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INITIAL PROVISIONING OF SECONDARY ITEMS--
A RECOMMENDATION FOR THE NORWEGIAN NAVY

by

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Initial Provisioning of Secondary Items--
A Recommendation for the Norwegian Navy

by

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Submitted in partial fulfillment of the
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ABSTRACT

Initial provisioning of secondary spare parts is an important process of the acquisition of a weapon system. It has a direct and powerful impact on system effectiveness and on future inventory costs. This thesis presents and analyzes existing models for secondary item provisioning and makes a recommendation for provisioning policies in the Norwegian Navy. The mean supply response time model is found to be the most appropriate model both for provisioning as well as for replenishments at periodic reviews. The model will also serve as a valuable tool in the budgeting process as it relates budget levels and their respective performance levels.

TABLE OF CONTENTS

I. INTRODUCTION

A. BACKGROUND

Provisioning can be defined as a management process related to the acquisition of logistic support items necessary to operate and support an end item through an initial period of service. This process includes the determination of the initial period to be covered, the development of a provisioning budget and determination of range and depth of spares to be procured. The term logistic support items refers in this thesis to secondary items only; i.e., spare and repair parts needed to maintain the availability of an end item.

The initial spare part determination has a direct and powerful impact on the effectiveness of a system--often for several years. If too few spares are procured, the system's readiness will suffer. If too many are procured the money needed for other investments is wasted. Spare part inventories constitute a huge amount of tied-up capital, much of which can be traced to the provisioning phase. Thus the initial spares investment from provisioning has a considerable economic impact on future inventory costs.

The initial spares procurement is a risky investment due to large uncertainties in predicting the spares requirements of a new weapon system. In determining these requirements one has to deal with uncertain reliabilities, maintenance concepts and deployment plans and, perhaps, changing configurations. And the more uncertainty there is in these factors, the more risky will be the provisioning buy with respect to under-and over-stocking.

Figure 1 illustrates the provisioning process after the provisioning budget is determined.

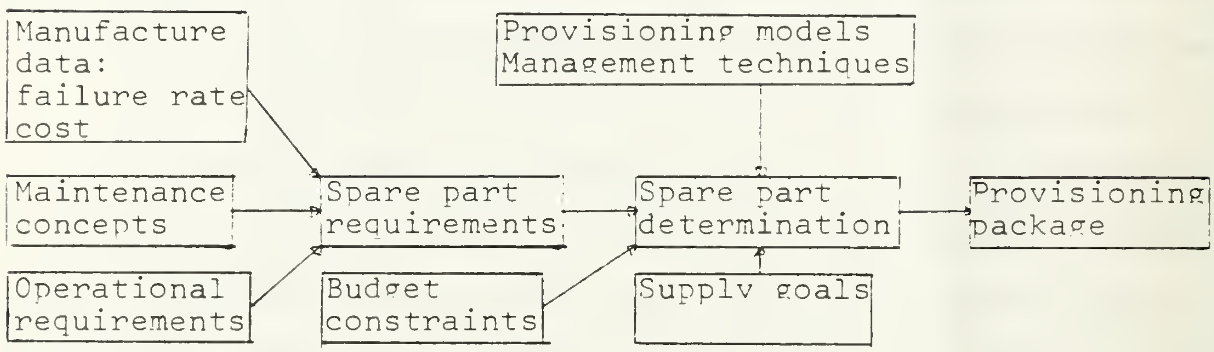

Figure 1. The Provisioning Process

The Norwegian Navy has no written policy on provisioning of secondary items. Provisioning is done manually; best judgment is applied to a contractor's proposed spare part list. However, increasing budget constraints in recent years have emphasized the need for revising existing procedures in spare part management of which the provisioning process is an important element. In the past whenever budget constraints were severe, spare part lists were always reduced in depth, not in range. This resulted in a supply system that was "nervous" for active items, but "fat" for slow or non-moving items. The latter represent as much as 75% of stocked items at the wholesale level. The large percentage of non-moving items suggest that the range of items stocked is much greater than necessary in spite of the fact that some of these are insurance items.

B. OBJECTIVE

The objective of this thesis is to present and analyze existing models for secondary item provisioning, particularly The United States Navy's models, in order to make recommendations that can serve as a basis for provisioning policies in the Norwegian Navy. This will be accomplished by:

- introducing performance criteria for a supply system;
- discussing ways that the provisioning budget can be determined;
- analyzing the provisioning interval of protection and the interface with the replenishment model;
- presenting models for spare part determination at the retail and wholesale level.

The calculations of war reserve requirements; i.e., requirements beyond the peacetime operations requirement, are not covered in the thesis.

C. STRUCTURE

The structure of this thesis is as follows:

Chapter II--introduces the reader to the cost-effectiveness concept applied to a supply system and alternative performance criteria.

Chapter III--presents the major aspects to be considered when grouping items for provisioning purposes.

Chapter IV--presents two methods of determing the provisioning budget.

Chapter V--presents three wholesale level models; the MSRT model currently being implemented in the U.S. Navy, the Gross Effectiveness model and the OPUS VII model, a multi-echelon model.

Chapter VI--presents three models for determining the retail level stockage; a fixed, a variable protection level and an optimization model.

Chapter VII--analyzes alternatives such as phased provisioning and supplier support.

Chapter VIII--summarizes the thesis and makes recommendations for the Norwegian Navy.

II. SUPPLY PERFORMANCE

A. INTRODUCTION

The objective of the provisioning process is to allocate the determined provisioning budget between different items in order to get the best value for the money. This allocation lends itself to a cost-effectiveness analysis where an objective function is optimized subject to one or more constraints. For the allocation problem, the objective function will be some performance criterion and the constraint will be the provisioning budget. The optimization problem can then be formulated as:

$$\text{maximize (minimize)} \quad \sum_{i=1}^{n} g_i(s_i) \; ;$$

$$\text{subject to} \quad \sum_{i=1}^{n} c_i s_i \leq B \; ;$$

where:

- $g_i(s_i)$ is the performance level for item i when s_i spares are stocked;
- $c_i s_i$ is the cost of purchasing s_i units of item i; and
- B is the provisioning budget available.

This optimization problem will only be appropriate if the performance of a system is the sum of the performances of all its components; i.e., the contributions from the individual items are assumed to be additive. Although this assumption of separability may not be valid in some cases, the assumption is a necessary simplification to make the problem solvable by marginal analysis or dynamic programming.

This chapter will discuss several reasonable criteria that exist for measuring the performance of a supply system.

B. UNITS SHORT

This criterion measures the number of units short over the protection interval. It considers the probability of being short of a spare when one is demanded. The goal in using this criterion would be to minimize the total expected number of units short over all the items. However, there are some drawbacks to this goal. It does not reflect the seriousness of a stockout. It also prefers a high demand and low cost item over a low demand, high cost item. For instance, suppose that a certain item costs $1 and has an expected demand of 5000 units per year and another costs $5000 with an expected demand of 1 unit per year. The goal of minimizing units short will result in investment of $5000 in the $1 item to avoid being short of 5000 units rather than invest in the $5000 item and thus avoid being 1 unit short. The discrimination against high value items can be somewhat compensated for by essentiality weighting the items as described in Chapter III.

Lastly, the criterion does not reflect the time aspect; i.e., how much time must pass before the backordered demand will be satisfied. This time is considered important by the users as it can seriously affect the availability of a weapon system. In order to compensate for the time aspect one could weight the units short by the amount of time the shortages exist; i.e., the longer an item is expected to be backordered the greater the weight it gets. This suggests that another performance criterion could be formulated which seeks to minimize essentiality-weighted time-weighted units short. That criterion will be considered in Section E.

C. ANNUAL TOTAL VARIABLE INVENTORY COSTS

This criterion includes the ordering costs, the holding costs and the stockout costs per item. The goal would be to minimize the sum of the expected annual values of these costs. While the first two costs can be quantified, the shortage cost is very difficult to estimate. The shortage or stockout cost attempts to represent the expected ineffectiveness of a shortage in terms of monetary value. The difficulties in establishing proper values for the stockout costs render this criterion unattractive.

D. OPERATIONAL AVAILABILITY

Operational availability is defined as the probability that a system will operate satisfactorily when called upon at any point in time and when used under stated conditions.

The operational availability formula as stated in Reference 1 is:

$$A_o = \frac{MTBF}{MTBF + MTTR + MSRT},$$

where:

MTBF is the mean time between failures requiring corrective maintenance;

MTTR is the mean time to reapir these failures; and

MSRT is the mean supply response time.

Maximizing availability for a system would be the most appropriate goal from a user's point of view. However, the true availability is almost impossible to calculate. To make the criterion workable one has to make a set of assumptions that will render the criterion less accurate. The main assumption is that operational availability can be expressed by the formula above. This is a simplification since availability of a system is a function of the operational use, the availabilities of the system's components and the system configuration [Ref. 1]. One would also have to assume that the failure of one component is independent of the failures of other components, and one would have to assume a probability distribution for the time between failures and for replacement times (usually taken to be exponential). As a consequence, the computation of operational availability could be rather inaccurate. Finally, difficulties in obtaining values for

MTBF and MTTR makes it undesirable to implement in the Norwegian Navy.

E. MEAN SUPPLY RESPONSE TIME

The mean supply response time (MSRT) is an important element of the operative availability formula. The MSRT represents the expected value of the time the customer has to wait for a spare; i.e., the expected time it takes to fill a requisition. Figure 2 shows an example from the U.S. Navy [Ref. 2] for calculating the MSRT, considering three supply levels.

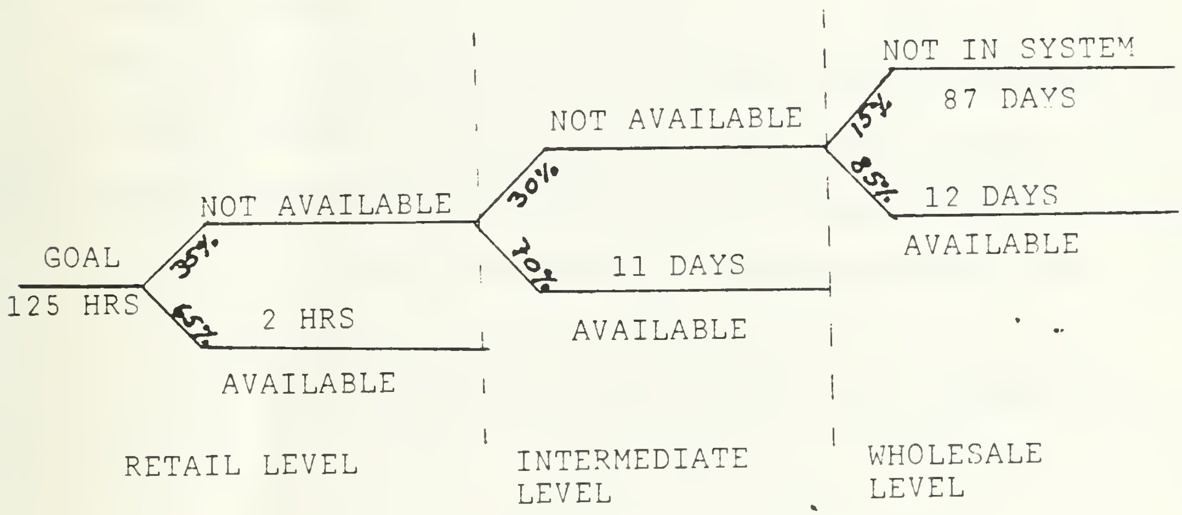

Figure 2. MSRT, An Example

At the point in time in a system's life cycle when the provisioning phase takes place, the design and thereby the

MTBF and MTTR are more or less fixed. This leaves the MSRT the only element that remains as a variable. Depending on how many spares are to be stocked and where, the A_o value will vary. Thus MSRT provides the main linkage between supply effectiveness and system availability. The goal would be to minimize MSRT.

This criterion will favor the high demand-low value items, but as with the units-short criterion, this can be compensated by weighting the items by essentiality.

F. GROSS EFFECTIVENESS OR FILL RATE

Gross effectiveness (GE) or fill rate can be defined as the ratio of immediately satisfied (filled) demands to the total number of demands measured over a representative time period. The goal would be to maximize GE. The fill rate can be applied to single items as well as all spares as a group, and the total demand can be stated as:

$$\text{Total demand} = \text{filled demand} + \text{unfilled demand},$$

or

$$\text{Total units satisfied} = \text{total demand} - \text{units short}.$$

The fill rate is calculated as:

$$\text{Fill rate} = 100 \times \frac{\text{filled demand}}{\text{total demand}}.$$

It is clear that maximizing fill rate or GE is equivalent to minimizing the units-short criterion. Gross effectiveness would seem to be more meaningful both from an operational point of view because it provides a description on how well the supply system is functioning.

A performance criterion closely related to GE is the supply material availability (SMA) which measures the filled demand to the number of demands for stocked items. The GE seems, however, more representative as a measure of supply performance as it also considers items where a no-stock decision has been made.

G. SUMMARY

In selecting a performance criterion for determining spare parts initial range and depth, one should select the one which best reflects the supply system's goals. It should also be as meaningful as possible to the operational side. For the Norwegian Navy the most appropriate criteria seems to be mean supply response time and gross effectiveness since they consider the impact of units-short, can easily be extended to consider military essentiality and do not require extensive data beyond that already available from the existing ADP system. Chapter V will show examples using these criteria.

Chapter III will discuss several ways of grouping items as used in this thesis to make the performance criteria workable for real world applications.

III. GROUPING OF ITEMS

An inventory system normally carries a variety of items which differs in relative importance, cost, demand, procurement lead time, size, etc. Some of the differences are important to identify in order to allocate the provisioning budget effectively. This chapter will discuss four ways of grouping items which will be used later in this thesis.

A. MILITARY ESSENTIALITY

The ranking of items with respect to their relative military essentiality is important for improving readiness. However, military essentiality is difficult to quantify since one has to establish a ranking order for the different functions based on the importance of the various operational tasks. In establishing the ranking order one should consider:

- the effect that an item's failures will have on the operation of its parent component;
- the effect of a failure of the parent component on its parent system; and
- the effect of a failure in the system on the mission capabilities of the weapon system.

For both the component and the system one would have to consider the existing alternatives and redundancies. An essentiality ranking system can be made simple, e.g., two categories: essential or non-essential, or it can be made more complex by use of a matrix as described below. The complexity of military systems should indicate that a simple ranking system will not suffice. The U.S. Navy has realized this and has established a new system as a first step toward quantifying military essentiality.

First an item's essentiality for the operation of its component will have to be established; i.e., whether the item is vital or non-vital. The U.S. Navy also uses a code for items affecting personnel safety. Secondly, the component's/system's impact on the mission capabilities can be categorized by a mission criticality code as described in Reference 2 and presented below in Table 1. The item essentiality code and the mission criticality code are then combined to reach the item's mission essentiality code (IMEC), which can be defined as:

4--Loss of a primary mission capability,

3--Severe degradation of a primary mission capability,

2--Loss of a secondary mission capability,

1--Loss of a minor mission capability.

The IMEC is the same as the mission criticality codes for the vital items. For non-vital items the IMEC is 1 regardless of mission criticality code. The fact that items can have different essentialities in different configurations can be resolved by selecting the highest item mission essentiality code of the item over all configurations. The IMEC can then be multiplied by a factor to compensate for different weighting

TABLE 1

Mission Criticality Codes [Ref. 2]

Impact if all alternatives fail:	Alternatives for mission accomplishment:		
	Redundant systems/ equipments available	Alternatives (excluding redundancies) available	Neither redundancies nor other alternatives available
Total loss of mobility, propulsion or life support	3	4	4
Severe degradation of mobility or total loss of a primary mission	2	3	4
Severe degradation of a primary mission	1	2	3
Total loss or severe degradation of a secondary mission	1	1	2
No mission impact	1	1	1

of missions. This factor will have to be determined by the operational community.

The Norwegian Navy consists mainly of small combatant units with limited capacity to carry spare parts. It is therefore a question of whether the IMEC system provides adequate discrimination of items for use in provisioning at the retail level in the Norwegian Navy. On the other hand, greater discrimination will make implementation more difficult and expensive. Determination of a military essentiality code system for the Norwegian Navy should therefore be based on a heuristic approach where the effect on the applied provisioning and replenishment models is analyzed. The U.S. Navy has a heuristic method shown below that may be useful; i.e., mission criticality codes may be based on maintenance history or Casualty Report history [Ref. 2].

As indicated under the discussion of performance criteria, an essentiality weight should be applied to avoid focusing on the high-demand-low-cost items rather than those items which are essential from a military point of view. However, implementing essentiality codes is expected to be expensive and time consuming. It is therefore recommended that one start the implementation on the most important weapon systems as well as all new systems being introduced.

B. MAINTENANCE CODING

For provisioning purposes there will also be a need for a maintenance coding of the items, indicating whether an item can be replaced by a ship's crew. This information is vital when allocating spares at the retail level. This code would have to be separate from the IMEC as the latter also will be used when provisioning at the wholesale level.

C. DEMAND

1. Demand Categories

Items differ greatly in demand frequency. Generally speaking, one can divide items into two groups: demand-based and non-demand-based (non-moving items). Figure 3 shows the percentages of demand/non-demand items of the wholesale inventory for the Norwegian Navy [Ref. 13] where the non-movers represent items without demand during the last five years, slow-movers < 20 demands per year and fast-movers $\geq$ 20 demands per year. Based on this figure it is clear that different

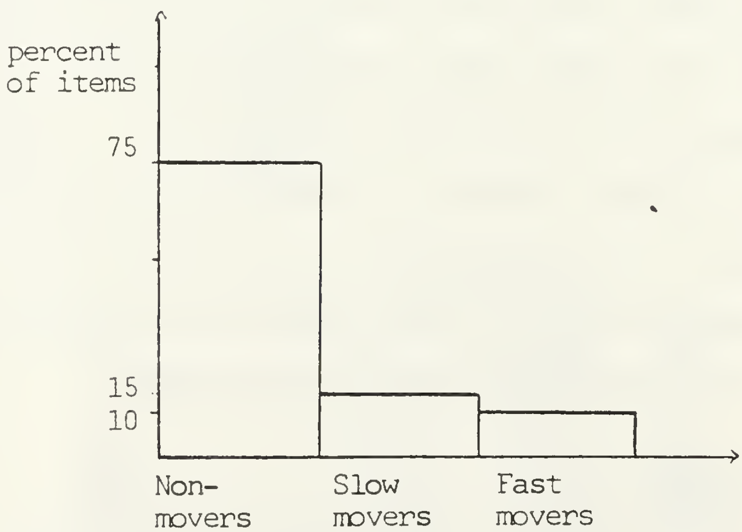

Figure 3. The Percentages of Demand/Non-Demand-Based Items of the Wholesale Inventory in the Norwegian Navy

attention should be given the two groups during the provisioning as well as during the replenishment phase.

Demand-based items are items with anticipated recurring demand. All other items can be defined as non-demand based items or insurance items. Insurance items are items with no realistic prediction of demand but if there is a failure or loss, the lack of a replacement item will seriously reduce the primary mission capability of a weapon system.

2. Demand Forecasting

Estimation of the total number of failures and thus the demand for a new item is the first step in the process of assessing the number of spares needed during a given provisioning protection interval. The estimation of an item's failure rate and consequently its spare part consumption is normally based on input from the manufacturer who describes the reliability characteristics of each individual item, and a proposed maintenance program from the user who describes the missions or operations. The technical data from the manufacturer includes the predicted unscheduled and scheduled replacement rates for each item. The failure rate is calculated through reliability tests and predictions. With the assumption of exponential lifetime the relationship between the reliability and the failure rate of an item is given by

$$R(t) = \exp(-\lambda t) ,$$

where:

$R(t)$ = reliability (i.e., the probability that a system will perform in a satisfactory manner for t units of time when used under specified conditions [Ref. 1]; and

λ = failure rate.

The failure rate of one item is normally assumed to be statistically independent of failures of other items.

The exponential lifetime assumption is equivalent to an assumption of a constant failure rate. It is, however, common in new weapon systems to observe failure rates over time which take the famous bathtub shape shown in Figure 4 [Ref. 3]. Figure 4 shows that there frequently are three different phases in a system's life cycle. The wear-in period is characterized by a higher than predicted failure rate. This is due to several factors:

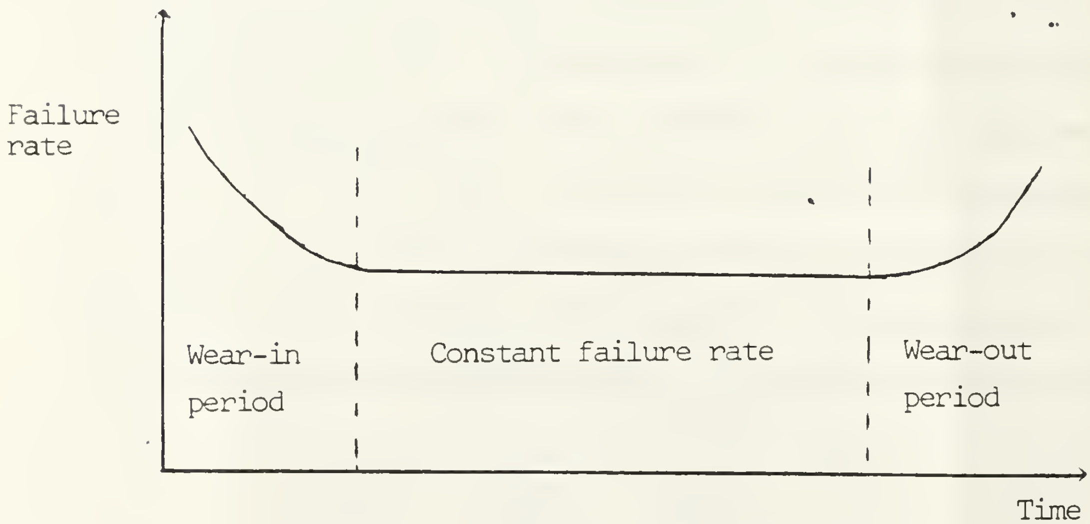

Figure 4. A Typical Failure Rate (Bathtub) Curve

a) The system as delivered from the manufacturer, suffers from component variations and mismatches, etc., which have to be debugged during the initial use period.

b) The operator and maintenance personnel are not yet familiar with the equipment, thereby inducing faults to the system.

c) The logistic support is not yet fully provided at all echelons. This may be true for large and complex systems.

In the next period in the system's life the failure rate is constant. This could be the result of the original item settling down to a constant failure rate and/or the modification process designed to improve the original failure rate. This is the failure rate that is usually stated by the manufacturer. Likewise provisioning models usually assume this constant failure rate.

This assumption of a constant failure rate may result in an insufficient number of spare parts. On the other hand, the process of trying to define and quantify the factors which lead to a higher failure rate during the wear-in period would be very difficult if possible at all. Although perhaps not "correct," the constant failure rate assumption will result in less expensive answers than the other states.

In the wear-out period the failure rate increases due to technical wear because the component/system is reaching the end of its designed life cycle. Although military components/systems often find themselves in this state due to extension of the life time horizon, it is not important to be concerned with this portion of the failure rate curve for the provisioning problem.

The constant failure rate assumption has shown to be valid for many electronic systems. However, even if that assumption is not generally valid for other systems, it seems to be a necessary simplification for forecasting demand when no experience data are available.

The program data supplied by the user/customer includes the maintenance and operating schedule which both have impact on the spares demand. The maintenance schedule specifies when maintenance is to be undertaken and shows when spares are planned to be replaced. The maintenance schedule is based on the maintenance steps detailed by the manufacturer. The operational data states the number of operating hours per time period, normally a year (this is the value of t in the reliability formula). The expected demand for spares will therefore be a linear function of the number of operating hours.

The initial estimate of the demand rate per installed part per year is called the technical replacement factor (TRF) by the U.S. Department of Defense [Ref. 4]. After gaining some demand history for an item the TRF is replaced by the best replacement factor (BRF) which is based on the number of units actually used per item per year. Its value is computed using the following formula:

$$\text{BRF} = \frac{\text{Parts used/demanded per year}}{\text{Installed parts population}} .$$

A method for making the transition from basing the demand entirely on the TRF to entirely on the BRF is suggested by Reference 2.

New BRF = a(new average rate of demand) + (1-a)TRF ;

where the a is varied from 0 to 1 by increments of 0.25 every six months. Thus after two years the BRF is entirely based on demand experience. For large differences between the initial TRF and the BRF, it would be appropriate to increase the "a" factor quicker so that the experience data is reflected in the BRF sooner.

In demand forecasting, as in the other calculations, the quality of the input data has direct impact on the quality of the output data. The impact of erroneous estimation of the failure rate can be illustrated by the following example. Given that demand for a spare follows a Poisson distribution with an expected demand rate of 10 per year (BRF = 0.005, annual operating hours = 2000) and a required protection level of 90%, the BRF is first varied to show its impact on spares calculation.

% change in BRF:	-50	-25	-10	0	+10	+25	+50
Expected demand:	5	7.5	9	10	11	12.5	15
# of spares to achieve 90% prot.:	8	11	13	14	15	17	20

The example shows that if the actual failure rate is 25% higher than expected, 17 spares are needed to achieve 90%

protection. However, since 14 spares are stocked only 72.5% protection is achieved; i.e., the demand is under-estimated by about 21%. Using the same data but varying the number of operating hours shows a similar effect.

% change in operating hrs.:	-50	0	+50	+100
Expected demand:	5	10	15	20
# spares to achieve 90% protection:	8	14	20	26

The number of spares to achieve 90% protection is not linear with respect to operating hours. When operating hours doubles the expected demand, the number of spares needed increases less than proportionally.

J. Ferrier showed several examples in Reference 6, extracted from different NATO countries, that the original estimate of demand far exceeded the observed demand. The authors of Reference 4 also believed this to be true and therefore recommended the number of months of a program used in demand forecasting (called the Program Time Base) should be a function of total dollar value. For example, high value items should have a Program Time Base of 3 months.

To keep track of the accuracy of the initial estimate (TRF) as well as the BRF development, a demand history file is needed that will have to be created for the Norwegian Navy. This file will prove to be a useful tool in provisioning of a new system. Because estimation of the demand is the keystone on which the provisioning process is based, careful attention should be paid to the quality of the estimate.

D. COST

Item cost is a major factor in managing inventories. Cost categories are suggested by the ABC curve [Ref. 9]. Figure 5 illustrates the typical relationship that about 20% of the items managed account for about 80% of total value.

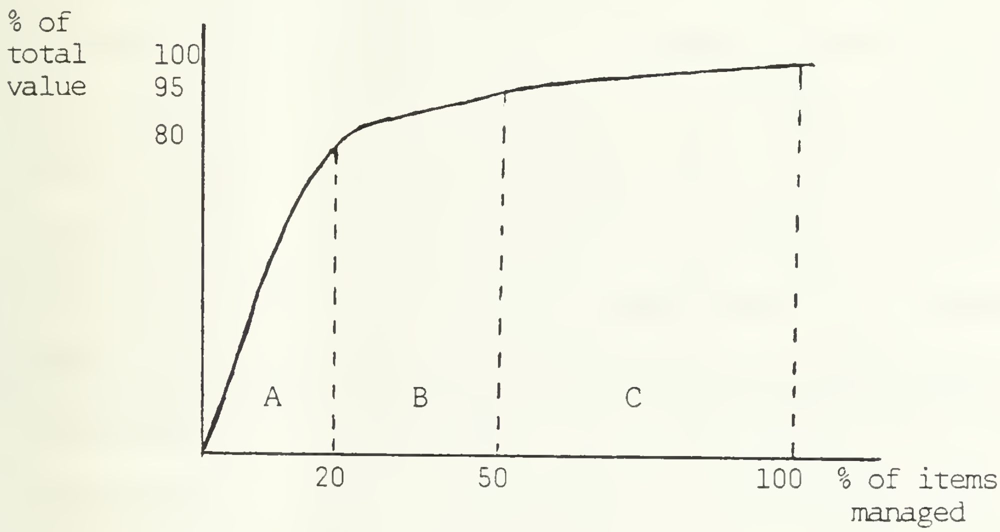

Figure 5. A Typical ABC Curve

Typically repairables have high cost and low demand and constitute the major part of the inventory investment while for consumables the opposite is true. Also, inventory costs are associated directly with inventory value. This should imply that one has to pay more attention to the selection of repairables. This is done by the U.S. Navy where repairables and consumables are separated in developing and allocating the provisioning budget.

IV. CREATING A PROVISIONING BUDGET

How large should the "optimal" provisioning budget be and how can it be justified? The initial budget estimate is typically made from experience with similar system's acquisitions at the time of program inception. In the U.S. Navy this is considered to be about 10% of hardware costs.

It is important to emphasize that the provisioning budget is usually determined well in advance of actual procurement of the spares. At this time there is generally much uncertainty around specific item estimates of unit prices and failure rates. These uncertainties diminish towards the time of provisioning the spares because more knowledge about the items is obtained. Based on this new data, new spares requirements are calculated and their total value could differ significantly from the previously determined budget. This could result in a more constrained provisioning budget than originally planned. The budget methodology should therefore provice both a cost-effective mix of spares as well as the least difference between the initial budget value and funds required based on later computations.

The most appealing approach is to specify a goal for the selected performance criterion, and then determine the minimum cost for achieving this goal for all demand-based items during the provisioning interval. As an optimization problem this can be stated as similar to the optimization problem in Chapter II, Section A; namely,

$$\text{minimize} \quad \sum_{i=1}^{n} c_i s_i \; ;$$

$$\text{subject to} \quad \sum_{i=1}^{n} g_i(s_i) \;\leq\; (\text{or} \geq)\; G \; ;$$

where G is the minimum acceptable level of system performance.

To solve the problem one can either calculate the solution to the problem for various different budget levels by marginal analysis or dynamic programming as will be shown in Chapter V and choose the smallest budget which satisfies the goal, or use a Lagrange multiplier approach, which can be stated as:

$$\text{minimize } F(S,\theta) \;=\; \sum_{i=1}^{n} c_i s_i + \theta\left(\sum_{i=1}^{n} g_i(s_i) - G\right) \; ;$$

where θ is the Lagrange multiplier representing the change to be obtained in the budget by an increase (decrease) in the value of the goal [Ref. 12]. Through iterations using a search technique such as bisection search [Ref. 8] the value of θ is determined so that $\sum_{i=1}^{n} g_i(s_i)$ approaches G.

To assure that items with very low demand but high mission criticality are stocked, minimum threshold quantities should be established (e.g., have a minimum of one spare for items with IMEC 3 or 4). The comparable depths for insurance items and the necessary spare quantities for the retail level must then be added to arrive at the total provisioning budget.

Applying the grouping considerations from Chapter III, the provisioning budget could be generated in three portions; one for repairables, one for consumables and one for insurance items as is done in the U.S. Navy. This would provide a more desirable result when essentiality codes are not available. As a tool for justifying a provisioning budget the approach of determining the minimum costs for a desired performance goal seems logical. This way the budget is more easily defended as changes in budget level can be directly related to expected performance. Cost-effectiveness curves may prove useful in conveying this relationship (see Chapter V).

Before leaving this chapter, it is of interest to note that the unit cost can be subject to a high degree of uncertainty at the time of the provisioning budget development. According to Reference 3, understating the unit cost to varying degrees is a general phenomenon. But applying too low a unit cost will result in a very conservative budget. This, together with a provisioning policy that constrains the provisioning quantities from fear of over-procurement, could produce a severe budget constraint. Chapter V will discuss the unit cost sensitivity of an optimization model.

V. WHOLESALE LEVEL MODELS

A. BACKGROUND

Operational availability requirements starting from POC tend to drive one in the direction of buying a large quantity of spares early. However, this can lead to a high penalty cost of provisioning the wrong spares due to uncertain input data. The provisioning process therefore faces the problem of minimizing spares investment while providing an adequate support for the end items. This chapter will cover three different optimization models:

- the mean supply response (MSRT) model;
- the gross effectiveness (GE) model;
- the OPUS VII model, a multi-echelon model;

for allocating the provisioning budget at the wholesale level, i.e., the provisioning budget left over after the allocation on the retail level is done. By wholesale level in this thesis is meant the inventory held by the Norwegian Naval Material Command to support its geographical area and the national level. The MSRT and the GE models are presented as they both represent a meaningful effectiveness criterion and can be easily implemented since they do not require extensive input data. The latter part seems important for a small navy that has limited resources of manpower and funds. The OPUS VII model is a multi-echelon model that allocates a provisioning package to various support levels using various performance criteria. The OPUS VII is used by the Swedish Air Force.

Wholesale level insurance items and possible minimum thresholds of very low demand items with high IMECs should be selected manually and out of a separate portion of the budget. Insurance items have, by definition, no expected demand. A stock or no stock decision will therefore have considerable impact on a system's life cycle costs. This can be shown by a simple example: an investment in insurance items of $1 million will, after 20 years (a normal life horizon for a military system) and 21% interest rate, have a future value of $45.3 million assuming no demand and ignoring phase out costs. The interest rate in the example is equal to the holding cost for repairables used in the U.S. Navy.

The vast majority of items, the demand based, can be selected according to an optimization provisioning model. In the U.S. Navy such models are for use among items new in the supply system. For existing items the decision may be to increase the reorder point (ROP) from POC for a new system, or to let the replenishment model catch up with the increase in demand. If the demand for an item is expected to increase substantially and/or the current inventory level is insufficient to meet the non-recurring demand of retail outfittings, a procurement will be necessary to avoid backorders. For new items the selected performance criterion and its desired level along with the available budget can be used to determine the range and depth of spares. Figure 6 shows a typical relationship between spares investment and achieved performance in which the theory of diminishing returns is apparent. As more money is spent on spares provisioning, less additional performance is achieved per dollar invested.

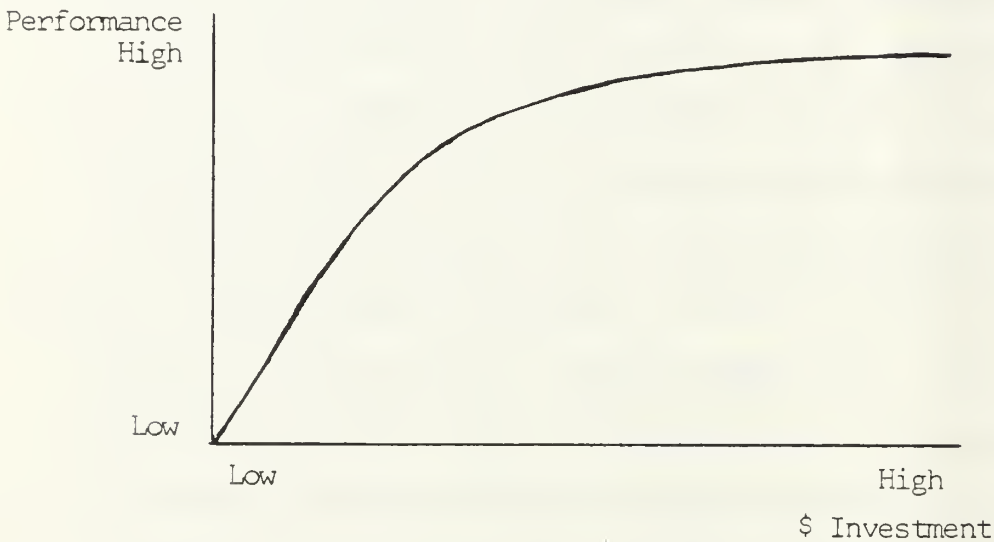

Figure 6. A Typical Cost-effectiveness Curve

The use of cost effectiveness curves provides a tool for a decision maker to determine what level of investment is optimal for his program; e.g., at what point does the diminishing return rate become so high that it is not profitable to add additional depth.

B. THE MEAN SUPPLY RESPONSE TIME MODEL

The mean supply response time (MSRT) model developed in Reference 5 considers the expected shortages over the provisioning interval and the length of time that each shortage exists. The model expresses how long one will have to wait until the next buy will be received. The model assumes that demand is satisfied immediately if spares are available, otherwise the demand is backordered and satisfied when the first replenishment buy arrives. Figure 7 illustrates how the time-weighted units short are calculated for an item. The area beneath the time axis expresses the penalty function for being short which is identical to the time each backorder lasts.

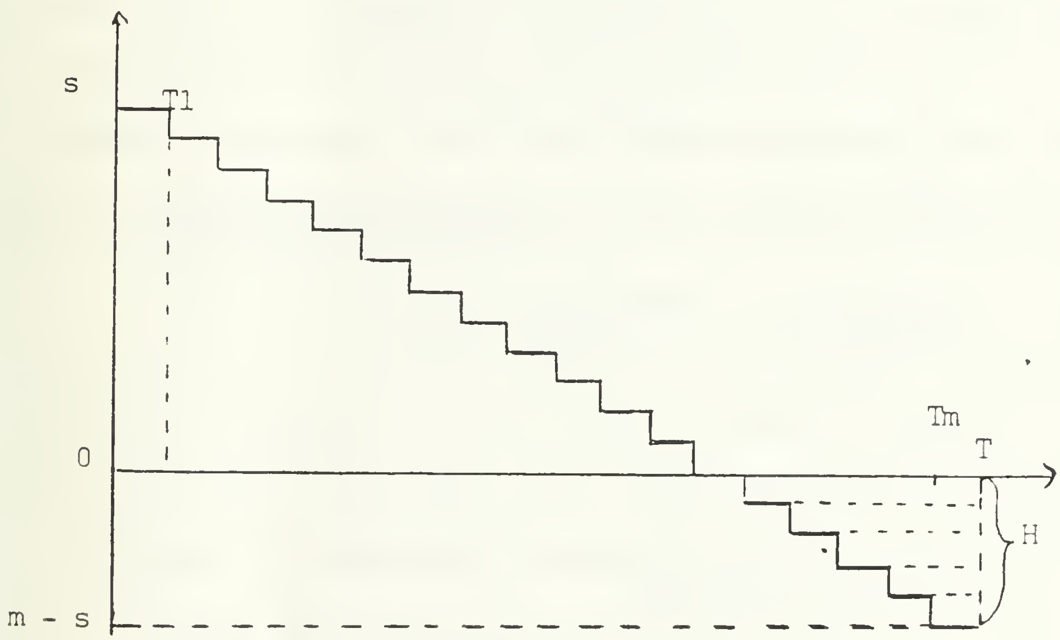

Figure 7. Net Inventory Over Time

A penalty occurs when the demand (m) is greater than or equal to the number of stocked spares (s) plus one. T in the figure represents the end of the provisioning interval (when the first replenishment buy is received). The sum of the expected time-weighted units short (TWUS) can be stated by the formula (Ref. 5],

$$E(TWUS) = \sum_{m=s+1}^{\infty} \frac{T(m-s)(m+1-s)}{2(m+1)} \times \frac{(\lambda T)^m e^{-\lambda T}}{m!} .$$

The formula uses the standard Poisson distribution since only one spare is assumed demanded at a time.

The TWUS can be used as a model for allocating the provisioning budget, but the MSRT model seems more meaningful operationally and will therefore be emphasized. Dividing E(TWUS) by the expected demand during the provisioning interval yields that portion of MSRT due to the shortages. Total MSRT as a function of the number of spares is given by

$$MSRT_i(s_i) = \frac{E(TWUS)_i}{\lambda_i T_i} + k_i ;$$

where:

- $\lambda_i T_i$ is the expected demand during the provisioning interval T_i; and
- k_i is a time factor that expresses the delay in satisfying a demand when there are units still in stock.

In the following examples this factor is assumed zero. The MSRT for all items in a provisioning package is then calculated as:

$$MSRT = \frac{\sum_{i=1}^{n} (\lambda_i T_i) MSRT_i(s_i)}{\sum_{i=1}^{n} \lambda_i T_i} .$$

Essentiality weighting may also be necessary to prevent the low cost, high demand items from crowding out the high cost, low demand items. This can easily be done by replacing $\lambda_i T_i$ by $E_i \lambda_i T_i$ in the formulas above. The total MSRT for the provisioning package would then be:

$$MSRT = \frac{\sum_{i=1}^{n} (E_i \lambda_i T_i) MSRT_i(s_i)}{\sum_{i=1}^{n} E_i \lambda_i T_i} .$$

1. Solution Procedures

The goal in using this model is to minimize this MSRT subject to a constraint on the procurement budget. Two solution procedures are practical. Marginal analysis is a decision-making procedure that can be used on a problem if it is a sum of separable functions. In this case the ratio for a given item is

$$\frac{MSRT_i(s_i+1) - MSRT_i(s_i)}{c_i} .$$

The steps are:

a) Set all $s_i = 0$.

b) Compute the ratio for an item.

c) Compute the ratio for the next item and compare.

d) The current winning ratio is compared with the ratios of the other items until the minimum ratio is found.

e) For the winning item, s_i is increased by one unit. If the sum of $c_i s_i$ of the winning item(s) is less than the budget or performance constraint, the procedure is repeated from step c. If the constraint is breached, the procedure concentrates on those items with unit costs $\leq$ the remaining budget.

The marginal analysis will not guarantee optimal results, but for use in large provisioning packages it is very efficient and comes very close to the optimal solution. "How close" can also be computed [Ref. 11].

This solution procedure can terminate with a remaining budget larger than the unit costs of some of the items. This can be avoided by selecting the next highest ratio that does not breach the budget limit each time that a constraint "breaching" occurs. Although this may not create an optimal solution, it will use up more of the budget and increase the overall performance of the provisioning package.

The second solution procedure is dynamic programming which uses a multi-stage approach by dividing the problem into subproblems or stages with the number of stages corresponding to the number of items being considered. The problem is then solved "backwards" from the last stage when determining the best decision. Dynamic programming will guarantee the optimal solution, but requires large amounts of storage space and long running times when solved on a computer. In the following example only marginal analysis will be applied.

2. A Comparison

Since the Norwegian Navy currently utilizes no model or prescribed technique for wholesale provisioning, a comparison with the MSRT model is not possible. A fixed protection level model (90% protection) is selected as an example of illustrating the possible gains from applying an optimization technique. Table 2 illustrates the difference in achieved performance between the models using a budget level that would provide the 90% protection level for all items. The table is based on the following assumptions:

- demand is expected demand over the provisioning interval;
- the provisioning interval is set equal to 12 months;
- essentiality codes are set to 1 for all items.

As expected, the MSRT optimization model will yield the highest MSRT of any proposed model for a given budget. The table shows quite a large improvement in performance by the MSRT model; from 3.04 to 1.97 days which represents a 35.4% improvement. For the MSRT model the allocation was stopped when the next item to be included would breach the budget. If the budget left over is allocated among the items (with the highest ratios) whose unit costs do not breach the budget, the performance level of the MSRT model would be reduced to 1.8 days. This final value represents a 40.8% improvement in performance as compared to the fixed protection

TABLE 2

Performance of Two Provisioning Models
For A Hypothetical Example System

			NUMBER OF SPARES STOCKED:	
ITEM #	DEMAND	COST ($)	MSRT	90% FIXED PROTECTION LEVEL
1	2.358	23.66	7	4
2	0.786	7.25	5	2
3	0.786	23.66	5	2
4	0.393	4.25	4	1
5	3.191	96.75	6	6
6	0.393	7.25	3	1
7	3.930	2.28	11	7
8	3.930	78.42	7	7
9	4.716	238.20	6	8
10	0.786	3230.20	2	2
11	1.960	1432.70	2	4
12	0.462	250.00	3	1
13	3.678	77.35	7	6
14	1.619	154.70	4	3
15	3.238	111.70	6	6
16	1.619	154.70	4	3
17	0.462	500.00	3	1
18	0.786	83.20	4	2
19	3.191	98.70	6	6
20	3.238	154.70	6	6
21	0.854	243.09	3	2
22	1.572	6.25	7	3
23	3.238	154.70	6	6
24	7.860	0.81	17	12
25	7.860	2.89	15	12
MSRT in days			1.97	3.04
Budget $21,386.75				
Budget left:			$807.77	0

level model. The table also shows that the MSRT model has a tendency to emphasize the low cost fast moving items when essentiality weighting is not used.

Using the data in Table 2 one can develop a series of MSRT values for a series of budget values and then plot a cost effectiveness curve as shown in Figure 8. This curve emphasizes the opportunities for making trade-offs between optimal MSRT values and investment levels.

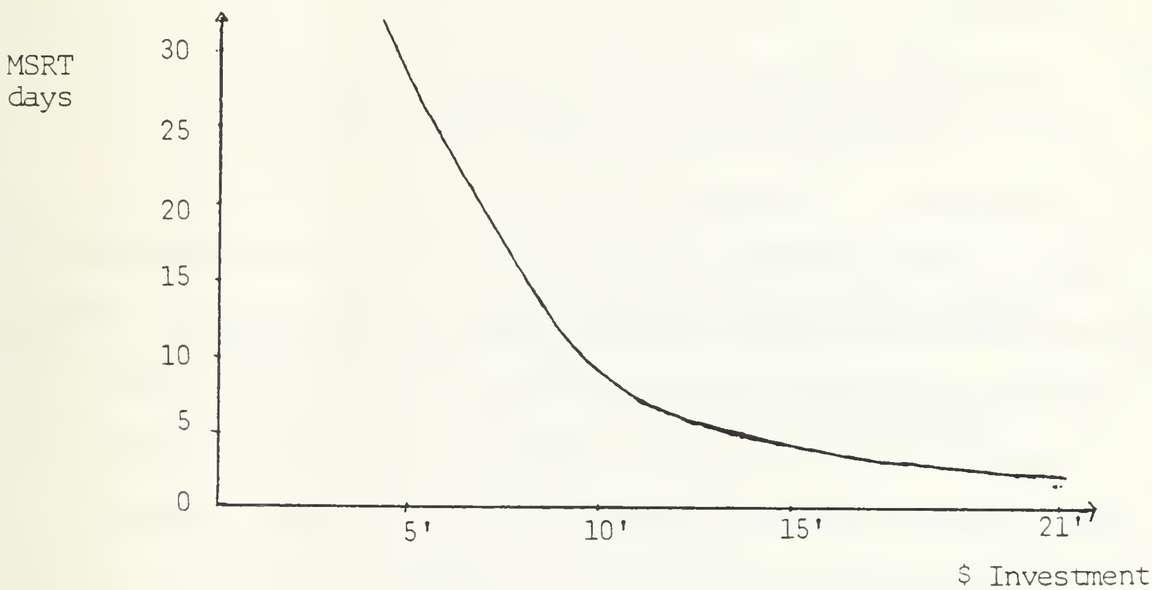

Figure 8. A Cost Effectiveness Curve for the MSRT Model for the Example Data

3. Constraints

The allocations in Table 2 using the MSRT model did not consider any constraints on the minimum depth of stocking. In order to obtain minimum protection levels, minimum thresholds can be set. For example, setting this depth equal to the median demand during the provisioning interval would assure a protection level of 50%. For the MSRT model this requires that the levels of several items be increased causing decreases in several others. This results in an increase in the total MSRT for the provisioning package from 8 to 18.2 days, a 127.5% increase at a provisioning budget of $10,694 (the constraint would not be active at the budget level in Table 2).

A constraint on the lower bound of the MSRT may be also necessary; e.g., suppose MSRT < 0.01 days may be appropriate. Although this constraint might not be active in most cases, it can help prevent undesirable results such as the procurement of large quantities of low cost items. This lower bound constraint could be set higher for selected expensive items if a lower safety level was acceptable.

If these various constraints are active the result will be higher MSRT values than would be provided by the unconstrained MSRT model. However, they may prove necessary for real world implementation of the model.

4. Sensitivity Analysis

An important factor in considering a provisioning model is its ability to deal with unreliable engineering and supply data that is available at the time of provisioning. Figure 9 illustrates the effect of changing the failure rate (BRF) on all items in Table 2. A budget level of $10,000 is used.

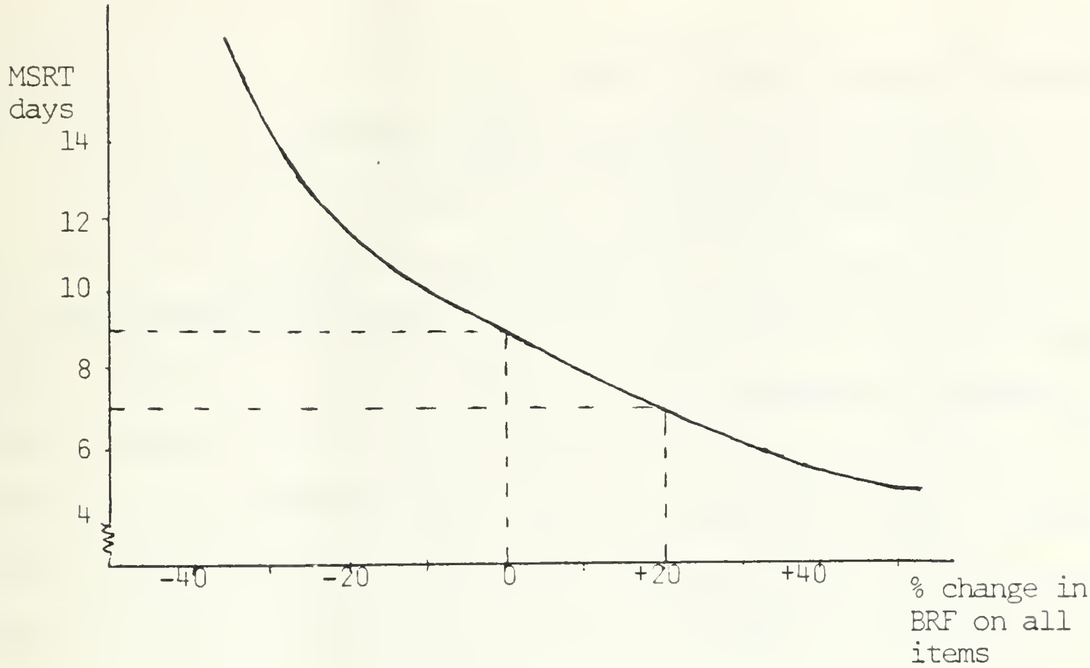

Figure 9. The Effect of Changing BRF on the Optimal MSRT Value for the Example Data

The figure indicates that if all the failure rates in this example proved to have been 20% optimistic, this would result in a 27% increase in MSRT. From this point the MSRT increases rapidly as the failure rates are increased.

The MSRT model will be more sensitive to unit cost changes than a non-optimization model since it considers unit cost to be a major factor in the determination of the most cost effective spare part mix. Due to the marginal analysis technique, a cost increase of an item will result in less spares stocked of that item, and conversely. Reference 14 shows that when the provisioning budget is determined by an optimization model, unit cost changes will have less impact on the budget level than if a non-optimization model was used.

C. THE GROSS EFFECTIVENESS MODEL

The gross effectiveness model (GE) minimizes units short over the provisioning interval. It considers the ratio of expected filled demand to total expected demand; i.e., the fill rate of all items demanded. The expected filled demand E(F) can be described as:

$$E(F) = \text{Expected Demand} - \text{Expected Backorders}$$

$$= \lambda_i T_i - E(BO_i)$$

Dividing by expected demand yields the GE per item:

$$GE = 1 - E(BO_i)/\lambda_i T_i$$

The total number of backorders in a cycle is graphically shown in Figure 7 as the height H. Since backorders first occur when m > s, the $E(BO_i)$ can be stated as

$$E(BO_i) = \sum_{m=s+1}^{\infty} (m_i - s_i) p_i(m_i) \ ,$$

where:

$p_i(m_i)$ represents the Poisson distribution.

Weighting by essentiality factors gives [Ref. 5]:

$$GE = 1 - \frac{\sum_{i=1}^{n} E_i \sum_{m=s+1}^{\infty} (m_i - s_i) p_i(m_i)}{\sum_{i=1}^{n} E_i \lambda_i T_i} .$$

The last part of the formula is identical to a units short model, but the GE model is emphasized as it seems more meaningful as an operational performance criterion. The solution procedures suggested for maximizing GE are again marginal analysis or dynamic programming. The aggregate GE for the provisioning package is calculated as:

$$GE = \frac{\sum_{i=1}^{n} E_i \lambda_i T_i \times GE_i(s_i)}{\sum_{i=1}^{n} E_i \lambda_i T_i} .$$

The GE model yields the optimal solution when the goal is to maximize GE. It provides substantially better results than a fixed protection level model as shown in Table 3. The same assumptions and data apply as for Table 2. As can be seen in the table, applying the GE model improves the overall performance of the provisioning package from 0.9664 to 0.9878.

The large budget left over is due to the fact that item #10 was the next item to be included in the marginal analysis solution technique. If items with lower unit costs are considered, this will increase the gross effectiveness to

TABLE 3

Performance of Two Provisioning Models
For A Hypothetical Example System

NUMBER OF SPARES STOCKED:

ITEM #	DEMAND	COST ($)	GE	90 FIXED PROTECTION LEVEL
1	2.358	23.66	7	4
2	0.786	7.25	5	2
3	0.786	23.66	4	2
4	0.393	4.25	4	1
5	3.191	96.75	7	6
6	0.393	7.25	4	1
7	3.930	2.28	12	7
8	3.930	78.42	8	7
9	4.716	238.20	8	8
10	0.786	3230.20	1	2
11	1.960	1432.70	3	4
12	0.462	250.00	3	1
13	3.678	77.35	8	6
14	1.619	154.70	5	3
15	3.238	111.70	7	6
16	1.619	154.70	5	3
17	0.462	500.00	2	1
18	0.786	83.20	4	2
19	3.191	98.70	7	6
20	3.238	154.70	7	6
21	0.854	243.09	3	2
22	1.572	6.25	7	3
23	3.238	154.70	7	6
24	7.860	0.81	19	12
25	7.860	2.89	17	12
Gross Effectiveness			0.9878	0.9664
Budget	$21,386.75			
Budget left			$1642.49	0

0.9906. Both the GE model and the MSRT model emphasize the low-cost high-demand items.

The computation of GE in Table 3 does not include any constraints on depth. A minimum requirement for GE for individual items will result in a reduction in the aggregate GE for a provisioning package. In addition a per item upper bound on GE of 0.9999 would be reasonable to prevent serious "over-stocking" of items. The unconstrained model results also provide information about the least cost combination of spares to attain any level of gross effectiveness (or protection against stockouts). As with the MSRT model, the desired level of performance and/or the appropriate investment can be determined from analyses of curves similar to Figures 8 and 9.

D. THE OPUS VII MODEL

While the previous models have both been single echelon models, the OPUS VII model developed by Systecon AB, Sotckholm, considers an arbitrary number of echelons. The OPUS VII model is one of several models developed for spares provisioning by that same company. The model which is primarily meant for repairables, makes a cost effective evaluation of alternative maintenance and support system configurations and selects the initial spares mix and its allocation within the support organization. OPUS VII offers the user a selection between four performance criteria [Ref. 10] which resemble (although calculated in a different way) those discussed in Chapter II:

- Probability of successful mission performance;
- System operational availability;
- Mean waiting time for a spare (= MSRT);
- Risk of a shortage of a spare, when it is needed. The expected number of units short criterion is not offered.

Instead of applying the piece-part point of view, this model structures the end items into:

- systems;
- line replaceable units (LRU);
- shop replaceable units (SRU).

When a system fails at the organizational level a demand for a LRU is generated. LRU are units that are replaced at the organizational level and sent to the intermediate or depot level for repair. A LRU consists of one or more SRU's which are sent from the intermediate to the depot level for repair. This way of structuring the items makes it possible to take into account the impact of being short an SRU on an end item. The support organization must be structured in a hierarchal way; i.e., every unit at the organizational level must be supported by one or more stations at a higher level. The model's minimum requirement is that there exists at least one demand generating station (one unit at the organizational level) and at least one end support station.

The basic assumptions used in the OPUS VII model are [Ref. 10]:

- Demand is Poisson distributed;
- The mean values of turnaround times between the echelons are known;

- A failure of one type of item is statistically independent of that of any other type of item;

- No batching of items for repair;

- Repair times are statistically independent; i.e., no queueing is assumed.

Since an LRU or SRU may be part of several different system types, the model has the capability to handle several systems in one run. To do this requires rather extensive input data as described in Appendix A.

The model provides an allocation of LRU's and SRU's to the specified support elements for a range of investment levels. It then produces a cost effectiveness curve similar to those described above. This is done through an optimization technique that is done in steps according to the number of echelons involved. First, only LRU's are considered for procurement at the depot level. LRU's are selected by a marginal analysis until the budget constraint or performance target is met. Thus, a number of points on the first effectiveness curve is calculated. Second, SRU's for the depot level and LRU's for the intermediate level are considered. Points on cost-effectiveness curve number one are then selected and, for each point the spare candidates are selected by marginal analysis within the given constraints, resulting in a set of new effectiveness curves. The envelope of these curves then becomes effectiveness curve number two. Third, the organizational level is included applying the same procedure as in the second step. This results in the final cost effectiveness curve for the provisioning package. To cope with the uncertainty aspect in input data, the model has the ability to perform sensitivity analysis on the major variables.

Similar to the previously discussed models, the OPUS VII model also yields the best allocation of a procurement budget to an assortment of spares with respect to the assumptions and the selected objective. Although the model has limitations on the number of different LRU's and SRU's which can be handled per run, this can be resolved by making several runs and then matching the results together. The OPUS VII model requires considerably more input data than do the other models; data that is often difficult to obtain at the time of the provisioning buy, and is more complex to use. These limitations seem severe when handling large provisioning packages. However, the OPUS model could serve as a useful tool in the stocking decisions for small provisioning packages to the Norwegian Navy.

E. SUMMARY

Of the models covered above, the model that seems best to meet the Norwegian Navy's needs for wholesale provisioning is the MSRT model since it:

- applies the most operationally meaningful effectiveness criterion;
- explicitly considers the time delay that arises if demand is backordered.
- considers each item's military essentiality;
- does not require extensive input data.

VI. RETAIL LEVEL MODELS

A. BACKGROUND

Retail level inventories are intended to allow the combatant units to operate an entire patrol without any supply support from external source. The goals of retail level inventories can be stated as:

- minimizing the risk of aborting a patrol due to lack of spare parts; and,
- minimizing the expected cost of over-stocking spare parts.

Three different models for determining the range and depth of spare parts will be analyzed in this chapter:

- a fixed protection level;
- a variable protection level;
- the MSRT model.

Before considering the models, the appropriate restrictions will have to be identified. First, the endurance interval or support period has to be specified. This interval will vary according to operational requirement; e.g., 45 days or less when operating in coastal areas. Second, only items for which the crew has the capabilities to remove and replace are to be considered. This creates the requirement for a maintenance coding on all items. And last, the available storage space must be determined. Then having decided upon the interval and possible spares candidates, the range and depth are determined according to some model.

B. FIXED PROTECTION LEVEL

The U.S. Navy uses two fixed protection level models. The FLSIP model [Ref. 2], considers an item having at least one demand per 90 days (corresponding to a 90 days endurance interval); i.e., (BRF annual $\times$ number of parts i)/4 $\geq$ 1, to be a demand based item. The depth is then calculated according to the given protection (fixed) level using the Poisson or the normal distribution; i.e., 90% of all requisitions are expected to be filled. Figure 10 illustrates the protection level concept using the normal distribution. By stocking the expected demand 50% protection is achieved. Fixing the protection level at 90% is the same as saying that 10% or less stockouts or back orders are allowed.

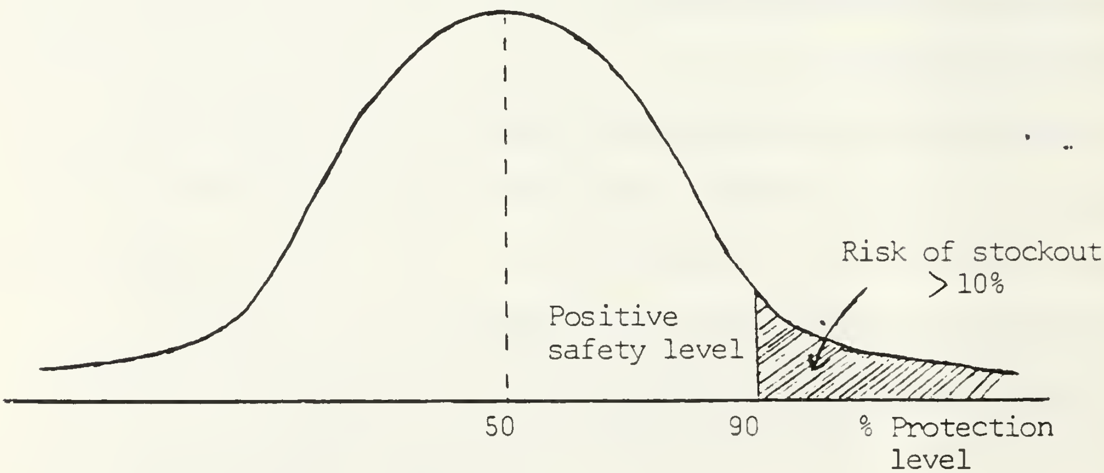

Figure 10. The Protection Level

For items with an expected mean demand of 20 or more for the endurance interval, the normal distribution is used. For fewer expected demands the Poisson distribution is used.

For insurance items or demand based items with very low demand but a high IMEC, a cut-off point with respect to demand within the endurance interval must be decided. The FLSIP model uses quarterly demand > 0.0625 (1 demand in 4 years) as the cut-off point for essential items.

The MODFLSIP model divides the equipment into primary (items with mission criticality coes of 3 or 4) and secondary (MCC 1 and 2). Based on the mean demand over the 90 day period the inventory level is found according to the following rules [Ref. 2]:

Primary item:		Sècondary item:	
Mean quarterly demand	Level	Mean quarterly demand	Level
< 0.025	0	< 0.0625	0
0.025-0.49	1 MRU	0.0625-0.99	1 MRU if MEC = 1 or 5
0.50 -0.99	2 MRU's		
1.0 -19.99	the Poisson distribution (90% protection)		
20.0 ≤	the normal distribution (90% protection)		

In contrast to the FLSIP model, the MODFLSIP supports more of the low demand primary items. Due to all the uncertainties surrounding the provisioning buy, possible large savings could occur by deferring the procurement of the very low or non-demand items until sufficient field data is available.

However, since lack of primary items would cause serious degradation in mission availability, the decision to defer the procurement of primary items at the retail level must be carefully evaluated.

C. VARIABLE PROTECTION LEVEL

While the fixed protection models do not differentiate between the item's essentialities for demand based items, such a distinction can be achieved by a current variable protection model in the U.S. Navy--the Maintenance Criticality Oriented model (MCO) [Ref. 2]. By specifying five maintenance criticality codes (MCC) as shown in Appendix B, the items can be divided into groups according to their essentialities. The protection level can then be specified per essentiality group. The following are typical of the subdivisions [Ref. 8]:

	% of total	Protection level (Probability of satisfying demand)	
MCC	items	min	max
1	(46%)	10.00	50.00
2	(30%)	50.00	84.13
3	(14%)	95.54	99.87
4	(7%)	99.99	99.99
5	(3%)	100.00	100.00

The number of spares is then calculated using the Poisson distribution and the mean demand over a 90 days period. The protection level for MCC 1 is set between 10-50%; i.e., one allows a negative safety level for most of the spares carried. For MCC's 4 and 5 the model has an additional lower bound of one MRU. Although the MCO model uses MCC for grouping the items, military essentiality codes would also be feasible.

A variant of the variable protection level model is the cost category model [Ref. 3]. This model provisions each item to a protection level that depends on the item's unit cost; the higher the unit cost the lower the protection level. The high value items are bought in smaller quantities than the low value items; e.g., items costing < $1000 is provisioned to a protection level of 90%, between $1000 and $5000 to 80% and above $5000 to a 65% protection level. The model is based on the ABC curve concept, and can result in an overall fill rate that is higher for a lower item cost than using the fixed protection level model.

D. THE MEAN SUPPLY RESPONSE TIME MODEL

The MSRT model can also be applied at the retail level. This model would allow the use of essentiality weights and maximum and minimum thresholds (protection levels) for MSRT for each item category. Since MSRT is a part of the operational availability formula, the MSRT model has the advantage of linking the retail inventory to system readiness. It seems also to be a logical approach to utilize the same performance criterion at both the retail and wholesale level, thereby facilitating the measure of overall supply system performance.

In the case where limited storage capacity is the dominating constraint, the range and depth of items can be determined using marginal analysis as was done for the MSRT model described earlier. Now, however, the ranking would be based on the difference in MSRT by stocking one more unit of the item divided by a units cubic measure rather than its unit cost [Ref. 11].

E. A COMPARISON OF THE MODELS

So far the models have not considered the items configuration within a system. How do the retail models solve the problem of items in parallel or series configuration? Figure 11 shows a system with the two items A and B connected in series. Item A has twice the failure factor and costs ten times as much as item B. Due to the higher failure rate,

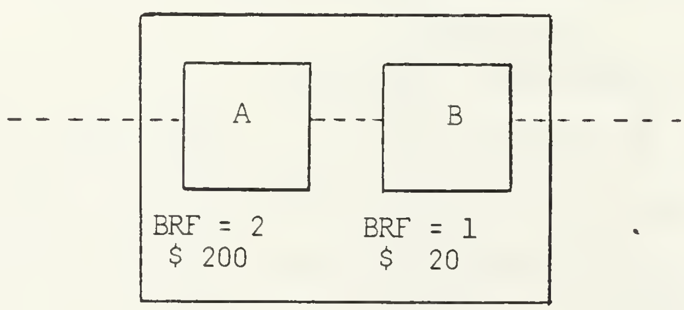

Figure 11. A Series Configuration

a spare of item A is more likely to be stocked than item B by the fixed protection level models. The MSRT model, on the other hand, would select item B first as this is the most cost-effective item to stock. However, any one item will cause the system to go down until it is replaced. This fact is not considered by any of the models.

Figure 12 shows a system where two identical items are connected in parallel resulting in a failure rate that is twice as high as if only one item was used (BRF × Number of identical itesm). The higher the failure rate the higher is the possibility of being spared under the fixed protection level model. A failure of one item, however, will not result

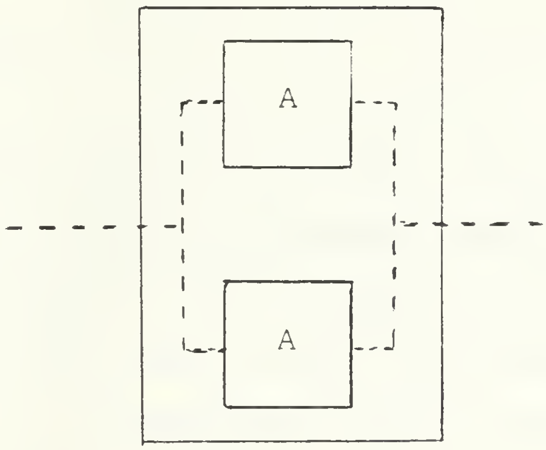

Figure 12. A Parallel Configuration

in a system failure since the other item will still perform the system's functions. Only when both items fail will the system go down. Thus, sparing of redundant items will have less impact on system availability than sparing of non-redundant items. This fact is not considered by the fixed protection level models. By the use of essentiality weighting the MCO model and the MSRT model will reflect the less importance of a redundant item; i.e., a redundant item will have a lower essentiality code.

The effect of variations in unit cost on the provisioning budget will depend on the model used. For the fixed or the variable protection models, an increase or decrease in unit cost will be reflected entirely in the budget requirement since the cost is not considered when determining the spares mix to be provisioned. The MSRT model, on the other hand, considers the unit cost as a major element when determining the most cost effective spares mix. Therefore this model reflects unit cost changes to a less degree in the budget requirement.

Determining the retail level spares requirement in the Norwegian Navy will to some extent be a manual process due to the small sizes of the combatant units. The MSRT model when applied with essentiality codes seems to be the most appropriate of the retail models considered.

VII. THE PROVISIONING INTERVAL

A. DEFINING THE INTERVAL

Provisioning, by definition, provides protection over the initial phase of a system's life cycle. The length of this phase or interval has a major impact on the number of spares to be provisioned and thereby the magnitude of the provisioning budget. The provisioning interval at the wholesale level can be described as in Figure 13:

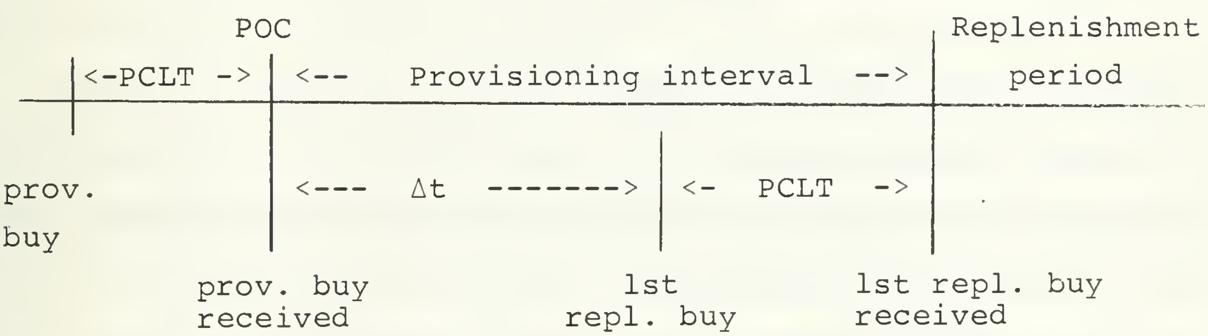

Figure 13. The Provisioning Interval

where:

PCLT = procurement lead time (production lead time + administrative lead time); and

POC = preliminary operational capability; i.e., the point in time where a system is assumed to be fully operational and in need of support from the supply system.

The provisioning interval will depend on when the first replenishment buy is triggered. This will be a function of the associated replenishment model, the size of the provisioning buy and the item's PCLT.

Optimally, the reorder point (continuous review) or the maximum operating level (periodic review) of the replenishment model should have been considered by the provisioning model; i.e., the provisioning quantity should be based upon the reorder point/maximum operating level. This interdependency makes an integration of a provisioning and a replenishment model computationally difficult. As a consequence, no such integrated model is used.

1. The Replenishment Model

The Norwegian Navy is currently using a continuous review model for wholesale replenishment. The model assumes a steady state environment; i.e., the demand rate is assumed constant. But this may not necessarily be true during the demand development period (DDP); the time from POC until sufficient field experience has been obtained for the BRF to be forecasted entirely upon actual demand. The model also assumes that an order is placed when the reorder point is reached. This may, however, not be a valid assumption in a navy where limited resources sometimes make it necessary to defer spare part procurement. If there were not sufficient procurement funds available during the DDP, the continuous model offers no remedy; e.g., if the provisioning budget was insufficient to cover the spare reguirements, this would result in an immediate large procurement requirement at the POC which would go uns

Neither the reorder point nor the procurement quantity are based on the availability of funds, nor does it consider any priority of the items; i.e., the items that reach their reorder point first are recommended for procurement first. When the available funds are exhausted no further procurements can be made until the next allocation of funds is made. As only the demand distribution is assumed known, one does not know when a procurement requirement will arise. Thus, there is little or no economic control. However, an average demand rate can be assumed to get some idea as to when the inventory average will hit the reorder point.

The above deficiencies can be avoided by applying the MSRT model as a periodic review replenishment model. The available spare parts budget can be allocated, for example, every 3 months. This interval will increase the model's responsiveness to changes in demand. By making successive provisioning buys, one achieves:

- a spare part allocation that is cost-effective for the available budget and in accordance with the provisioning buy;
- preference allocation that considers items according to their military essentiality code;
- complete economic control with available funds;
- improved planning of budget and procurement personnel resources.

A major disadvantage is the increased workload for the manager and the procurement department. Applying the MSRT model at periodic reviews might also produce higher total average annual variable costs (= order costs + holding costs + shortage costs) than the continuous review model when that model us used optimally. However, in a severely constrained budget environment that model will also be heavily constrained so that order quantities are reduced or, more importantly, the reorder point is reduced. Any possible cost differences should be evaluated.

2. <u>The First Replenishment Buy</u>

When applying the MSRT model as the periodic review replenishment model, the gain of setting the $\Delta t = 0$ can be shown graphically in Figure 7. If one assumes that the first replenishment buy is made at POC, the buy is received at Tm, while it would be received at T if triggered at Tl by

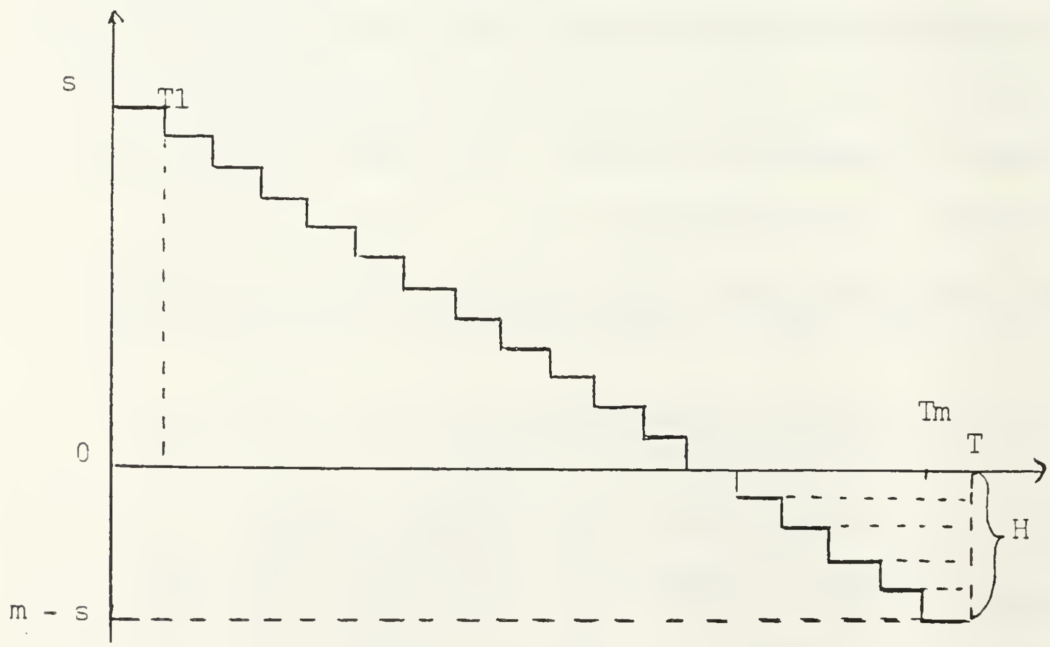

Figure 7. Net Inventory Development

the first demand, assuming that the PCLT is constant. Deferring the first replenishment buy will increase the probability of stock out. The area (T-Tm) × (m-s) represents the increased penalty of being out of stock by deferring the first replenishment buy until the first demand occurs. This penalty will increase as the first procurement buy is delayed, while the only gain to be achieved will be additional demand data. It seems, therefore, reasonable that the replenishment model take over at POC (i.e., $\Delta t = 0$).

3. Summary

It seems appropriate for the Norwegian Navy to consider using the MSRT model with periodic reviews as a replenishment model starting at the POC of a weapon system. This would result in a provisioning interval equal to the PCLT as well as a consistent use of the MSRT performance criterion over a weapon system's life cycle.

B. PHASED PROVISIONING

Phased provisioning can be defined as a deferral of the purchase of all or some of the required spare parts until the later stages of production [Ref. 7]. The deferred quantity is placed in a production buffer stock at the supplier's plant and is available upon requisition with far shorter lead times than normal. The buffer stock will have to be reviewed during the production period. Items with higher usage than anticipated can then be kept in the buffer stock or purchased while items with lower usage than expected can be released to production of the remaining systems. The last review must be undertaken a production lead time before the last system is to be delivered. The buffer stock can consist of parts in any stage of completion--from raw material to finished parts. The quantity of any item should not exceed the number required in production of the remaining systems if the maximum benefit from the phased provisioning is to be achieved.

Phased provisioning reduces the risk of under- or over-provisioning. Under-provisioning can be avoided by increasing production of items in the buffer stock, and over-provisioning can be avoided by deferring the procurement decision until sufficient field data are available, the production design has settled down and the deployment and maintenance plans have been developed. To benefit from phased provisioning a production program must last for some years to allow time to gain experience with the first system(s). The more uncertainties with respect to the provisioning data the more advantageous phased provisioning would be. Items to be included in the buffer stock can be selected using the following criteria [Ref. 7]:

- insurance items;
- items with low demand but high IMEC;
- expensive items (repairables);
- items with long lead times;
- items where the design changes are likely.

Figure 14 shows an example of phased provisioning of 5 systems

```
Date          JAN 86     JAN 88  JUNE 88  JAN 89  JUNE 89
System #        1          2        3        4       5

              POC
   ----------|---R-----R--|---R--|---F--|------|---
   <  PCLT  >|                    |< PCLT >|

Initial                                       order
requirement       R = revision   F = final    arrives
                  of requirement requirement

PCLT = 9 months
```

Figure 14. The Phased Provisioning Concept

The figure shows that the procurement decision of a typical low demand item for this system can be deferred for 2 1/2 years providing 21 months of actual field experience in which to base the procurement.

Phased provisioning is of value where the contractor's estimates of TRFs are not close to observed failure rates and when installation schedules change. The potential savings from the use of phased provisioning will depend on the supplier's holding cost to be charged and the availability of the tiems in the buffer stock. If items are likely to be over-procured due to uncertainties about their characteristics, and more accurate data can be obtained during the production phase, potentially large savings can be realized.

On the other hand, if under-procurement is the case, no saving will be obtained except for shorter lead times. This time gain can be substantial depending on the stage of completion of the items in the buffer stock. The potential savings will depend on how much of the spares requirement is kept in the buffer stock; the larger the buffer stockis, the higher will be the potential savings. In conclusion, Reference 7 shows that the phased provisioning concept has a potential of large savings because it allows one to hedge against uncertainties.

C. ALTERNATIVE APPROACHES

Supplier support is another approach for increasing the provisioning interval while reducing the investment risk [Ref. 7]. The supplier is given the responsibility for all maintenance and spares for a weapon system during a specified period starting from POC. During this period the specific item's characteristics, maintenance actions, deployment, etc., can be observed, thus reducing the risk for under-/over-procurement of spares when the buyer takes over at the end of the supplier's support period. Since the supplier is given the responsibility for all maintenance, supplier support will include all items, not only the expensive ones. The supplier support concept is similar to phased provisioning except from the maintenance part.

Another alternative is to procure spares that are produced concurrently with items to be installed in the end items. By combining spares and production quantities one can achieve lower unit prices due to improved production planning, reduced set up cost per unit and control with the item's configuration. However, no hedge against under-/over-provisioning is obtained which implies that this alternative is best used for items with know requirements and stable design.

D. SUMMARY

The length of the provisioning interval normally is used to decide the size of the provisioning buy. The more time allowed to update the demand data before the first replenishment buy is made, the longer the provisioning interval will be. The risk of over-procurement is reduced by constraining the provisioning interval, or only considering a small segment of it in determining an item's depth. Alternative approaches such as phased provisioning and supplier support can prove particularly useful for a small navy where spare parts are provisioned for mostly small series of weapon systems.

VIII. SUMMARY/RECOMMENDATIONS

A. SUMMARY

This thesis has considered a cost-effective concept of initial spare part provisioning. By analyzing several performance criteria the mean supply response time criterion is recommended to be the most appropriate for the Norwegian Navy for provisioning at the wholesale and retail levels.

In order to implement a model based on this criterion, several ways of grouping items have been presented. The mean supply response time model using marginal analysis is also found to be very useful as a method of determining the provisioning budget. The use of an optimization technique is shown to produce a significantly more cost-effective mix of spare parts than a fixed protection level model while alternative approaches as phased provisioning and supplier support are found to be useful approaches to hedge against over-/under-provisioning of expensive and low demand items.

B. CONCLUSION

The use of an optimization model implies a performance criterion to measure the applicable effectiveness. The criterion that seems most appropriate for the Norwegian Navy is mean supply response time (MSRT). The minimization of this criterion subject to a budget constraint will produce an optimal spares mix at both the wholesale and retail levels that:

- explicitly considers the time delays that arise if demand is backordered;
- considers the item's military essentiality;
- is operationally meaningful;
- is an element of the operational availability formula;
- does not require extensive input data.

The model will require the setting of performance levels (goals) especially when applied at the retail level. It will also require the use of a military essentiality coding scheme in order to focus on the most essential items. At the wholesale level, the MSRT model provides an efficient tool for the budget development process because it can show the relationship between each budget level and its expected performance. Finally the MSRT model can be used with periodic reviews as a replenishment model starting at the time of preliminary operational capabilities of a weapon system.

The provisioning interval, which is an important factor in determining the size of the provisioning buy, should be set equal to the procurement leadtime of an item to reduce the probability of over-procurement. Long production periods, however, offer the potential for phased provisioning and its associated potentially large savings by deferring the provisioning buy of expensive and low or non-demand items.

C. RECOMMENDATIONS

For the Norwegian Navy it is recommended that:

- the mean supply response time model be selected for initial spares provisioning at the wholesale and retail level and that marginal analysis be used as the solution procedure;

- provisioning budgets be based on the use of the MSRT model;
- military essentiality codes be developed for all spares, beginning with essential existing weapon systems and all new systems being introduced.
- the provisioning interval be constrained to only the procurement leadtime with the first replenishment buy being made as soon as possible after the time of preliminary operational capability of a weapon system;
- phased provisioning be applied where applicable;
- the MSRT model with periodic reviews is applied as replenishment model;
- a history file be established for initial forecasting and development of item BRF's.

APPENDIX A

THE OPUS VII MODEL--REQUIRED INPUT DATA

1. SRU--data
   - Number of different types of SRU
   - For each type: failure rates and unit price.

2. LRU--data
   - Number of different types of LRU
   - For each type: failure rates and unit price
   - For each type that is modularized into an SRU: identification of those types of SRU it contains.

3. SYSTEM--data
   - Number of different types of systems
   - For each type: identification of those types of LRU it contains, and the number of units of every such type.

4. DEMAND GENERATING STATIONS (DGS)--data (retail level)
   - A reference to the next higher Support Station (SS)
   - Identification of the different types of systems allocated to the DGS and the number of each. Each system must also be given a specific utilization rate.
   - Fault location time.
   - Time to repair the system by removing and replacing a defective LRU, including subsequent check-out time.

- Time to have a spare unit delivered from the next higher SS, given no shortage exists.

5. SUPPORT STATION--data (intermediate level)
   - A reference to one or several other SS's to which propagated demands are addressed.
   - A discrete propagated demand probability distribution defined on those other SS.
   - Identification of the different types of LRU and/or SRU which may be kept in stock. Each of these types has a specific repair factor which is the proportion of defective units that are to be repaired at this station.
   - Fault isolation time for every type of LRU and SRU.
   - Time for removing and replacing a defective unit including subsequent check-out time.
   - Time to repair a LRU or SRU if repaired at this station.
   - Time to have a spare unit delivered from the next higher SS given that no shortage exists there.

6. END SUPPORT STATION--data (wholesale level)
   - Data as for SS above except that demand is not propagated to any other SS.

APPENDIX B

MAINTENANCE CRITICALITY CODES

Consequence of part failure:

MCC 1 Non-availability of part will have no impact.

MCC 2 Non-availability will have minor impact on a ship's ability to perform any of its missions.

MCC 3 Non-availability impacts the operation of parent equipment and results in loss of the ship's ability to perform one mission.

MCC 4 Non-availability causes loss of more than one mission.

MCC 5 Non-availability causes a safety hazard to the crew.

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