQ + OSTQ)\}^{1/2}$

$RCQ = DDR \times DRP \times RCT$

$OSTQ = DDR \times (1 - DRP) \times OST$

for MRRL items, $RO = SLQ + OLQ + OSTQ$

where

$SLQ = (3 \times OSTQ)^{1/2}$

$OLQ = DDR \times 60$

$OSTQ = DDR \times OST$

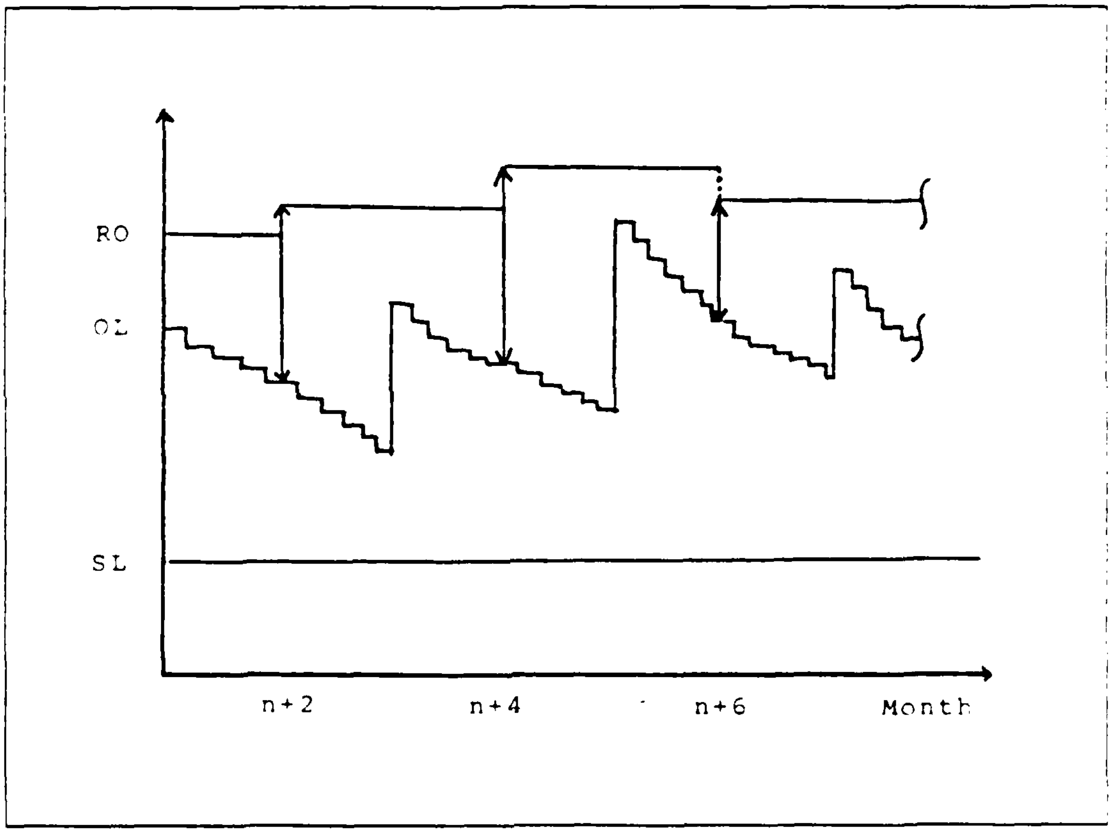

Figure 2.2 The Korean Air Force Repairables Periodic System.

F. SUMMARY AND PROBLEM STATEMENTS

The model lacks consideration of any kind of system goal such as fill rate or mean supply response time etc. Presumably, its focus is on the total annual inventory cost. As mentioned earlier, this approach does not have much relevance to the military inventory problem. Even when we looked at the problem in the context of inventory cost optimization, several shortcomings were noticed.

Note that calculation of RO lacks consideration of the stochastic characteristics of the inventory problem. Also, it does not specify the wear-out rate and the regeneration rate, which are crucial parameters in dealing with the repairables inventory problem. Lacking these parameters in the calculation of RO, it uses SLQ, RCQ and OSTQ, which result in conservative inventory management.

The DDR (daily demand rate) is the mean of a stochastic process. However, the model treats demand as if it were deterministic. The only consideration for the stochastic nature of demand is found in the computation of the safety level quantity. Even there, the actual probability distribution is not considered.

As evidence of the model's shortcomings, the model recommends very large amounts of stock for some items and also incurs many stockouts for other items.

III. OVERVIEW OF MANAGING REPAIRABLE ITEM INVENTORY SYSTEMS.

A. INTRODUCTION.

As the weapon systems installed in modern aircraft and ships become increasingly sophisticated and complex, repairable items represent an important subset of the total inventory of items which are managed by the military supply system.

Sherbrooke has estimated in 1968 that approximately 52% of the total investment in spare parts in the United States Air Force was in repairable items which at that time accounted for about ten billion dollars. By 1975 the percentage had risen to about 65%. Schrady estimated that the United State Navy's investment in repairables was approximately 58% of their total dollar investment in inventory. [Ref. 2: p. 253]

In general, repairable items are supported by a two-echelon inventory and repair system as illustrated in Figure 3.1. When a repairable item fails at the base level, it is returned to base supply and a new serviceable unit is issued from the rotatable pool. If possible, the failed item is then repaired by the base maintenance organization and returned to the rotatable pool at base supply. Sometimes, however, the failed item must be returned to depot where more sophisticated equipment and specialized skills are available to repair it. In this event, the base submits a requisition to the depot supply organization to obtain a serviceable replacement from the depot's rotatable pool for the failed item. When we consider the condemnation of repairables, there should be an inflow of new items to depot level supply from the procurement process. The item manager in depot level supply should look at the materials flow of all echelons, and then, place a replenishment order to resupply the condemned repairables. At times, forward base locations will be supplied from another closely located base - so called, lateral resupply. For other items, a manufacturer may provide both the source of procurement for new assets and the source of repair for failed items.

There are several factors which have extensive effects upon the entire repairables management system; i.e., on the levels of repair maintenance, repair costs and time.

The three levels of maintenance are:

(1) The lowest level (such as ship), called the organizational level.

(2) The intermediate level such as a tender or shore Intermediate Maintenance Activity.

(3) The depot level such as a Navy Shipyard, Naval Air Rework Facility or a Commercial Repair Activity.

The decisions concerning which maintenance levels will repair the failed items subsequently affects the supply support provided at the organizational level. If an item is repaired at the organizational level, repair equipment and maintenance personnel must be made available at that level. However, if the item is not repairable at that level, then the question is whether the item can be replaced at the organizational level. If so, functional spare items must be carried at the organizational level. Organizational level repairables will normally be transferred to the next higher echelon of repair if the repairs cannot be accomplished at the organizational level. The intermediate level maintenance is the same case.

B. REPAIRABLES INVENTORY MODELS

Currently, there exist various mathematical models for determining stockage levels for the repairable item inventory system. The existing models can be classified into three general classes: continuous review; periodic review; and models based on cyclic queuing systems. Regardless of the classification, however, many repairable item inventory models can be considered to be a special type of multi-echelon model - distribution systems are often composed of a hierarchy of warehouses that stock goods for distribution to other warehouses and to retail stores where demand for these goods originates.

1. METRIC Model

a. Background

The METRIC model was developed over a period of years by a research group at the RAND Corporation and was presented in the literature by Sherbrooke (1968) and extended by Muckstadt (1973). METRIC was developed with the ultimate goal of implementation and a slightly modified version of METRIC was actually implemented by the U.S. Air Force.

b. The General System

The basic METRIC model considers a two-echelon system in which independent bases (lower echelon) are supported by a repair depot (upper echelon). Fig 3.1 shows the general scheme of the two echelon system considered by METRIC.

Each of j bases stocks i spare parts. At the occurrence of a failure (it could be more than one), the failed item is either replaced by available base stock or back ordered if the base stock is not available. The item is inspected to determine the extent

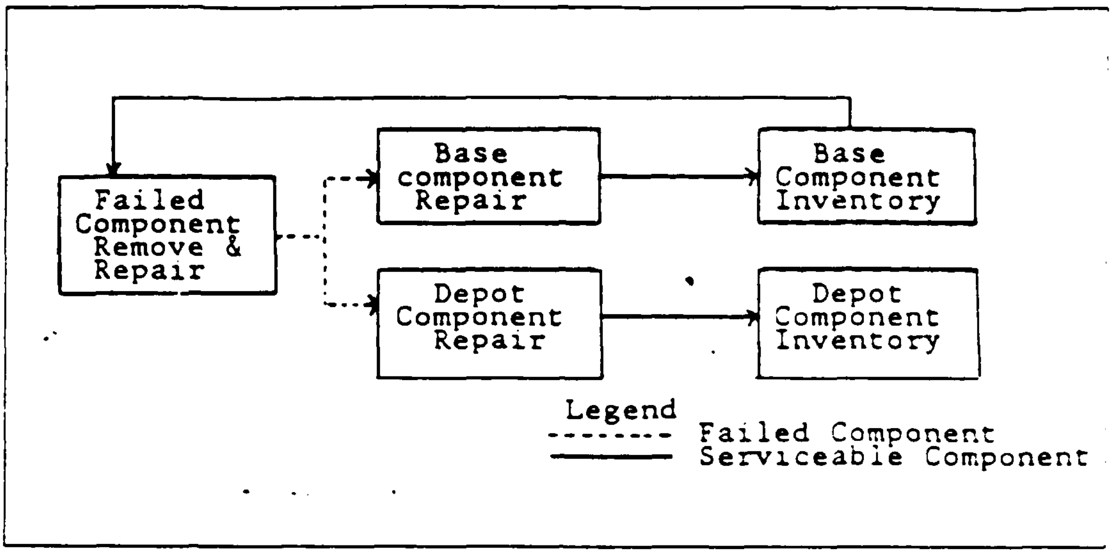

Figure 3.1 The Two-Echelon System considered by METRIC.

of repair required. If the repair can be made at the base , the unrepaired item enters base repair. If the item cannot be repaired at the base level, it is shipped to the depot. Upon shipping the item to the depot, the base places an order with the depot for a replacement, so that the inventory position for item i at base j can be maintained. [Ref. 3: p. 122]

c. *Assumptions*

For the purpose of reasonable approximations, the following assumptions are made by METRIC.

(1) Demands for item i at base j are generated by a stationary compound poisson process with rate λ_{ij} and compounding distribution with mean f_{ij}.

(2) With a probability of r_{ij}, a failed item of type i at base j can be repaired at the base. With probability $(1 - r_{ij})$, the item must be repaired at the depot.

(3) The expected base repair time, A_{ij}, the expected order-and-ship time from the depot to base j, O_{ij}, and the expected depot repair time, D_i, for item i are known constants.

(4) All items can be repaired. That is, the system is completely conservative with no condemnations allowed.

(5) There is no lateral resupply (transshipment) among bases.

(6) Successive base repair times are independent identically distributed random variables.

d. Model Formulation

By assumption (1), demand in this system follows a compound Poisson process. A compound Poisson process may be thought of a series of customers who arrive following a Poisson process, each of whom can demand an amount that is independently and identically distributed according to a compounding distribution.

Assume that item i is stocked at each of j bases, and the customers who place demand for the item at each base have a known mean arrival rate of λ_j, $j = 1,2,3, \ldots\ldots, J$. When a customer arrives at a base to place one or several demands, he turns in an equal number of carcasses. By the assumption (2), these carcasses can be repaired at base level with probability of r_{ij}, while $(1 - r_{ij})$ is the probability that they must be repaired at the depot. The arrival of carcasses from base j at the depot is described by a Poisson process whose mean is $(1 - r_{ij})$ times the mean of the Poisson customer arrival process at base j. Therefore, the total demand at the depot for item i is compound Poisson, with mean customer arrival rate:

$$\lambda = \sum_{j=1}^{J} \lambda_{ij} (1 - r_{ij})$$

Let f_{ij} be the mean demand per customer at base j. Then, the mean depot demand rate for unit i is:

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

where

θ_{ij} = the mean demand rate for item i at base j

In the special case of the logarithmic Poisson process, the probability that x customer demands are in the repair resupply process is negative-binomial with parameters q and K. (Note : $K = \lambda T \ln q$ where λ is mean customer arrival rate and T is average resupply time)

$$p(x \mid \lambda_{ij} T_{ij}) = (K + x - 1)!\,(q - 1)^2 \quad (K - 1)!\, x!\, q^{x+k}$$

$$x = 0,1,2,\ldots\ldots\ldots, \quad q \geq 1, \quad k \geq 0$$

where

q = the variance to mean ratio of $p(x \mid \lambda_{ij} T_{ij})$

$K = \lambda_{ij} T_{ij} f_{ij} / (q - 1)$

T_{ij} = average resupply time for a demand for item i at base j

A_{ij} = base repair cycle time - the average time required to repair item i at base j

D = depot repair cycle time - the average time required to return an item to the depot, repair it, and to place the item into depot serviceable stock

O_{ij} = the order and shipping time - the average time required for a requisition to be transmitted from a base to the depot, and to transport a requested serviceable unit back to the requesting base

$\delta(S_0)$ = average depot delay - the average delay incurred in filling a requisition at the depot due to temporary unavailability of serviceable units. The average delay is expressed as a function of the depot repair cycle time D and S_0 denotes the total stock levels assigned to the depot

Then,

$$T_{ij} = r_{ij} A_{ij} + (1 - r_{ij}) \{O_{ij} + \delta(S_0)\}$$

Since it takes an average of D time units for an arrival to complete the repair process, the probability distribution of the number of units in the depot repair cycle is compound Poisson with mean of λD. Hence, the expected number of units back ordered at the depot is:

$$BO(S_0 \mid \lambda D) = \sum_{x > S_0} (x - S_0) P(x \mid \lambda D)$$

As mentioned in the beginning, the objective of METRIC is to minimize the sum of backorders for all item i and for all bases j within a budget constraint. Thus, the METRIC problem will be represented as follows:

$$\text{minimize} \sum_{i=1}^{I} \sum_{j=1}^{J} BO_{ij} (S_{i0}, S_{ij})$$

$$\text{subject to} \sum_{i=1}^{I} \sum_{j=0}^{J} C_i S_{ij} \leq C$$

$S_{ij} \geq 0, \ 1 \leq i \leq I, \ 0 \leq j \leq J$

Where

S_{ij} = the decision variables

C = the total amount of budget available

C_i = the cost of item i

S_{io} = the depot stock for item i

e. Solution Technique

The METRIC problem is solved by using the generalized Lagrangian Multiplier method suggested by Fox and Landi. [Ref. 4: pp. 258-261]

Let Φ be a Lagrange multiplier associated with the budget constraint. The Lagrange function is written:

$$\sum_{i=1}^{I} \sum_{j=1}^{J} BO_{ij}(S_{ij} \mid \lambda_{ij}T_{ij}) - \Phi \sum_{i=1}^{I} \sum_{j=0}^{J} C_i S_{ij}$$

The auxiliary problem attempts to minimize this equation. By trial and error, we try to find the value of Φ which satisfies a given constraint. Therefore, we need to solve the above equation for several values of Φ, and choose that value of Φ for which the required resources are closest to the budget limit. Fox and Landi suggest a binary search procedure. Their computational experience found that at most six bisections were required to obtain budget allocations that were within one half of 1% of the original budget C.

The objective function is separable in the items. Dropping the subscript i in the original problem allows us to rewrite the equation as:

$$\min \sum_{i=1}^{I} BO_i(S_j \mid \lambda_j T_j) - \Phi C_i S_{ij} - \Phi C_i S_{io}$$

Since $BO_j(S_i \mid \lambda_j T_j)$ is discretely convex for a given S_{io} [Ref. 4: p. 260], the optimum base level is obtained by simply finding the smallest non-negative integer satisfying:

$$BO_j(S_i + 1 \mid \lambda_j T_j) - BO(S_j \mid \lambda_j T_j) \geq \Phi C_i S_{io}$$

2. Mod-METRIC Model

a. Background

Mod-METRIC model was developed by Muckstadt to deal with problems which the METRIC approach did not consider. Mod-METRIC considers the relation of parts hierarchy and tries to solve this multi-indenture level problem. Mod-METRIC was implemented by the U.S. Air Force as the method for computing repairable stock levels for the F-15 weapon system. [Ref. 5: p. 471]

Most repairables contain subassemblies or other components which are also repairable. For example, if an end item is an aircraft engine, it may have modules for intake, combustion and exhaust. If an engine fails, it is replaced by a serviceable engine from base stock. The failed component is then repaired either at the base or depot level depending upon the complexity of repair. A serviceable module from the base stock, if available, will replace the failed module, and the repaired engine is placed in base engine stock. Figure 3.2 shows the general scheme of materials flow in Mod-METRIC model.

b. Assumptions

The assumptions stated in METRIC are also applicable to Mod-METRIC except (1). Instead of compound Poisson demand in METRIC, Mod-METRIC assumes that the demand process is the simple Poisson process.

c. Model Formulation

In METRIC, the objective is to minimize expected base orders for all items subject to an investment constraint. The Mod-METRIC objective, however, is to minimize the expected base backorders for the end item subject to an investment constraint on the total dollars allocated to the end item and its components. This difference is caused by the hierarchical maintenance relationship between the module and the end item. As an example, an engine backorder indicates that an aircraft is missing an engine and is unavailable to perform its flying mission. Modules, on the other hand, are used only to repair engines. A backorder for a module only delays the repair of an engine. The impact of module backorders and engine backorders is clearly not the same. Figure 3.3 shows the difference between the METRIC spare parts concept and the multi-indenture concept.

Let T_i denote the average engine resupply time at base. By the nature of the repairables, T_i depends on several factors. When it is repaired at base level, T_i would be the time it takes to flow through the base maintenance system. If it is

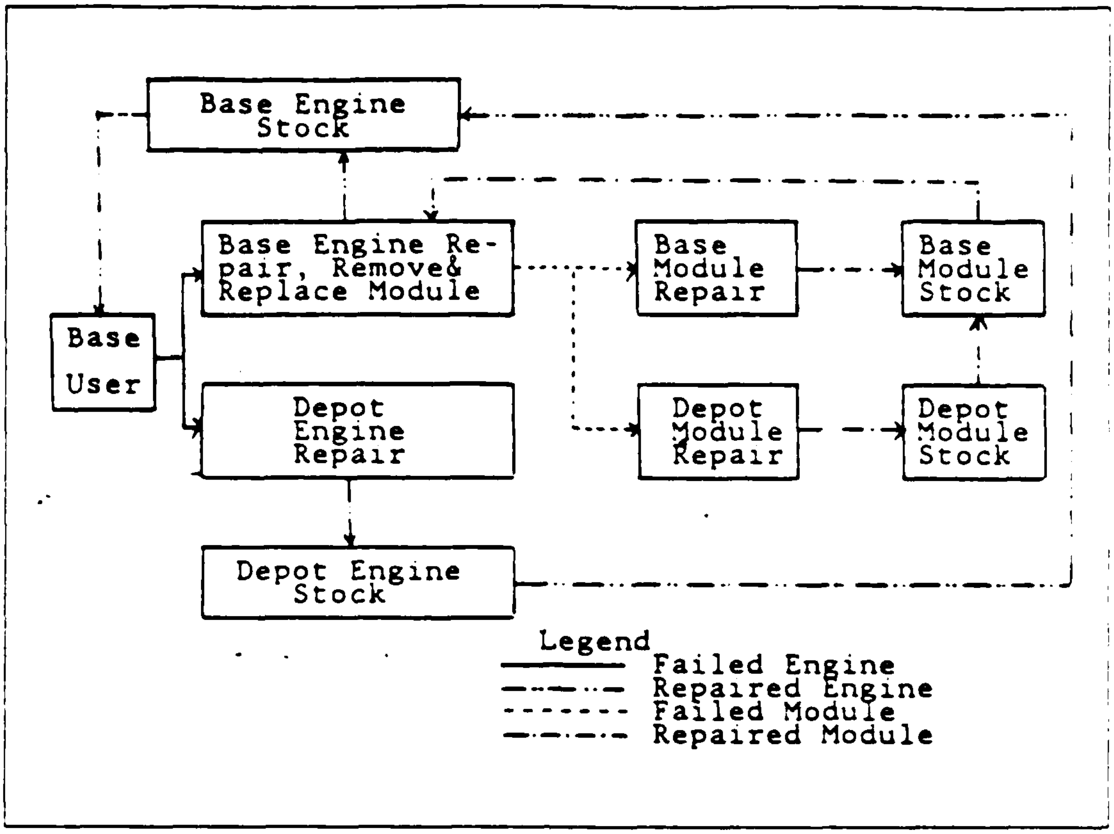

Figure 3.2 Mod-METRIC Repair Process.

repaired at the depot, T_i consists of time to place the depot order for a serviceable part and to receive the part from the depot, assuming a serviceable asset is on hand at the depot. However, when there are no serviceable assets on hand at depot, an additional delay is included in the resupply time.

$$T_i = r_i B_i + (1 - r_i)\{A_i + \delta(S_0 D)\}$$

where

r_i = the probability an engine will be repaired at base i
B_i = the average resupply time, given an engine is repaired at base i
A_i = the average order and ship time for an engine at base i
S_0 = the depot engine stock
D = the average depot repair time
$\delta(S_0)D$ = the delay days per demand

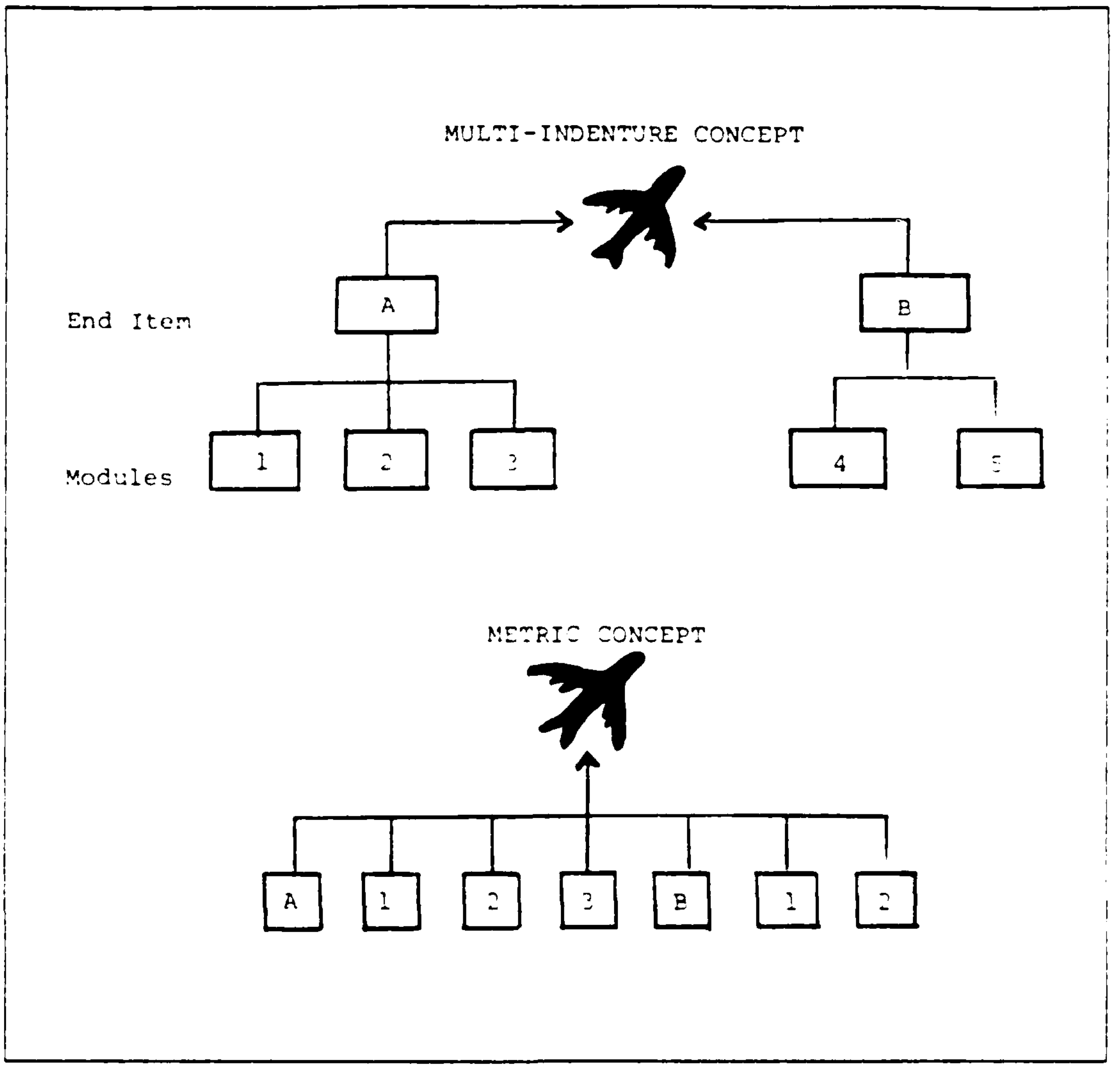

Figure 3.3 The Multi-Indenture Concept.

$\delta(S_0)D$ can be derived by following manner. The expected number of engines back ordered at the depot is:

$$BO(S_0 \mid \lambda D) = \sum_{x > S_0} (x - S_0)\, P(x \mid \lambda D)$$

where

$$\lambda = \sum_{i=1}^{I} (1 - r_i)\, \lambda_i$$

λ_i = the daily engine removal rate at base i

In other words, this expression is the expected number of units on which delay is being incurred at a random point in time. Dividing this expression by the expected number of demands per day yields a statistic which has the dimension of delay days per demand.

$$\delta(S_0)D = B(S_0 \mid \lambda D) / \lambda$$
$$= \text{expected backorders} / \text{expected daily demand}$$

Further, B_i could be divided into two components. That is, B_i is equal to the average remove and replace time, given that the necessary module is available, plus the expected delay due to the unavailability of the module which is required to repair the engine. Then,

$$B_i = R_i + \Delta_i$$

where

R_i = the average repair time at base i if modules are available
Δ_i = the average delay in base engine repair due to the unavailability of a needed module

Further, assume that the engine should be repaired by the failure of module j. Then, Δ_{ij} is the expected delay in engine base repair time due to a back order on module j at base i. Thus,

$$\Delta_{ij} = \sum_{x_{ij} > S_{ij}} (x_{ij} - S_{ij})\, P(x_{ij} \mid \lambda_{ij} T_{ij}) / x_{ij}$$

where

λ_{ij} = average number of daily removals of module j at base i
S_{ij} = stock level of module j at base i
T_{ij} = average resupply time for module j at base i

Then,

$$T_{ij} = r_{ij} B_{ij} + (1 - r_{ij})(A_{ij} + \delta_j D_j)$$

where

r_{ij} = the probability that a failure isolated to module j will be repaired at base level
B_{ij} = average base repair time for module j at base i
A_{ij} = average order and ship time for module j at base i
D_j = average depot repair time for module j

$$\delta_j = \sum_{x > S_{0j}} (x - S_{0j})\, P(x \mid \theta_j D_j) \quad \theta_j D_j$$

S_{oj} = the stock level of module j at the depot, and

$$\theta_j = \sum_{j=1}^{J} \lambda_{ij} (1 - r_{ij})$$

Consequently, the expected delay in engine repair at base i due to module unavailability is:

$$\Delta_i = (1 / r_i \lambda_i) \sum_{j=1}^{J} \lambda_{ij} \Delta_{ij}$$

Thus, expression T_i represents all the system components including the depot engine and modules stock level, and the base modules stock level. By using this relationship, the engine and module stock levels can be derived. Finally, the mathematical statement of the problem is:

$$\min \sum_{i=1}^{I} \sum\nolimits_{x > S_i} (x_i - S_i) P(x_i \mid \lambda_i T_i)$$

$$\text{subject to } \sum_{i=1}^{I} (C_E S_i + \sum_{j=1}^{J} C_j S_{ij}) + \sum_{j=1}^{J} C_j S_{oj} + C_E S_o \le C$$

where

S_i = stock level of base i
C_E = unit cost of an engine (end item)
c_j = unit cost of module j
C = dollar budget limit

d. Solution Technique

Unfortunately, the above equation is not separable, because T_{ij} is a complex function of the S_{ij}. Thus, Muckstadt recommended that it should be broken down into two parts; the component subproblem and the end item subproblem. Even after the break-down of the problems, however, it requires the solution of many subproblems each of which corresponds to a particular division of the available budget between components and end items. The solution procedure is as follows.

(1) First allocate the budget C into C_1 and C_2 for components and end items respectively.

(2) Allocate C_1 among components so as to minimize the expected end items repair delays summed over all bases subject to the budget constraint C_1. This problem is mathematically represented as:

$$\min \sum_{j=1}^{J} r_j \lambda_j$$

$$\text{Subject to} \sum_{j=1}^{J} (C_j S_{oj} + \sum_{i=1}^{I} C_j S_{ij}) \leq C_1$$

This problem can be solved using the METRIC technique.

(3) Given the result from the above step, compute the average resupply time T_i for the components of each base. Then, allocate the remaining budget C_2 so as to minimize the expected end item base backorders. The METRIC budget allocation procedure may again be used.

(4) Above steps provide a set of proposed stock levels upon a given allocation of the budget among the end items and components. These steps then are repeated several times using new values for C_1 and C_2 to establish the best allocation.

3. Dyna-METRIC Model

a. Background

Dyna-METRIC was developed by the RAND Corporation to provide an analytic method for studying the transient behaviour of component-repair inventory systems under time-dependent operational demands and logistics decisions like those that might be experienced in wartime. Note that the past work regarding the repairable item stockage prior to Dyna-METRIC only dealt with the steady state inventory system with constant average demand rate and service rate. These steady state assumptions may provide a good approximation during peace time operations. In wartime, however, demands for components may suddenly jump very high relative to the previous peacetime operation and then may decrease gradually or, in some cases, drastically due to attrition of the system.

A key characteristic of the model is its ability to deal with the dynamic or transient demands placed on component repair and inventory support caused by time variables in a scenario that includes sortie rates, mission changes, phased arrival of component repair resource, interruptions of transportation, and the like, all of which would be experienced in wartime. It computes how given resource levels and process times would contribute to war-time capability. By exploiting the mathematical structures of its underlying equations, Dyna-METRIC suggests that the alternative cost effective repair or stockage resource purchases would achieve a target aircraft availability goal throughout the war time scenario. [Ref. 6: pp. 4-6]

b. The System

Dyna-METRIC considers a three echelon inventory repair system such as that shown in Figure 3.4. Each base has an in-house repair facility which may have various test and repair capabilities. This base repair facility may be supported by several Centralized Intermediate Repair Facilities (CIRFs). Each operating base is capable of conducting only limited types of maintenance, usually limited to simple removal and replacement operations at the flight line. It should be noticed that some of the bases are associated with a CIRF while others are not. They have direct flows of parts to the depot.

A depot is represented as existing outside of the model. It is seen from the model's point of view, as an infinite source of supply located some order and ship time away.

The actual focus of the model is on the set of repair facilities and arrows in the diagram, in other word, the pipeline. The level of each part in each pipeline is calculated for a given day. These parts are then considered not available for use on an aircraft. These aggregate numbers are then subtracted from the total number of parts of each type which are available to determine the number of mission capable aircraft for that day. These aircrafts then fly the required number of sorties as defined by the user.

c. Assumptions

The major assumptions of Dyna-METRIC which distinguish it most from the others are shown below.

(1) Demand for items are generated by a nonhomogeneous Poisson process with intensity function $m(t)$ and mean value function $r(t) = \int m(s)ds$. The functions, $m(t)$ and $r(t)$, will be defined later. t denotes a arbitrary time. Thus, the demand process is dynamic.

(2) The repair process is independent of the arrival process and has slack repair capacity so that each repairable item demanding repair immediately receives services with average service time based on the function $F(s,t)$. $F(s,t)$ will be defined later.

(3) The subcomponents failure sets are nonintersecting. That is, no more than one subcomponent can fail or be demanded in the repair of each assembly.

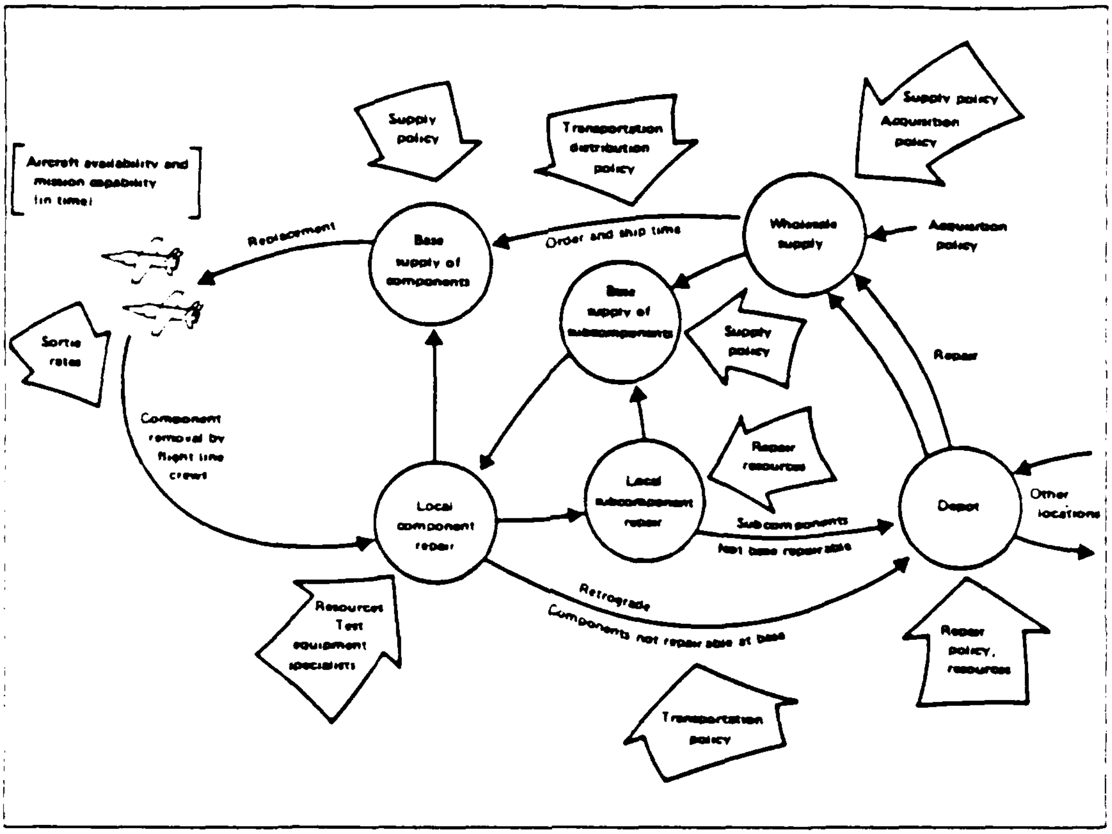

Figure 3.4 Major Dyna-METRIC Components.

d. The Mathematical Model

(1) *Time Dependent Pipeline Equations.*

Since the major objective of the system is to avoid the loss of aircraft mission capability due to a shortage of correctly functioning components on the aircraft, it is necessary to compute the number of components awaiting repair, being repaired, being on the way to and from another echelon of repair, and partially repaired but awaiting spare parts. Each state is a pipeline that contains some of the total inventory components. Each pipeline segment is characterized by a delay time that arriving components must spend in the pipeline before exiting the segment. The model expands each component's expected pipeline size into a complete probability distribution for the number of components currently undergoing repair and on order, so the probability distribution for all components can be combined to estimate aircraft availability and sorties.

Under the assumptions that the probability distribution of repair time is independent of the failure process, the average number of components in the repair pipeline will be:

$$\lambda_{ss} = dT$$

where

d = average daily failure rate
T = average repair time

With the further assumption that demand has a Poisson probability distribution, the probability that there are K components in the pipeline at any point in time would be:

$$P(K \text{ in pipeline}) = {\lambda_{ss}}^{K} e^{-\lambda_{ss}} / K!$$

However, in Dyna-METRIC demand is a function of time so that:

d (t) = (failure per flying hour)
x (flying hour   sorties at time t)
x (number of sorties day per aircraft at time t)
x (quantity of the component on the aircraft)
x (percentage of aircraft with the component)

Also, in place of a constant average repair time, T, the dynamic model uses the probability that a repair started at time s is not completed at time t. That is:

F(t,s) = Probability (component entering at s is still in repair at t)
= Probability (repair time > t-s when started at s)

The average number of components in the pipeline is derived by combining those two functions. Consider only those components that arrived in an interval of time, Δs, centered at time s. Then,

$$\Delta\lambda(t, s) = d(s)\, F(t,s)\, \Delta s$$

where

$\Delta\lambda(t, s)$ = expected number of components in the repair pipeline at time t that arrived during the interval around s
d(s) = daily failure rate at time s
F (t, s) = Probability that a component is 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 time other than s and F(t) is independent of the probability distribution generating the demand rate, then:

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

Further assume that Δs is very small, so that:

$$\lambda(t) = \int_0^t d(s) F(t, s) \Delta s$$

With the additional assumption that the component failure probability distribution is Poisson, $\lambda(t)$ is the mean of a time-varying (nonhomogeneous) Poisson process. That is, the probability of K components in repair at time t is:

$$P(K) = \lambda(t)^K e^{-\lambda(t)} / K!$$

where

$$\lambda(t) = \int_0^t d(s) F(t, s) ds$$

(2) *Time Dependent Component Performance Measure.*

The component measures typically computed by the Dyna-METRIC model are:

R(t) = ready rate at time t - the probability that an item observed at time t has no backorders

FR(t) = fill rate at time t - the probability that a demand at time t can be filled immediately from stock on hand

EB(t) = expected back orders - the average number of shortages of a component at time t

VBD(t) = variance of the backorders, a measure of the random variation of back orders

DT(t) = average cumulative demands by time t

The ready rate is given by:

$$R(t) = \sum_{K=0}^{S(t)} P\{(K|\lambda(t)\}$$

Since the definition of the fill rate is the probability that a component will be available when a demand is placed, it is therefore the probability that demands have left at least one component available, that is, the sum of the probabilities of demands less than the stock level. Expected backorders are given by:

$$\begin{aligned} EB(t) &= \textstyle\sum_{K > S(t)} \{K - s(t)\}\, P\{K \mid \lambda(t)\} \\ &= \lambda(t) - s(t) + \sum_{K=0}^{S(t)} \{s(t) - K\}\, P\{K \mid \lambda(t)\} \end{aligned}$$

For K greater than s(t), there will be backorders of {K - s(t)}. The probability of any demand level, that is K, is P{K | λ(t)}, and the expected value of the backorders is merely the product of the various values the backorders can take on times the probability of a demand at that given value. The variance in backorders is given by:

$$VB(t) = \textstyle\sum_{K > S(t)} \{K - s(t)\}^2 P\{K \mid \lambda(t)\} - \{EB(t)\}^2$$

(3) *Time Dependent Optimal Determination of Spare Parts to Meet an Operational Objective.*

The fact that pipelines have time-dependent probability distributions means that the optimal mix of spare components at one point in time may not be the optimal mix at another. Thus, the approach to take is to compute, for each time of interest, the marginal increase in spare parts to achieve a given capability over those already input or determined for a previous time. [Ref. 6: pp. 61-65]

In determining the supply level, the model attempts to provide enough spare parts to give the desired confidence at the lowest cost at each point in time of interest. Thus the objective function is the total cost of spare parts.

Let,

S_i = the spare parts level for component i
C_i = the unit cost of component i

α = the desired confidence level

K_n = the non-mission capable rate not to be exceeded

$P(K_n, S)$ = the probability that the non-mission capable rate is less than K_n given a stock level S

Then, the problem to solve is:

$$\text{minimize} \sum_{i=1}^{I} C_i S_i$$

$$\text{subject to } P(K_n, S) \geq \alpha, \quad S_i \geq S_{io}$$

where

S_{io} = the input stock level or previous time optimization stock level for component i

Assuming complete cannibalization, $P(K_n, S)$ equals:

$$P(K_n, S) = \prod_{i=1}^{I} P^i(Q_i K_n)$$

where

$$P^i(Q_i K_n) = \sum_{K=0}^{S_i + Q_i K_n} P_i(K)$$

$P_i(K)$ = the probability of exactly K failure of component i

The necessary condition for the performance constraint to be met is to have:

$$P^i(Q_i K_n) \geq \alpha \text{ for each } i$$

Then marginal analysis is used to determine the best mix of additional components to achieve the desired goal. This process proceeds by investing in one additional component at a time which is selected by finding the component that gives the largest increase in the logarithms of the confidence level at the lowest cost. That is, we determine:

$$\Delta_i \ln P(K_n, S) \quad C_i$$

where

$$\Delta_i \ln P(K_n, S) = \ln \{P(K_n, S^i) \quad P(K_n, S)\}$$

$$S^i = (S_1, S_2, ---, S_{i+1}, ------)$$

The component for which supply is increased one unit is the one whose index solves:

$$\max \Delta_i \ln P(K_n, S) / C_i$$

This process continues until the given confidence level is achieved. At this point, the resulting value of S is the efficient solution of the base stockage problem.

4. The U.S. Navy UICP Repairables Model

a. Introduction

UICP stands for Uniform Inventory Control Program. All models being used by the Navy and their associated concepts are incorporated in a series of ADP (Automated Data Processing) programs and files called the Uniform Inventory Control Program (UICP). Within the UICP application, there are three models; one for the procurement of consumables, one for the procurement of depot level repairable items (DLRs) and another for the repair of DLRs.

Although the latter two models for DLRs are separate and distinct, their solutions are linked in a unique way to ensure their safety level requirements are not inconsistent.

Basically, the UICP inventory models are cost minimization models. The UICP model attempts to minimize the sum of three variable cost components: ordering cost, holding cost and backorder cost.

b. Assumptions

The development of the UICP formulas for inventory levels follows the approach used by Hadley and Within in their book. [Ref. 7: pp. 162-165]

The assumptions are:

(1) A continuous review system. Wholesale inventory level requirements assets are known by Inventory Control Point (ICP) at all times.

(2) Steady state environment. The key characteristics of the items managed by the ICP are constant over the forecast period. Those are the forecasted average values, variances of the random variables of the rate of customer demand, procurement leadtime, depot repair times, depot repair survival rate and the rate of carcass returns.

(3) To eliminate difficulties in modeling large asset deficiencies to the reorder level or the repair level at the instant of procurement or repair review, it is assured that an order for procurement or repair is placed when the assets reach the reorder level or the repair level and that customer demand and carcass returns do not occur in more than one unit per transaction.

(4) The unit procurement cost or repair cost of an item is independent of the magnitude of order quantity or repair quantity.

(5) The cost of a backorder and the time-weighted costs of a backorder can be accurately quantified.

(6) The reorder level and repair level are always non-negative.

(7) The cost to hold one unit of stock in the inventory is proportional to the unit cost of the item.

(8) No interaction exists among families of items or individual nonfamily items or both. Each family or nonfamily item's inventory levels requirements are calculated independently of those of other families or nonfamily items.

c. UICP Depot Level Repairables (DLRs) Procurement Model

The repairables procurement model starts with a total variable cost (TVC) equation which is to be minimized. A notable difference from the model for consumables is the inclusion of the receipt of Ready-For-Issue (RFI) assets from a repair process in the DLR model. [Ref. 8: Chapter 3 Appendix A]

(1) *Ordering Cost.*

Let,

A = administrative cost to order
D = forecasted quarterly recurring demand
B = forecasted quarterly regenerations
Q = economic order quantity

Then,

$4(D - B)/Q$ is the expected number of procurements per year.

Thus, the annual ordering cost is given by $4(D - B)A/Q$.

(2) *Holding Cost.*

Let,

I = % cost per dollar of inventory held annually
C = item cost (replacement)
L = procurement leadtime
T = repair turnaround time
R = repair level
$F(x)$ = the function of probability distribution of leadtime demand

To meet demands during leadtime, we must have material on hand as much as:

$$DT + (D - B) \times (L - T)$$

Then, holding cost is given by:

$$IC\,[Q / 2 + R - \{(D - B) \times L + B \times T\} + \int_{x > R} (x - R)\, F(x)\, dx]$$

Let,

λ = shortage cost per requisition short
E = military essentiality weight
F = quarterly requisition frequency

Then, $(\lambda E)\{4(D - B) / Q\}\, F / D \int_{x > R} (x - R)\, F(x)\, dx$ equals the cost of the expected number of backorders in a year.

The TVC equation is symbolized by:

$$TVC = 4(D - B)A / Q + IC\,[Q / 2 + R - \{(D - B) \times L + B \times T\} + \int_{x > R} (x - R)\, F(x)\, dx\,] + (\lambda E)\,\{4(D - B) / Q\}\, F / D \int_{x > R} (x - R)\, F(x) dx\,.$$

Then, by setting $dTVC / dQ = 0$

$$Q = [8(D - B)\,(A + \lambda EF / D) \int_{x > R} (x - R)\, F(x)\, dx / IC]^{1/2}$$

Also, by setting $dTVC / dR = 0$, we find:

$$\int_{x > R} (x - R)\, F(x)\, dx = QICD / \{QICD + 4\lambda\, EF\, (D - B)\}$$

Because the expression $\int_{x > R}(x - R)F(x)dx$ is the cumulative distribution for leadtime demand, the shaded area under the normal curve in Figure 3.5 represents the probability of demand exceeding the reorder point in an order cycle, this is the quantity defined as RISK.

Note that since Q and R are related, the reorder quantity Q cannot be solved independently. Thus, UICP approximates Q by using a variation of the economic order quantity formula:

$$Q = \{8(D - B)A / IC\}^{1/2}$$

Then, $QICD / \{QICD + 4\lambda EF(D - B)\}$ can be computed for RISK determination.

d. UICP Depot Level Repairables Repair Model

The repair model also starts with a total variable cost equation viewed largely independently of the procurement problem. [Ref. 8: Chapter 3 Appendix A] Note that its time horizon is the depot level repair turn around time. The total

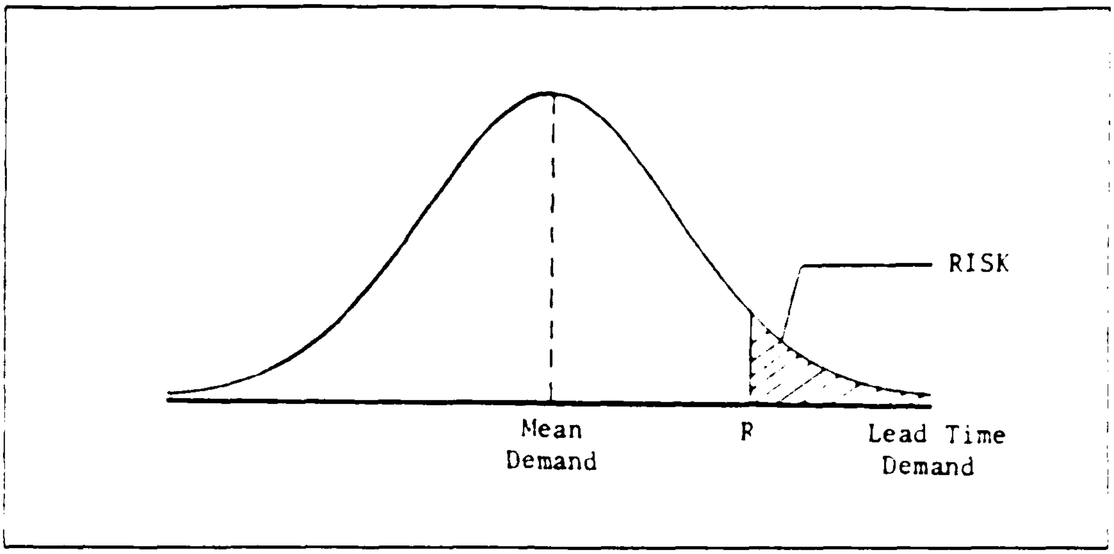

Figure 3.5 Leadtime Demand.

variable cost equation for the repair model is the sum of the order cost, holding cost and backorder cost. That is:

TVC = (number of repair orders per year) x
(cost per repair order) +
(cost to hold one unit per year) x
(average number of units held) +
(cost per requisition backordered) x
(number of depot level turnaround times per year) x
(number of requisitions backordered per depot level turnaround time)

Let,

Q_2 = economic repair quantity
A_2 = repair administrative order cost
C_2 = repair price
R_2 = repair level
$F_2(x)$ = probability distribution of demand during repair turnaround time
λ_2 = repair shortage cost

Then,

$$TVC = 4 \min(D, B)A_2 \quad Q_2 + IC_2 \{Q_2 \quad 2 + R_2 - (D \times T)$$

$$+ \int_{x > R_2} (x - R_2) F_2(x)\, dx\} +$$

$$(\lambda_2 E) \{4 \min (D, B) / Q_2\} F \quad D \int_{x > R_2} (x - R_2) F_2(x) dx$$

By setting $dTVC / dQ_2 = 0$

$$Q_2 = [\{8 \min (D, B) (A_2 + \lambda_2 E F \quad D \int_{x > R_2} (x - R_2) F_2(x)\, dx\} \quad IC_2]^{1/2}$$

Also, by setting $dTVC / dR_2 = 0$

$$\int_{x \geq 0} F_2(x)\, dx = Q_2 IC_2 D \quad \{Q_2 IC_2 D + 4\lambda_2 EF \min (D, B)\}$$

Again, Q_2 and R_2 are related. The UICP model approximates Q_2 as follows:

$$Q_2 = \{8 \text{ Min} (D, B) A_2 \quad IC_2\}^{1/2}$$

Then, $Q_2 IC_2 D \quad \{Q_2 IC_2 D + 4\lambda_2 FEB\}$ can be computed by using the above result.

e. Integrated Repairables Model

As stated earlier, the requirements computed by the procurement and repair models are accomplished independently of each other. As a result, this leads to a carcass constrained situation. That is, the computed procurement inventory level for an item does not provide sufficient carcasses to allow repairs at the computed repair inventory level.

To solve this problem, Naval Supply Systems Command (NAVSUP) has made some changes. Under the model integration, there is only one RISK formula. [Ref. 8: Chapter 3 Appendix A]

$$RISK = IC_3 D \quad (IC_3 D + \lambda FE)$$

where

$$C_3 = (B \quad D)(C_2) + (1 - B \quad D)(C)$$

Also, rather than using a procurement leadtime or a depot level repair turnaround time, it uses an average acquisition time as the time horizon for computing the safety level. The average acquisition time (L_2) is defined by:

$$L_2 = (1 - B \; D) L + (B \; D) T$$

It is clear that L_2 is the weighted average of the procurement leadtime and the repair turnaround time because D - B represents the quantity to be procured and B represents the quantity from the regeneration.

5. NPS (Naval Post-Graduate School) Model

a. Background

The NPS model was developed by F. R. Richards with assistance from C. L. Apple and K. Y. Kho in an effort to improve the U.S. Navy UICP repairables model.

As we have already seen in the solution technique portions of the METRIC and Mod-METRIC models, both require lengthy iterative search procedure for solving for the optimal value of the parameters. That is, to find the optimal base stock levels which satisfy the given constraints, one must choose the value of a Lagrangian Multiplier by trial and error. This process is repeated every time the depot stock level is changed. Thus, it is a heavy computational burden to find the optimal solution for a system which has several thousands of components.

The NPS model has reduced the required computation time down to less than one twentieth of that required by the METRIC. This was accomplished by accounting for the the special characteristics of the system for managing repairables in the U.S. Navy [Ref. 9: p. 51]. However, the NPS model was developed, not as a multi-echelon model, but as a wholesale level model for repairables. The stockage levels for the retail level (base or ship) are determined using other models. The U.S. Navy uses the Coordinated Shipboard Allowance List (COSAL) and Fleet Logistics Support Improvement Program (FLSIP) model for the determination of retail level stockage requirements. the METRIC family of models.

b. Assumptions

The major assumptions of the NPS model are as follows.

(1) Demands for item i are generated by a simple Poisson process with rate λ_i.

(2) There is a probability P_i that a failure of item i will result in an attrition, i.e. condemnation.

(3) Repair times, replenish times, and transportation times are random variable with known means.

(4) There is no lateral resupply (transshipment) among bases.

c. Model Formulation

The objective of the NPS model is to find the level of wholesale stock (S_{i0}) for each of the I items which minimizes the shipboard (base) MSRT (Mean Supply Response Time) subject to a budget constraint. Because the NPS model does not deal with base stock levels, a separate policy is applied to calculate the stock level of each base and its results are incorporated into the NPS model to determine the wholesale stock levels. It is frequently the case that a base may wish to achieve a specified ready rate assuming no support from a higher echelon (depot). The NPS model also suggests some computational simplifications to the procedures actually used to determine the base stock levels in the COSAL and FLSIP models.

Kho suggested that the stock level for each base can be approximated very accurately and rapidly using regression function [Ref. 9: p. 50]. The NPS model incorporates this notion of a specified base ready rate and stock level and attempts to determine the depot stock level S_{io} required to achieve a specified Mean Supply Response Time (MSRT) goal.

The mean supply response time is the expected length of time the equipment is unavailable for use upon failure due to spares shortages. It is obtained by dividing the total expected delay of the wholesale system by the total expected number of failures. [Ref. 10: pp. 60-62]

Assume the wholesale level ICP stocks S_{io} units for item i. Then, the expected number of backorders at a randomly selected time is given by:

$$BO(S_{io}) = \sum_{x > S_{io}} (x - S_{io}) P(x : \lambda_i T_i)$$

where

S_{io} = stock level of item i at the wholesale ICP

λ_i = expected number of demands per time unit upon inventory for item i

$P(x : \lambda_i T_i)$ = probability of x units of stock reduction for item i

T_i = mean stock replenishment time (time to replace an inventory loss through repair or procurement for item i)

Note that T_i is affected by the base stock level. The larger is the base stock level, the smaller will be T_i. The value of T_i is also affected by the repair doctrine and the procurement doctrine. Clearly, in order to minimize MSRT, the optimal repair and ordering doctrines are one-for -one. That is, do not batch for either repair or replacement. However, the NPS model realizes that other considerations (unstated in the model formulation) sometimes force repairs and replacements to be batched. The NPS model adjusts the T_i values appropriately to incorporate queueing times when batching takes place. $BO(S_{io})$ also gives the expected number of shortage days per day [Ref. 7: p. 20]. Thus, dividing $B(S_{io})$ by the expected number of demands per day (λ_i) gives the average length of time a customer must wait for the satisfaction of a demand. That is:

$$D_i = \sum_{x > S_{io}} (x - S_{io})\, P(x : \lambda_i T_i) / \lambda_i$$

where

D_i = the mean supply response time for item i

In the NPS model, this is the mean supply response time for the resupply cycle and will be denoted as $MSRTRS_i$. Considering the shipping time from the wholesale ICP to the each base (T_s), the mean supply response time for the wholesale system ($MSRTW_i$) is given by:

$$MSRTW_i = T_s + MSRTS_i$$

Also, this is average resupply time for each base, and is determined solely by the depot stock. As mentioned earlier, the objective of the model is to compute the wholesale stock level necessary to meet a specified MSRT goal at the base level.

Let, $BO_{ij}(S_{io}, S_{ij})$ be the expected number of backorders for item i at a randomly selected time for base j. Then,

$$B_{ij}(S_{io}, S_{ij}) = \sum_{x > S_{ij}} (x - S_{ij})\, P(x : \theta_{ij})$$

where

S_{ij} = base j stock level for item i

θ_{ij} = $MSRTW_{ij} \lambda_{ij}$: this is the mean demand at base j for item i during an average resupply time and is a function of S_{io}

Since $B_{ij}(S_{io}, S_{ij})$ is the expected number of shortage days per day, the average delay per failure or the mean supply response time for the base is $B_{ij}(S_{io}, S_{ij})$ λ_{ij}. The average MSRT across all the bases for item i is given by:

$$MSRT_i = \sum_{j=1}^{J} BO_{ij}(S_{io}, S_{ij}) / \lambda_i$$

$MSRT_i$ is constrained not to exceed MSRTG (Mean Supply Response Time Goal). Hence, the objective of the model is given as:

find the smallest S_{io}, $1 \le i \le I$ to satisfy

$$\sum_{j=1}^{J} BO_{ij}(S_{io}, S_{ij}) / \lambda_i \le MSRTG, \quad S_{ij} \ge 0, \ 1 \le i \le I, \ 0 \le j \le J$$

where

$$\lambda_i = \sum_{j=1}^{J} \lambda_{ij}$$

This unconstrained formulation ignores any budget constraints and results in each item satisfying the MSRT goal. The procedure can be modified easily as described below using marginal analysis to satisfy an overall MSRT goal (overall items) at minimum investment cost.

d. Solution Technique

Step 1. Determine the base stock levels S_{ij} from ready rate consideration.
Set the initial depot stockage vector to be
$(0,0,\ldots,0)$. i.e. $d_i = S_{io} = 0$ for $i = 1,2,\ldots,m$.
Step 2. Compute $T_{ij}(d_i + 1)$ for $i = 1,2,\ldots,m$ and $j = 1,2,\ldots,n$.

and $$BO_i(d_i) = \sum_{j=i}^{J} BO_{ij}(d_{ij}, S_{ij}).$$

Step 3. Compute $BO_i(d_i)\ C_i$ for $i = 1,2,\ldots,m$ and let k
be that index for which this ratio is maximum.
Step 4. Let $d_k = d_k + 1$.
Step 5. Compute $MSRT = \sum \lambda_i MSRT_i / \sum \lambda_i = \sum BO_i(d_i) / \lambda$.
Step 6. If $MSRT \leq$ Goal, stop. Otherwise go to step 2.

6. Availability Centered Inventory Model (ACIM)

a. Background

ACIM was developed by CACI Inc. under the sponsorship of the Ship Support Improvement Project, Naval Sea System Command, PMS-306, and approved by the Chief of Naval Operations for use in determining consumer level stockage quantities for selected equipments in March 1981. [Ref. 11: pp. 1-2] However, this model was initially used as a part of a larger model (LSEE : Logistics Support Economic Evaluation) which provided necessary inputs and enabled comparisons with other Navy stockage policies. After this, successive refinements for the simplifications of the solution procedure and associated computer programs have been done for several years until its approval.

This model was originally designed to calculate inventory levels for all items in the parts breakdown of an equipment and at all stockage facilities in a multi-echelon support system. Thus, ACIM is capable of computing levels for all ships, intermediate maintenance activities, and depots that use or support the equipment. However, this model is mainly used in the provisioning process to compute shipboard allowances to achieve specified weapon system readiness levels which have not been achieved with the standard protection level models.

b. Availability Measure

ACIM recognizes that the purpose of a supply system is to provide sufficient support so that a weapon system is operational when it is needed. The terminology used to describe this goal is operational availability (A_O). ACIM defines A_O by the following formula [Ref. 12: p. 5]:

$$\begin{aligned} A_O &= \text{up time} / (\text{up time} + \text{down time}) \\ &= \text{MTBF} / (\text{MTBF} + \text{MTTR} + \text{MSRT}) \end{aligned}$$

where

MTBF = mean time between failures
MTTR = mean time to repair
MSRT = mean supply response time

A_O may also be interpreted as the probability that the equipment is in an operable condition at a random point in time. Among the three factors of A_O, the MTBF and MTTR are system parameters outside the control of the supply system and are viewed as constants. MSRT is the only term which depends on stockage postures, it is therefore the one that the ACIM model focuses on to achieve a given value for A_O.

c. Assumptions

(1) All parts are organized in terms of equipment with a top-down breakdown that can be represented as an arborescent network similar to the example given below. Any part may be totally consumable, totally repairable, or any mix thereof.

(2) Stocking maintenance facilities are organized in a hierarchical structure according to supply maintenance flows which can be represented as an arborescent network as illustrated below. Each facility has a colocated maintenance and supply capability. The facility at the top of the structure is assumed to have an infinite supply of all items.

(3) External demands upon supply are stationary and compound-Poisson distributed.

(4) All stockage locations use a continuous review, (S - 1, S) ordering policy.

(5) Mean Time to Repair (MTTR) is defined to include all equipment downtimes that are not supply related.

(6) There is no lateral resupply (transshipment) among bases.

(7) Items repaired at any location are assumed to be returned to collocated stocks for issue.

(8) If, for a given facility in the network, the stocks are physically distributed in several places, it is assumed that the resupply time for direct customers (net lower echelon) is independent of the location.

(9) The ordering policy assumption precludes consideration of economies of scale for resupply. That is, all ordering is on a one for one basis.

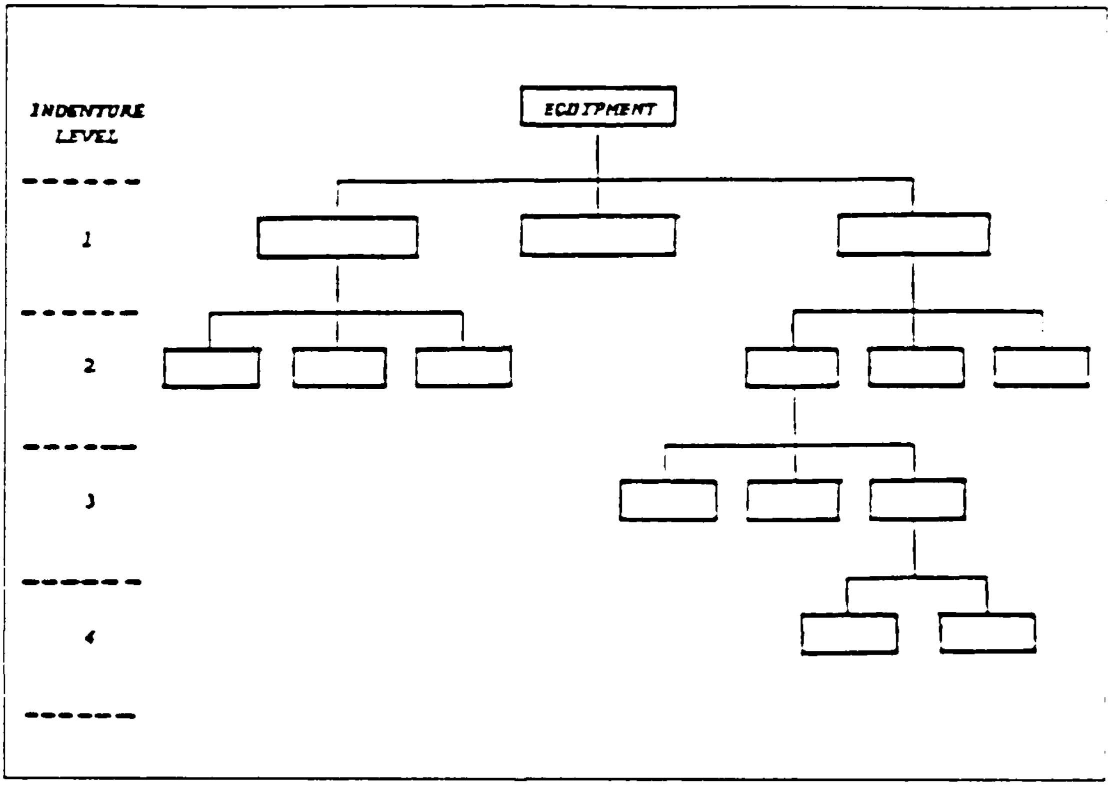

Figure 3.6 ACIM Top-Down Parts Structure.

d. Model Formulation

The goal of ACIM is to maximize the operational availability (A_0) of a weapon system subject to a given inventory budget. With the definition given above of A_0 and with the view that MSRT is the only term which is affected by the stockage decision, the developers of ACIM argue that the allocation which maximize A_0 is equivalent to the allocation which minimizes MSRT.[3] ACIM therefore actually attempts to minimize MSRT subject to the given constraints.

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[3] F. R. Richards and A. W. McMasters show that the allocation which maximize A_0 is not necessarily the same as the one which minimizes MSRT [see Ref. 13 : Appendix C].

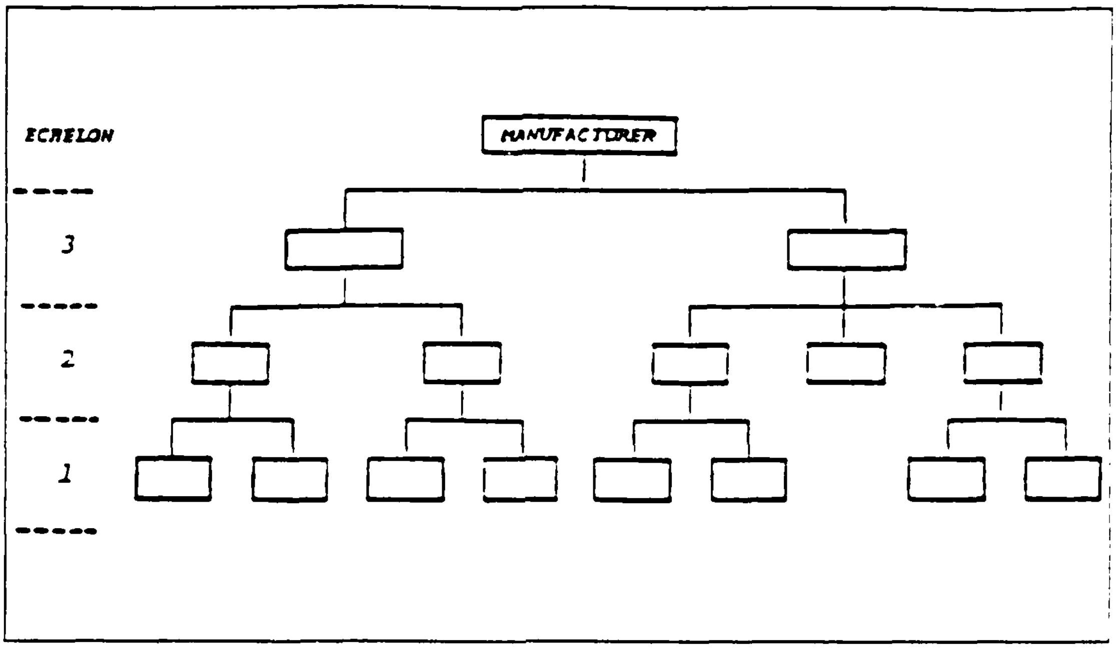

Figure 3.7 ACIM Supply/Maintenance Structure.

Let i be an arbitrary item in equipment e (which may be e itself). Let u = 0 represent an arbitrary facility in the support system and u = 1, 2, 3, ------, represent facilities at the next lower indenture, i.e., those facilities that submit items for repair directly to or obtain resupply from facility o. Then, the objective can be explicitly stated as follows:

find values for S_{kv} which minimize D_{iu} for all user locations u

subject to $\sum_{k,v} C_k S_{kv} = B$

where

C_k = unit cost of item k
B = given budget for spares procurement
D_{iu} = expected delay per demand upon inventory for item i at location u (MSRT for item i at location u)
S_{kv} = the level of inventory for item k at location v where v is the resupply source for location o

D_{iu} is one of the components of M_{iu} which is defined as the mean time to return a failed unit of item i at location u to a serviceable condition. M_{iu} is given by:

$$M_{iu} = D_{iu} + T_{iu}$$

where

D_{iu} = expected delay per demand upon inventory for item i at location u

T_{iu} = mean time to repair item i at user location u (for on-equipment repair)

D_{iu} in turn is given by:

$$D_{iu} = 1 / \lambda_{iu} \sum_{x \geq S_{iu}} (x - S_{iu})\, P(x : \lambda_{iu} T_{iu})$$

where

S_{iu} = stock level of item i at location u

λ_{iu} = expected number of demands upon inventory for item i at location u

$P(x : \lambda_{iu} T_{iu})$ = probability of x units of stock reduction for item i at location u

T_{iu} = mean resupply time (time to replace an inventory loss) for item i at location u

T_{iu} is given by:

$$T_{iu} = r_{iu}(L_{iu} + L'_{iu}) + (1 - r_{iu})(R_{iu} + R'_{iu})$$

where

r_{iu} = probability that a demand for item i upon inventory at location u results in a loss (discard or sent elsewhere to repair) which must be replaced through resupply

L_{iu} = average resupply leadtime assuming stock is available at the resupply source

L'_{iu} = additional resupply leadtime due to expected shortage at the resupply source

R_{iu} = average shop repair cycle assuming availability of spares for items within i at the next lower indenture level

R'_{iu} = additional shop repair cycle due to expected shortages of spares for items within i at the next lower indenture level

Since, ACIM assumes that MTBF and MTTR are independent of the stockage policy, minimizing D_{iu} is assumed to maximize A_{eu} (operational availability of a equipment at location u).

e. Solution

Assume that initial values for S_{iu} are given for all items and locations. These may all be zero or some minimum value given by policy or current assets. Then, compute the MSRTs of all items.

The next step is the application of the subproblem. The subproblem will be applied recursively to reach the optimal solution. That is, ACIM calculates, for each item, what the new MSRT would be if one additional unit of stock were placed against that particular item. Subtracting the new MSRT from the old MSRT and then dividing by unit cost of the item provides the model with a value which is multiplied by the item's demand to determine a selection-rank. After the selection number is calculated for each item, one unit of stock is added to the candidate with the highest selection rank number. The operational availability (A_0) is calculated and if the target A_0 has not been achieved, the model continues the same procedure.

Because, the ACIM problem is hierarchically related both in terms of parts and locations, the problem solution is initiated for item i at the bottom of the parts hierarchy and the location s at the top of the support system.

C. SUMMARY

Through out Section B of this chapter, we have reviewed the various inventory models and theories for repairable items which are currently in use in the military services or in the process of being evaluated. All the assumptions and the mathematical formulations of the models were stated and discussed. Due to the differences in the situations which deal with assumptions on the various inventory factors such as the demand process, the lead time, the objectives, the system description and operating policies, it is very difficult to decide which model is most appropriate.

IV. THE DEVELOPMENT OF THE NEW REPAIRABLE MODEL FOR THE KOREAN AIR FORCE

A. INTRODUCTION

In Chapter II, we summarized the system and the process of repairables management within the Korean Air Force. The general structure of the repairables management of the Korean Air Force is very similar to those assumed by the models described in Chapter III.

The purpose of Chapter III was to review the inventory models most widely used in practice to provide a basis for determining which model, if any, would be the most appropriate for use in the Korean Air Force. Comparisons of the various inventory models introduced in Chapter III and the existing Korean Air Force repairables model should give reasonable guidelines in determining what changes should be made in the Korean Air Force repairables management policy.

B. ANALYSIS OF THE INVENTORY FACTORS

1. Maintenance/Supply System Structure

The maintenance supply systems (hereafter 'systems') which were described by the models in Chapter III are mainly multi-echelon, multi-item systems with two echelons. Dyna-METRIC and ACIM deal with the problem of multiple echelons which can be extended to more than two levels. The METRIC family explicitly deals with two echelons, and the NPS model makes stockage decisions only for the wholesale (depot) echelon while considering those stockage levels provided by other models at the retail (ship, base) level. As shown in the Chapter II, the repairables management system of the Korean Air Force is a two echelon system which is composed of the DMM (the depot level ICP) and the subordinate air bases. Thus, the systems described by all of the models of Chapter III would be relevant for the Korean Air Force. Also, the objective of the Korean Air Force is to distribute the spares among the DMM and the bases in order to achieve the best effectiveness in terms of the whole system subject to budget constraints.

2. The Measure of Effectiveness

The following measures of effectiveness are all reasonable candidates for the focus of repairable item inventory models for the Korean Air Force.

a. *Fill Rate*

Fill rate is computed by taking the total number of units demanded at a base over a fixed period of time and dividing that number into the total number of units issued at the time they were are demanded. Thus, it is the percentage of demands that are immediately filled. In the US Navy, this is called SMA (System Material Availability).

b. *Time Weighted Units Short (TWUS)*

A backorder is defined as a stockout of one unit of stock from base supply. The total TWUS is determined by taking each backorder that is established during the course of a period of time, observing how many days it takes to satisfy the backorders, and adding up all these numbers.

The TWUS measure has an advantage over fill rate as a measure of performance, since it takes into account both the number of backorders and the length of time the backorders exist. To take an extreme example, a supply system with zero fill rate will still be very good if each backorder lasts only a couple of minutes. In this case, the fill rate gives a very poor indication of performance.

c. *Operational Rate*

Operational rate is the probability that, at any given point in time, there will be no stockouts from base supply (backorders). Operational rate is computed by counting up the length of time (in days) that no backorders existed and dividing this numbers by 365. This gives us the percentage of time during the year that no backorders were in existence.

Operational rate has an advantage over both the fill rate and backorders in that it may be directly related to the supply system's effect on operations. However, it has a disadvantage over both the fill rate and the average backorders in that it has a rather bothersome all-or-nothing character.

d. *Mean Supply Response Time*

Mean Supply Response Time is the mean time it takes for the supply system to respond to the demand for a replacement part or component. It is obtained by taking each stockout that is established during the course of a period of time, observing how many days it takes to satisfy the backorders, adding up all these numbers and dividing the sum by the total number of demands during that period. It is the average TWUS.

MSRT is important by itself as an indicator of the success of the supply system in meeting response time goals. As a measure, it considers both the likelihood of satisfying demands from stock on hand and the length of the delay in satisfying demands when the system runs out of stock.

e. The Average Number of NORS Aircrafts

NORS stands for "not operationally ready because of supply". The average number of NORS aircraft is computed by counting for each aircraft the number of NORS days during the course of a year, adding these numbers up for each aircraft, and finally dividing by 365. Considering that the purpose of a spare parts supply system for the Korean Air Force is to maintain the operational readiness of aircraft, the average number of NORS aircraft would certainly seem to be a reasonable measure of effectiveness. However, it has a critical disadvantage in its mathematical complexity. A stockage model attempting to optimize with respect to a NORS measure would require more restrictive assumptions than those optimizing with respect to the fill rate, the average backorders, MSRT, or the operational rate. Above all, its lack of "separability" is a cause of major mathematical problems.

Something to note is that the operational sector of the Korean Air Force has consistently suggested that the Korean Air Force supply system should be managed in operational terms, not by supply terms. That is, their imminent question has been " How many spares are needed to provide an operational readiness of x percent of the aircraft?" When we look at the problem in this context, NORS seems to be the best measure of effectiveness. However, early in 1969, Sherbrooke considered NORS as the measure of effectiveness when he developed the METRIC model. He employed actual data from the USAF's F-111 aircraft and determined that the solution given by METRIC resulted in an expected number of NORS aircraft which differed by only one percent from the allocation which was optimal with respect to the NORS measure.

Thus, a model which optimizes with respect to MSRT or TWUS would probably provide near optimal allocations with respect to other measures such as NORS or fill rate.

3. **Demand Process**

The demand processes of the models described in Chapter III are all stationary except for Dyna-METRIC. For peacetime support, it is probably reasonable to assume stationary demands since it is likely that changes over time in the demand process occur slowly. An assumption of a dynamic demand process would be reasonable for the case of the deployment of a new system or the phasing out of an old system. However, this is not the case for the Korean Air Force. Although we have excluded the non-stationary demand process, we still have to deal with the problem of the stochastic process associated with the demand pattern since enough is not known about the process which generates demands for items carried by an inventory system to be able to predict with certainty the time pattern of demands. In general, the best that can be done is to describe the demand in probabilistic terms.

The distributions most widely used for repairable items are the compound Poisson and the simple Poisson.

a. Poisson Demand

The Poisson distribution had been adopted in the Mod-METRIC model to describe the demand process during the resupply time. There is much empirical and theoretical support for the use of the Poisson process to describe demands for the typical repairable item. Furthermore, the Poisson assumption leads to reasonably straightforward computations. One of the key properties of the Poisson process which is exploited strongly in all of the METRIC models, the ACIM model, and the NPS model is the result due to Palm which says that one need only know the mean resupply time (i.e., the probability distribution is not required) in order to compute the distribution of the total number of units in resupply.

Let s be the spare stock for an item where demands are Poisson with rate λ and resupply time is an arbitrary probability distribution $\psi(t)$ with mean T. In the backorder case, the steady state probabilities of x units in resupply are given by the Poisson with rate λT, i.e.,

$$h(x) = \text{steady state probability that } x \text{ units are in resupply}$$

$$= (\lambda T)^x e^{-\lambda T} \quad x!, \quad 0 < x < \infty$$

Of note is that the number of units in resupply in the steady state is also Poisson for any kind of distribution for the resupply time. The distribution depends on the mean of the resupply distribution, not on the resupply distribution itself.

b. Compound Poisson Demand

The Poisson distribution is generalized to the compound Poisson distribution in the METRIC or ACIM model. In the compound Poisson demand process, there are batches of demands rather than single demands. But the distribution of time intervals is identical to that of the simple Poisson process. That is, the compound Poisson demand process is a process in which customers are generated according to a Poisson process and each customer demands an amount which has an independent discrete distribution. Figure 4.1 explicitly shows the difference between the simple Poisson process and the compound Poisson process.

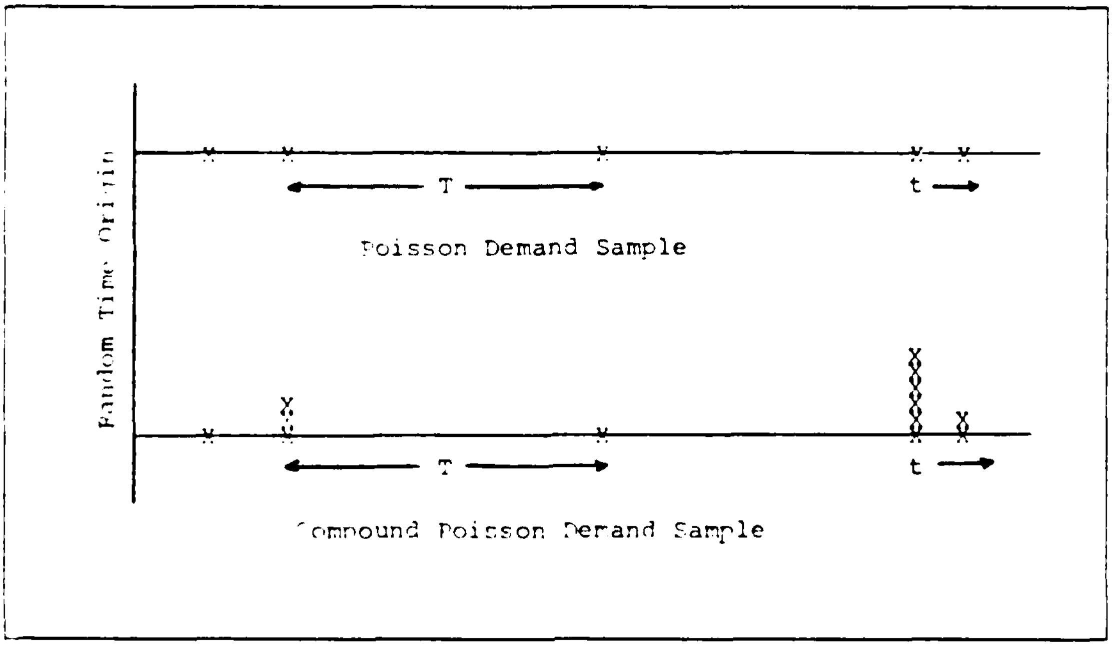

Figure 4.1 The Poisson Demand and Compound Poisson Demand.

The key to the computation in METRIC and ACIM is again Palm's Theorem extended to the compound Poisson distribution.

Let s be the spare stock for an item where demands are compound Poisson with customer arrival rate λ and the resupply time is an arbitrary distribution $\psi(t)$ with the mean T. Assume that when a customer is accepted, a resupply time is drawn from $\psi(t)$ that is applicable to all demands placed by that customer. In the backorder case, the steady state probabilities of x units in resupply are given by the compound Poisson with the rate λT, i.e.,

$$h(x) = p(x \mid \lambda T), \quad 0 < x < \infty$$

$p(x \mid \lambda)$ is given by:

$$p(x \mid \lambda) = \sum (\lambda^{y} e^{-\lambda} / y!) \, f^{y,x}, \quad 0 < x < \infty$$

where

x = the number of demands
y = the number of customers
$f^{y,x}$ = the probability that y customers demand the total of x units of an item

The Poisson distribution seems to provide a good approximation of the real world in the case of the repairable items. All of the models of Chapter III use the Poisson distribution or compound Poisson distribution except for the Navy's UICP model. The UICP model uses the Poisson, the negative binomial, or the normal depending on the frequency of demand and on the value of the items. As discussed in Chapter II, the Korean Air Force model which is presumably a cost minimization model, does neither specify nor adopt any kind of stochastic approach in dealing with their problem.

4. Repair Assumption

All the models introduced in Chapter III assumed implicitly the existence of adequate repair resources. The NPS model, however, does accommodate a constrained repair capacity through its ability to handle the batching of items for repair. As discussed in Chapter II, however, the Korean Air Force has been experiencing capacity constraints in their repair facility. This is why they categorize the repairables into MRS and MRRL.

The assumption of adequate repair capacity would tend to lead one to underestimate the number of carcasses in the depot repair cycle and the repair throughput times. This, in turn, will cause the model to underestimate backorders, TWUS, or MSRT or to overestimate operational availability.

5. Consideration of the Indenture Level

In the METRIC model, a backorder on a module and a backorder for an engine are assumed to be equally undesirable. Muckstadt, however, recognized that the backorders of a module and those of an engine affect the system in different ways. This is obviously correct since a backorder for a module only delays the repair of an engine, but a backorder for an engine results in an aircraft which is incapable of performing the mission.

Thus, it would be desirable to have a model which considers the hierarchical relations between components and the parent items in the model selected for the Korean Air Force.

6. Constraints

The budget available for investment in spares is either a constraint in all of the models or the objective is to achieved specified performance at the minimum budget. The essence of any inventory control problem is the trade-off between cost and system performance. As mentioned in the beginning of Chapter II, the budget constraint is also the major resource constraint for the Korean Air Force.

7. Condemnation

Although an item may be considered to be repairable, there certainly is a fraction of the items for which repair may not be possible or economical. Those items must be condemned. In Chapter II, it was revealed that the absence of complete consideration for condemnation is one of the drawbacks of the Korean Air Force model.

Since attrition can be a major consideration accounting for as much as 10% of all failed items, models lacking the consideration of condemnation are not considered to be viable one for use by the Korean Air Force. The METRIC family of models do not consider attrition.

8. Summary

Table 3 summarizes the aspects of the various models considered in this thesis and relates the characteristics of each model to the needs of the Korean Air Force for managing repairable items. This table provide the basis for our recommendations given below.

TABLE 3
THE COMPARISONS OF THE INVENTORY FACTORS

Desirable features of a model for management of repairable items for the Korean Air Force.	Model						
	KAF	UICP	METRIC	Mod-METRIC	NPS	ACIM	Dyna-METRIC
1. Random demands, failures.	0	X	X	X	X	X	X
2. Random repair times, procurement times, transportation times.	0	X	X	X	X	X	X
3. Two echelon system.	X	0	X	X	L	X	X
4. Attrition allowed.	L	X	0	0	X	0	X
5. Optimize with respect to an operational measure of effectiveness or a service level.	0	0	X	X	X	X	X
6. Allow for budget constraints.	0	L	X	X	X	X	X
7. Allow for repair capacity constraints.	L	0	0	0	L	0	X
8. Be computationally feasible for a system managing thousands of items.	X	X	0	0	X	0	0
9. Link the repair and procurement decision.	0	0	X	X	X	X	X
10. Multi-indenture levels allowed.	0	0	0	X	0	X	X

Key : 0 = No Capacity L = Limited Capability X = Provide Full Capability

C. SUGGESTION FOR THE KOREAN AIR FORCE REPAIRABLES MANAGEMENT

The investment in repairables takes up a substantial portion of the Korean Air Force stock fund. Also, the management of the repairables has a direct influence on the operational readiness of aircraft.

The models in Chapter III give us guidelines on how the problems can be solved through the mathematical modeling of the real world system. But each of them has a different purpose or specializes in a problem which the others concentrate on less. However, the analysis of the models which has been done in this chapter enables us to determine which model can best fit into the Korean Air Force system for the management of the repairables even though it may not pertain to the exact situation which faces the Korean Air Force.

As the results of the analysis, the possible model for the Korean Air Force would be the one which has the assumption of the compound Poisson demand, or simple Poisson demand and which uses the time weighted units short or MSRT as the measure of effectiveness. The candidates are METRIC, Mod-METRIC, and the NPS model. Each of these models considered the budget constraint.

The METRIC models consider stockage decisions at two echelons (the base and depot) ; the NPS model focuses only on the stockage decisions of the depot but does consider the base stock levels in making the depot decision. The Korean Air Force repairables management system is a two-echelon system. However, as in the case of the U.S. Navy, activities at the lower echelon (the airbase) prefer to determine their own stockage levels independently of the rest of the system. These stockage decisions are presently made heuristically based on the experience of inventory managers and the levels are a function of the desired readiness of the aircraft squadrons and on the available resources. Thus, a model like the NPS model which accounts for the stockage levels at the lower echelons in determining the stockage level at the depot and which focuses on a measure like MSRT would be appropriate for the Korean Air Force. The METRIC family of models pays a heavy price for the multi-echelon solution capability. That price is the computational burden. For a large number of items such as the thousands of repairables managed by the Korean Air Force, the METRIC models would impose serious computational problems. The computational burden is even more serious when one considers the multi-indenture level situation addressed in Mod-METRIC.

Finally, it is important that the model used by the Korean Air Force allow for attrition since attrition accounts for a significant fraction of all of the failures of items. Taking into consideration all of the factors discussed above, the authors believe that a model like the NPS model be adopted for use by the Korean Air Force. It captures most of the essential features of the Korean Air Force repairables management system - random demands, random leadtimes, attrition, two levels of supply, a measure of effectiveness that is operationally oriented, and a constraint on the budget. Furthermore, it is computationally feasible, even for thousands of items. It would, however, require the use of some other model to determine base stock levels, and it does not accommodate multiple indenture levels.

V. SUMMARY AND CONCLUSION

In Chapter II, we gave a brief overview of the Korean Air Force repairables management system. The functions and relations of the organizations such as the DMM, DME and DST was described. The model used for the management of the repairables was discussed. The shortcomings of the mathematical model were identified.

In Chapter III, various theoretical inventory models were analyzed in terms of the system concept, assumptions and the mathematical formulations of the models. It was noticed that each model has a unique aspect which differentiates it from the others. Also, it was found that the maintenance supply system descriptions of each model were similar to that of the Korean Air Force. Thus, in Chapter IV, the demand process assumptions and the measure of effectiveness of the models were analyzed so that their relevance to the Korean Air Force could be identified. Other factors such as the type of the constraints or the considerations of the indenture levels were also considered.

As the final part of this research, the authors suggest that the best candidate for the inventory model which is to be implemented for the Korean Air Force should be the NPS model. This is the result of the analysis on the various inventory models based on the major factors of the inventory models and on their relevance to the Korean Air Force.

Finally, the authors admit that there are still several shortcomings in the NPS model in describing the Korean Air Force problem. The NPS model ignores multiple indenture levels ; it does not determine base stock levels ; and it makes no attempt to optimize the actual repair process or to explicitly consider constraints in the repair process. We suggest that the additional research be done to eliminate these shortcomings in the NPS model with regard to its application to the repairables management system of the Korean Air Force.

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