Examining Stock Positions in Military Logistics

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Abstract

Decisions concerning stock positioning, range, and depth are always complex. The problem is further compounded by multi-echelon inventory systems and multi-indenture parts. This research examines the inventory issues involved in such a complex system and presents a decision methodology and assessment that includes demonstrating the use of commercially available software based on the vari-metric algorithmic approach.

Keywords

indentured parts, multi-echelon inventory, readiness, reparable parts, vari-metric

I. Introduction

Inventory control problems present similar challenges to both military and civilian operations. The complexities of inventory decisions for distribution systems lie in factors such as the demand patterns, the structure of the inventory system (whether it is single- or multi-echelon), necessary budget constraints, desired customer service levels, and, in the case of spare parts, the parts hierarchy. While minimization of cost is often the objective in business and industrial situations, for the military, readiness is usually the prime objective.

For many years, military researchers have systematically dealt with the relationship between resources and readiness, particularly spare parts resources. Readiness is defined as "the ability of US military forces to fight and meet the demands of the national military strategy." [1] Stocking the correct mix and quantities of spare parts that are needed to keep equipment operational is critical to military readiness.

The objective of this research is to assist military logistics planners in determining the best range and depth of inventory items to stock at a military installation in order to meet the prescribed fill rate, thus ensuring a high level of readiness. Their goal is to push inventory closer to the point of use. The inventory system is a multi-echelon structure, with the base supplied by a depot and by larger distribution centers. The focus is on Class IX items, reparable parts. Stocking decisions for repair parts require more complex analysis due to factors such as failure rate, repair time, commonality of component parts, and parts hierarchies (indentures). The military's readiness goals add another level of complexity to the problem. Thus, determining optimal stock policies for this multi-echelon multi-indenture inventory system provides a distinct challenge. Such complexity attests to the necessity of appropriate software for obtaining solutions to the problem. The examination of this software is described in the following sections.

II. Literature Review

Military inventory requirements for reparable items (Class IX) have motivated a large body of research work. Following a brief history of the Navy's establishment of measures of material readiness, Burdick [2] describes the process of readiness based sparing, an integration of design, configuration management, maintenance, and logistics support. Availability, Ao, as the measure of material readiness is defined as the probability that a system is up and ready to perform as intended. It is a function of the measures of reliability, maintainability, and supportability. Formulated in the mid-1960s by Sherbrooke, the Multi-Echelon Technique for Recoverable Item Control (METRIC) model is used for analysis of parts inventory in a multi-echelon system, with results expressed as expected cost and service. Muckstadt [3,4] extends the model to include the multi-indenture structure that links components, assemblies, and end products. By comparing the performance/cost trade-offs achieved by single echelon inventory models versus those from multi-echelon models, Muckstadt [5] shows that a multi-echelon approach performs better for all levels of inventory budgets. Sherbrooke [6] defines various types of one-for-one replacement (S-1,S) inventory models. He begins with a single-site model and advances in complexity to multi-echelon and multi-echelon/multi-indenture models. The multi-echelon/multi-indenture model is known as *vari-metric* and is the foundation for the development of the software described below. These models minimize the expected number of backorders in an inventory system.

III. Methodology

The following introductory definitions are basic to the vari-metric description and formulae that follow:

- LRUs (line replaceable units) are first indenture parts, the components of an end item.
- SRUs (shop replaceable units) are parts at the second indenture, or lower, level in the parts hierarchy. They are components that make up LRUs.

Sherbrooke [6,7] describes the repair/replacement process that is modeled by vari-metric as follows:

> The combined multi-indenture, multi-echelon process begins when an LRU fails and is brought into base supply. If base supply has a spare LRU, it is issued; otherwise a base LRU backorder is incurred. The failed LRU has a probability of being repaired at the base; otherwise, if the repair is too complex, the LRU is sent to the depot for repair and a re-supply request for the LRU is placed on the depot.
>
> If the LRU is repaired at the base, we assume that one and only one SRU will be found to have failed. If a spare SRU is available, it is put on the LRU and the LRU repair is completed. The SRU has a probability of being repaired at the base; otherwise the SRU is sent to the depot and a re-supply request for the SRU is made on the depot.
>
> When an LRU repair/re-supply is completed, a backorder is satisfied if there are any outstanding; otherwise, the LRU stock on hand is increased by one. If the LRU is not repaired at the base, a similar process for SRU repair occurs at the depot.

The vari-metric math formulae incorporate the following measures:

- expected number of units in repair at a site or being re-supplied from a higher echelon (This measure is known as “the pipeline”.)
- variance of the pipeline
- average annual demand for SRU*i* at a base *j*
- average repair time in years for SRU*i* at a base *j*
- probability that a failure of SRU*i* at base *j* can be repaired at that base
- conditional probability that an LRU being repaired at base *j* will result in a fault isolation to SRU*i* where the sum of the probabilities = 1
- constant order-and-ship time from depot to any base of SRU*i* if the depot has stock on hand
- stock level for SRU*i* at base *j*
- number of units of SRU*i* at base *j* that are in repair or resupply at a random point in time
- mean and variance for the number of LRUs in depot repair
- mean and variance for the number of SRUs in base repair or resupply
- mean and variance for the number of LRUs in base repair or resupply
- availability at base *j* due to expected backorders on the LRU and its SRUs

The output is the expected number of backorders. From the minimization of backorders, a measure of the maximization of availability can be obtained [6,7].

The software examined for this research uses the vari-metric model as its foundation. After determining the expected base backorders as a function of depot and base stock levels for an LRU and its SRUs, the software uses optimization techniques to retain the best solutions. For each LRU family, an optimal function computes the sum of base backorders versus cost. Then a marginal analysis algorithm combines the results across LRU families to reach a system solution [6]. Figure 1 diagrams the analytical flow used in the software.

IV. The Software and Its Fit

The software is a spare parts stock optimization model that computes the least costly quantity and mix of spare parts under a variety of assumptions that the user defines about the operating and support systems. It uses an indentured parts list in defining multiple systems to be deployed at multiple sites, with no limit on the number of parts or levels of indenture. The software correctly handles parts commonality and multi-echelon inventory storage. The optimization objective is to minimize the expected number of backorders. The software can be used for budgeting, and initial and follow-on procurements, as well as for evaluating operational availability and the annual cost of a stock policy [8].

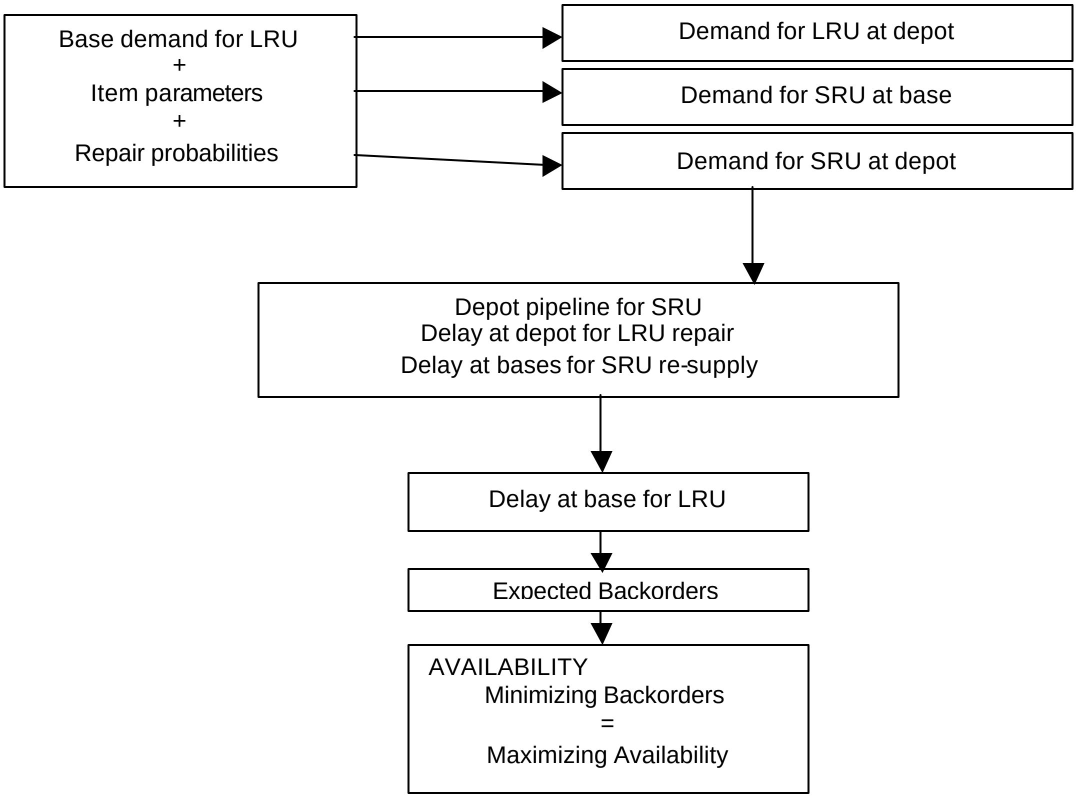

Figure 1. Analytical Flow

To use the software, the user defines the end items, the parts that make up the end items, and the sites, then sets starting and stopping conditions. Starting conditions deal with initial stock quantities. Stopping conditions are the "targets" or constraints of the optimization and include one or more of the following values: operational availability, spares budget, fill rate, average days delay per demand, and the slope of the availability versus cost curve. Calculations continue until the most demanding stopping condition is satisfied. Put into mathematical programming terminology, the problem is to minimize the expected number of backorders, subject to the constraints given as target values.

- *Operational Availability (Ao)*: A number less than one that represents the average fraction of equipment or end-items that are operational.
- *Budget Constraints:* A dollar amount not to be exceeded in purchasing spares.
- *Fill Rate:* The fraction, less than one, of operating site demands for 1st-indenture items that are met when orders are placed.
- *Average Days Delay/Demand:* Average delay in meeting demands for 1st-indenture items at the operating sites.
- *Slope of Availability vs. Cost Curve:* Reflects the increase in end-item availability per dollar invested. [8,9]

The software uses marginal analysis to optimize the stock mix. The marginal analysis technique determines at each step of its calculations the item and location that provide the greatest increase to availability per unit cost. For this analysis, it uses the expected backorder rates (EBO) as the criterion measure. Every time the model adds to stock, it chooses from among all parts and considers the impact of placing the item at any location. It computes how much the EBO will change if one more spare part is added to the stock and chooses the most advantageous part to add to the stock. The process continues until all the target values have been met.

V. Example and Tradeoffs

The software sets up a database from the user inputs and performs calculations on the relational data. There are seven screens where information is input plus a *Reports* screen that shows the output of a run. The first eight items below are the required data for getting basic results. These results can be used as a point of departure for basic planning purposes. The inclusion of as much "Other" data as possible will increase the accuracy and applicability of the results. With complete data inputs, optimal stock positioning determinations can be achieved. There is a set of defaults for many data points that can be used initially for missing data.

1. NSN—identification number and brief description
2. Price of the item
3. Procurement lead time
4. Weight and Volume
5. Number of breakdowns per million hours or Mean Time Between Failures
6. Parts hierarchy for each end item, including quantity of a component per assembly, and quantity of a component required for the end item to operate

Other data:

1. Internal and external order costs
2. Criticality factors (how important a component is to an end item)
3. Operating hours per week by site
4. Percentage of repairs possible for each item at each site
5. Repair cycle time and order/shipping time for each part at each supply site

Data may be imported from sources such as external databases, spreadsheets, and ASCII files.

Example for Class IX Equipment

The scope of this example model is limited by two conditions: the use of contrived data and the limit of the demonstration software to 15 parts. In spite of such constraints, the example serves to provide insight into the capabilities of the software. BASE is an operational site, and the supply sites are DEPOT, DISTRIBUTION1 and DISTRIBUTION2. We test the various scenarios of supply routing that follow:

1. DEPOT to BASE (3)
2. DISTRIBUTION1 to BASE (9)
3. DISTRIBUTION2 to BASE (8)
4. DISTRIBUTION1 to DEPOT to BASE (9, 3)
5. DISTRIBUTION2 to DEPOT to BASE (8, 3)

In this example, fifty cargo sets and 10 fuel systems are required at BASE. Fifty percent of the repair demand can be done at BASE, 80% at DEPOT, but none at the DISTRIBUTION sites. The order/shipping time (OST), a crucial factor in determining the best option, is given above in parenthesis. For each scenario, the OST for shipments from outside vendors to the highest level supplier is 9 days. Portions of the data for the Class IX equipment in this model are taken from the U.S. Army's Consolidated Publication of Component Lists [10].

The run variables are as follows:

STARTING CONDITIONS	STOPPING CONDITIONS (TARGETS)
Use shadow prices	Fill rate = 85%
	Average delay = 3 days

The project parameters are arbitrarily assigned and include the following:

Internal order cost	$100	Weight price	$20
External order cost	$200	Volume price	$20
Holding cost	15%	Lateral re-supply time	3 days

Tables 1 and 2 show the initial data for the end items, or Level 1 items, "fuel system" and "cargo set". Level 2 items for "fuel system" include pump assembly, filter separator, hose assembly, hose assembly—non-metallic, meter assembly, and adapter assembly. For "cargo system", the level 2 items are sling assembly, padlock, and chest. Results are given in Table 3.

In computing the optimal stock levels, the software assumes that there is no lateral re-supply. This is supply from another operating site (same echelon level) to satisfy backorders. The lateral supply time is generally shorter than the re-supply time from a higher echelon. The software evaluates the higher availability that could be obtained through the use of lateral supply.

Table 1. End Item Data for Class IX Items [8,9,10]

	Price	PLT	MRR 6	Criticality	VM Ratio	Wt.	Vol.	NFF	QPA (n)	QRA (k)	RIP	Cannibal
fuel system												
pump assembly	12309.00	30	57	1	1	2000	1000	0	2	1	0	yes
filter separator	4041.00	15	228	1	1	400	500	0	2	1	0	yes
hose assembly	340.46	5	228	1	1	15	10	0	1	1	0	yes
hose assembly-non metallic	495.42	5	228	1	1	15	10	0	2	1	0	yes
meter assembly	6238.48	21	114	1	1	50	25	0	1	1	0	yes
adapter assembly	169.07	3	450	1	1	10	15	0	6	1	0	yes
cargo set												
sling assembly	204.71	10	114	1	1	20	50	0	1	1	0	yes
padlock	5.84	5	57	1	1	1	0.5	0	2	1	0	yes
chest	1030.43	15	115	1	1	30	85	0	1	1	0	yes

PLT	procurement lead time: Input variable that represents the time to obtain a replacement assembly from a procurement source.
MRR6	maintenance replacement rate per million hours: Input variable that provides an estimate of the maintenance replacement rate per millon operating hours of one unit of the item on a single end-item or system. (One million hours is approximately 114 years.)
criticality	Item attribute indicating how important a part is to the operation of the system. Larger values indicate that the item is more important. Default is 1.
VM ratio	variance to mean ratio: A,B, and VMax are parameters to define the ratio: $VM = 1 + AM^B$, where A and B are constants and M is the annual demand for an item at an operating site. VMax is the maximum variance-to-mean ratio. Poisson demand is indicated by setting A and B to 0 and VMax to 1.
NFF	proportion of demand that occurs NOT because of failure: Input variable representing the proportion of demands for a spare part which arise for some reason other than a failure.
QPA(n)	Quantity per next higher assembly: Input variable that represents the quantity of a part in its immediate parent.
QRA(k)	Number required for operation: Variable representing the quantity of a spare part that can fail without the system failing.
RIP	repair in place rate: Input variable that represents the proportion of failures of an item that do not require its removal to restore its parent to operation. Used if no MRR6 value is given. Default is 0.
Cannibal	Item attribute indicating whether a component can be removed from one LRU to be used in the repair of another LRU. Use of cannibalization increases availability measures.

Table 2. Site Data for Class IX Items

	NRTS= Not repairable this station			RCT=Repair Cycle Time			Initial Stock: All values defaulted to 0
	BASE	DEPOT	DIST	BASE	DEPOT	DIST	
fuel system							Maximum Stock: All values defaulted to –1
pump assembly	0.5	0.2	1	5	9	0	
filter separator	0.5	0.2	1	5	9	0	
hose assembly	0.5	0.2	1	5	9	0	
hose assembly-non metallic	0.5	0.2	1	5	9	0	
meter assembly	0.5	0.2	1	5	9	0	
adapter assembly	0.5	0.2	1	5	9	0	Minimum Stock: All values defaulted to 0
cargo set							
sling assembly	0.5	0.2	1	5	9	0	
padlock	0.5	0.2	1	5	9	0	
chest	0.5	0.2	1	5	9	0	

NRTS represents the percentage of demand that is not reparable at a site. In the example above, 50% of demand can be repaired at BASE, while 80% can be repaired at DEPOT, but none can be repaired at the DISTRIBUTION sites, indicating that the DISTRIBUTION sites must be supplied by an outside source. Changing the NRTS value will change the allocation of spares among the operating and supply sites. RCT is an input variable that represents the average elapsed time measured from the moment a failed assembly reaches a repair facility to the moment it has reached that facility's ready-for-issue stockpile. The default value is 0 [8,9].

An important output of the software is a list of the optimal quantity of an item that should be stocked at each operational and supply site in order to achieve the fewest backorders. The quantities of reparable parts to stock at each site in each routing scenario follow in Table 3. For example, in Scenario 4 where DISTRIBUTION2 and DEPOT are supply sites and BASE is the operational site, there should be 7 adapter assemblies stocked at BASE, 6 at DEPOT and 0 at DISTRIBUTION2.

Table 3. Stock Quantities for Class IX Equipment

	Scenario 1		Scenario 2		Scenario 3		Scenario 4			Scenario 5		
Class IX--reparable equip.	DEPOT	BASE	DiST2	BASE	DIST1	BASE	DIST2	DEPOT	BASE	DIST1	DEPOT	BASE
adapter assembly	5	7	2	9	2	10	0	6	7	0	6	7
chest	2	2	3	2	3	2	0	2	2	0	2	2
filter-separator	1	0	2	1	2	1	0	2	0	0	2	0
hose assembly	1	2	1	2	1	2	0	1	2	0	1	2
hose assembly, non-metallic	1	2	1	3	1	3	0	1	2	0	1	2
meter assembly	0	1	0	1	0	1	0	0	1	0	0	1
padlock	3	4	2	5	2	5	0	3	4	0	3	4
pumping assembly	0	0	1	0	1	0	0	0	0	0	0	0
sling assembly	2	2	3	3	3	3	0	3	2	0	3	2

Table 4 shows that, in addition to meeting the target amounts for fill rate and average delay, the DEPOT to BASE scenario has the lowest budget, the lowest annual cost, and an Ao above 98%. Although this choice may seem straightforward, in multi-objective decision models, selecting the best option often involves additional analysis. We analyzed the results to pinpoint the best option by standardizing the results on 0-100 scales and weighting each of the objectives [11]. The scores from four sets of weighting factors are in Table 5, with the optimum supply scenarios highlighted.

Table 4. Performance Measures for Class IX Scenarios

ROUTING	Ao	Budget	Fill Rate (Target=85%)	Average Delay (Target=3)	Annual Cost
DEPOT to BASE	.98377	34,317	85.475	.70	61,766
DISTRIBUTION2 to BASE	.98800	77,404	88.091	.52	264,469
DDJC to BASE	.98689	78,073	87.962	.57	264,399
DISTRIBUTION2 to DEPOT to BASE	.98485	38,732	85.371	.66	68,014
DDJC to DEPOT to BASE	.98474	38,732	85.325	.66	68,020

Table 5. Total Scores

TOTAL SCORES—Class IX	Set A	Set B	Set C	Set D
DEPOT to BASE	41.08	41.63	70.54	23.25
DIST2 to BASE	60.31	60.15	30.92	80.15
DIST1 to BASE	48.27	50.59	24.14	71.80
DIST2 to DEPOT to BASE	47.25	45.89	68.58	24.46
DIST1 to DEPOT to BASE	46.40	44.87	68.15	23.20

The performance measures of the example were subjected to sensitivity analysis to determine at what point the best decision was no longer optimal. Table 6 shows the amount of change that can occur before optimality is affected when each performance measure is changed independently. Results show that the models are robust to changes in budget, average delay, and annual cost but are very sensitive to changes in Ao and fill rate.

Table 6. Sensitivity Analysis for Independent Changes

CLASS IX: Best structure = DIST2 to BASE in 3 weighting combinations	AMOUNT OF CHANGE	DECISION CHANGE?
Operational availability (Ao)	1% decrease	yes
Budget	<= 81% increase	no
Fill rate	1% decrease	yes
Average delay	<= 25% increase	no
Annual cost	<= 35% increase	no

VI. Conclusions

We have shown how a commercial off-the-shelf software application can be useful in solving the complex problems associated with optimal stock positioning of multi-echelon multi-indentured reparable parts common in military settings. The software includes optimization of the readiness measures that are vital to military operations. The example given shows the required data points and outputs. A brief analysis of the multi-objective results and some sensitivity analysis follow the example.

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