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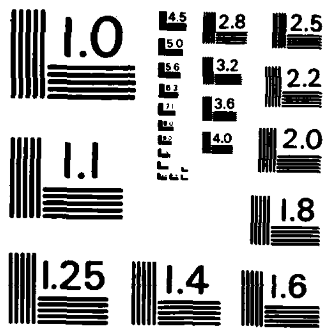

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AIR FORCE INSTITUTE OF TECHNOLOGY

ANALYSIS OF THE CRITICAL ITEM
PERFORMANCE OF THE GARDNER-DANNENBRING
AGGREGATE INVENTORY MODEL

THESIS

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Flight Lieutenant, RAAF

AFIT/GLM/LSM/85S-78

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THESIS

Presented to the Faculty of the School of Systems and Logistics

of the Air Force Institute of Technology

Air University

In Partial Fulfillment of the

Requirements for the Degree of

Master of Science in Logistics Management

David A. Thomson, BBus.

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Preface

This research has allowed me to expand my knowledge of inventory theory, an area in which I have become interested during the past few years. I wish to thank Major Doug Blazer for directing me to this particular topic, and Lieutenant Colonel Carlos Talbott for his advice and guidance.

David A. Thomson

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Abstract

A 1984 Air Force Logistics Management Center (AFLMC) study compared the Standard Base Supply System (SBSS) inventory models to ten alternative models. The AFLMC report concluded, in part, that an aggregate inventory system which minimizes backorders, subject to investment and workload constraints, better suits the operational needs of the Air Force than does a system which minimizes total variable costs. The AFLMC aggregate model was based on the Gardner-Dannenbring Two Lambda Aggregate Inventory Model, which does not discriminate between those consumable items which are critical to a mission and those which are not. This study investigated means of improving the model's critical item performance.

Considerable improvement was made possible by setting artificially low critical item unit costs, thereby increasing the proportion of funds allocated to critical items, but this improvement was at the expense of the model's non-critical item performance. Additionally, the model's critical item performance was marginally improved by reducing the workload slack in the model's solution. High backorder items, responsible for disproportionate numbers of backorders, were identified by an "item profile" of unit cost and demand rate. The benefits of cost reductions and

lower demand rates for the high backorder items (simulating the effects of component re-design) are demonstrated.

ANALYSIS OF THE CRITICAL ITEM PERFORMANCE OF THE GARDNER-DANNENBRING AGGREGATE INVENTORY MODEL

I. Introduction

Background

Traditional inventory models are based on a cost minimization principle, to meet the profit maximization objective of the commercial enterprises for which they were originally developed. The Department of Defense (DoD) adopted the models as a basis for inventory decisions, even though the objective of the DoD is not profit oriented. To be consistent with Air Force objectives, inventory management decisions should be directed towards maximizing the support for the force, within the limits set by the policy makers. The need for goal oriented management has been recognized; the 1978 Defense Authorization Act stated:

> The budget of the Department of Defense submitted to Congress for Fiscal Year 1979 and subsequent fiscal years shall include data projecting the effect of the appropriations requested for material readiness requirements.

A class of inventory models has been developed which can be structured to reflect the objectives and operating conditions of the Air Force. These models are called aggregate inventory models. They differ from the traditional models in that they are not based on variable costs which can be difficult to measure and highly subjective. Measurable aggregate variables, such as investment funds, storage space and workload, can be used to optimize an objective function which reflects the goal of the user.

A major benefit of the aggregate models is that an optimal solution to the objective function can be provided for any stated budget where that budget is a constraint of the model. Such control is not possible with the cost minimizing models which compute individual order quantities, with no constraint on aggregate inventory funds.

Air Force Management of Consumable Items

The objective of the Air Force inventory policy for Economic Order Quantity (EOQ) consumable items in the Standard Base Supply System (SBSS) is:

> to minimize the total of variable order and holding costs subject to a constraint on time-weighted essentiality weighted requisitions short (1).

The policy was introduced in 1970 by Department of Defense Instruction (DODI) 4140.39, and is applied through the use of cost minimizing EOQ inventory models.

The Air Force Logistics Management Center (AFLMC) recently conducted a study in which the SBSS models were compared to ten alternative inventory models. The comparison was made in terms of the number of backorders generated, number of orders placed, unit fill rates and total variable using sample data chosen as being representative of the Air Force consumable inventory. The best performing models were then re-tested, using consumable item demand data from England AFB. The AFLMC study report (2) concluded, in part, that an aggregate inventory system which minimizes backorders, subject to investment and workload constraints, better suits the operational needs of the Air Force than does a system which minimizes total variable costs. The recommendation of the report was:

> Observe the aggregate model's performance as part of the Civil Engineering Materiel Acquisition System (CEMAS). If the system performs as well as expected, implement the system for all Air Force retail level consumable items (2:13).

One result of the study was that, for a sample of 1,336 operationally essential (i.e., stockage priority codes 1 and A) consumable items from England AFB, the aggregate model with financial and workload constraints reduced the number of backorders from 8,125 to 957 for the demand sample period. However, the aggregate model considers all consumable items as equally critical, regardless of their mission impact. It does not discriminate between those consumables which are necessary for a mission (e.g., aircraft tyres) and those which are not (e.g., paper towels). A decrease in the number of backorders for mission critical consumable items may be possible if the relative importance of each item is reflected in the model.

The Air Force consumable inventory is predominantly made up of non-critical items, but the small proportion of critical items (18% in the England AFB data set) contribute directly to aircraft availability. A backorder for a critical item may result in a grounded aircraft, but the consequences of a stock-out of non-critical item are not as severe. A reduction in the number of backorders for critical items would be beneficial to the Air Force mission, and is a task which deserves concentrated management attention.

Investigative Question

Investigation is required to determine if the aggregate model's critical item performance can be improved by modifying the model to discriminate between critical and non-critical items and compute stockage policies which will concentrate on reducing the number of backorders for critical items.

II. Literature Review

Introduction

The majority of inventory theory research in the Air Force in recent years has dealt with repairable item models. A significant amount of that research has involved the use of availability measures to determine spares requirements. Some of the researchers have commented on the use of such measures for consumable item determinations. A summary of reported findings is included in this literature review in order to provide additional background to the problem of computing critical consumable item requirements.

Availability Models

> An availability model is a mathematical model that determines the relative worth-vs-cost of a wide range of possible quantities of spares for any specified level of weapon system availability. Thus, availability models . . . take explicit account of both cost and readiness in computing the best spares mix (3:iii).

Within recent years, a number of DoD sponsored studies (3,4,5,6) have recommended the use of readiness and sustainability goals for weapon systems and other end items as the basis for deciding the range and quantities of repairable items to to be held in inventory. The reports of these studies critize the use of supply oriented performance measures.

> It is common practise to manage DoD inventories to satisfy supply-availability (i.e. fill rate) goals . . . . Unfortunately,

> the link between supply availability and weapon system availability is far from direct. High fill rates, for example, are meaningless if substantial numbers of weapons are not-mission-capable for want of spare parts . . . . The best approach, when feasible, is to link inventory decisions directly to weapon system availability goals (4:ii-iii).

> The most compelling conclusion that emerges from this work is that across a wide range of weapon systems and scenarios, availability models constitute a significantly more cost effective approach to initial provisioning than the item oriented approach (3:iv).

> A serious drawback of such measures is that they do not look beyond the supply system to determine the impact of supply on the aircraft or other end items being supported (5:1-1).

The availability models in the literature compare alternative mixes of inventory items by marginal cost-benefit analysis of prospective inventory items, subject to a total cost constraint. The stockage policy is the item mix which maximizes system availability, within the budget.

Availability Models for Consumable Items

The availability models discussed in the literature maximize system availability with respect to repairable items only. Specific references are made to the exclusion of consumable items from these models. A Logistics Management Institute (LMI) study in 1972, entitled "Measurements of Military Essentiality", concluded that an Air Force model in use at the time, together with an Air Force codification scheme, could be adapted and extended to objectively consider military essentiality in the development of procurement plans for repairable items. LMI developed a military essentiality model which made use of the Air Force systems. As for consumable items, additional findings of the study were:

> The Air Force and LMI models...can be adapted to the development of procurement plans and budgets for certain high cost consumable parts considering military essentiality (6:2-3).

and

> No models were found, and none were developed by LMI which could be recommended for considering military essentiality in the development of procurement plans for low cost consumable parts (6:2-3).

The report added that the adaption of the repairable item model for use with consumable items was considered possible, but at prohibitive cost.

A 1982 LMI report on the use of availability models in the DoD listed two problems which "inhibit the Air Force's ability to include consumables in an availability model in the same way as recoverables" (4:2-4).

> The first is that models such as the LMI Aircraft Availability Model, METRIC, MOD-METRIC, VARI-METRIC, and SESAME are built on the assumption of an (S-1,S) reorder policy whereas consumables are managed with an (s,S) policy.
> The second significant problem with consumables is the relatively intractable mathematical character of the (s,S) reorder policy in a multi echelon system (4:2-4).

A re-order policy of (S-1,S) dictates that a maximum stock level of S is maintained. When one asset is removed from stock i.e., the stock level drops to S-1, a replacement asset is ordered. A re-order policy of (s,S) requires that a replacement order for (S-s) units is placed when the stock level reaches 's'.

The author of the report considered these two problems solvable, but only with technical difficulty.

Aggregate Inventory Models

A 1979 dissertation by Everette S. Gardner (7) proposed an aggregate inventory model which could minimize requisitions short (backorders) with constraints on both workload and investment. Gardner provided a summary of previous research in the field, stating that his research is distinguishable from previous efforts because of the computational feasibility of his model. "There have been several previous formulations of similar models, but non-trivial computational results have never been reported" (7:77). Gerson and Brown (8), Schrody and Choe (9) and Daeschner (10) all presented Lagrangian models to minimize either dollars short or requisitions short. Only Schrody and Brown presented computational results, but their model's algorithm was so complex that the tremendous computer storage requirements limited the model's use to inventory sets of less than 500 items.

Gardner presents his research in terms of a three dimensional plot of requisitions short, workload and investment. Any point on the "optimal policy surface" gives an optimal value for requisitions short, with corresponding values for the workload and investment level.

> The principal conclusion in this research is that any rational aggregate inventory decision must result in a point on the optimal policy surface. Any point located below the surface is impossible to obtain since the surface is optimal. Any point located above the surface is suboptimal, since workload, investment, or both could be reduced for the same level of shortages (7:81).

Gardner's model, with constrained investment and workload, was modified by AFLMC and used as the aggregate model in the inventory system comparison study (2).

III. Methodology

Introduction

The research is based on the Gardner-Dannenbring Two Lambda Aggregate Consumable Inventory Model, as described in (2) and (7), and as used by AFLMC in the previously mentioned inventory models comparison study. A brief description of the model will be given, followed by an explanation of the methods employed to attempt to improve the model's performance in computing stockage policies for critical items. With each method, the sensitivity of the model to changes to constraints and input parameters will be tested, to enable statements to be made about the behaviour of the model and about the suitability of the model for use in the Air Force.

Gardner-Dannenbring Two Lambda Aggregate Inventory Model

The Gardner-Dannenbring Two Lambda Aggregate Inventory Model, hereafter referred to as "the model", minimizes total backorders for a set of consumable inventory, subject to constraints on the value of average on-hand inventory and the number of requisitions raised. It is an aggregate model in that it determines the inventory depth stockage policies of a group of items by considering the entire range of items, rather than on an item by item basis as done by other consumable item inventory models. The AFLMC study report (2:21-23) provides the following explanation of the model.

The objective function represents the expected backorders per year by summing the products of the number of order cycles per year for each item and the number of units of each item expected to be ordered during a stock-out period, i.e.

$$\text{MINIMIZE} \quad \sum_{i=1}^{n} \frac{L_i^2 D_i}{Q_i} \sum_{x=R_i+1}^{\infty} (x-R_i)\, f_i(x) \qquad (1)$$

where:

L_i = customer lotsize for item i.

D_i = expected number of annual customers for item i.

Q_i = order quantity, in units, for item i.

R_i = reorder point, in units, for item i.

$f_i(x)$ = the probability of x customers demanding item i during the reorder leadtime.

The constant-Poisson probability distribution is used to represent the leadtime customer arrival and demand patterns, i.e.

$$f_i(x) = \frac{\left(\lambda_i t\right)^{x/L_i} e^{-\lambda t}}{\left(x/L_i\right)!} \quad ; \; x=0, 1L_i, 2L_i, \ldots (2)$$

where:

λ_i = customer arrival rate, per day.

t = replenishment cycle lead time, in days.

X = units ordered during the lead time.

The mean and variance are, respectively, $\lambda_i tL_i$ and $\lambda_i tL_i^2$.

The constraint on the value of average on-hand inventory is:

$$\sum_{i=1}^{n} P_i \left(\frac{Q_i}{2} + R_i L_i - \lambda_i t_i L_i \right) < I \qquad (3)$$

where:

P_i = unit price for item i.

I = on-hand inventory constraint in dollars.

Further, the workload constraint is:

$$\sum_{i=1}^{n} \frac{L_i D_i}{Q_i} < W \qquad (4)$$

where:

W = the maximum number of yearly requisitions.

A Lagrangian function is formulated by adding the constraint function and the objective function as:

$$\pounds(Q_i, R_i, \ell_I, \ell_W) =$$

$$\sum_{i=1}^{n} \frac{L_i^2 D_i}{Q_i} \sum_{x=R_i+1}^{\infty} \left(x-R_i\right) f(x)$$

$$+ \quad \ell_I \left[\sum_{i=1}^{n} P_i \left(\frac{Q_i}{2} + R_i L_i - \lambda_i t_i L_i - I \right) \right]$$

$$+ \quad \ell_W \sum_{i=1}^{n} \left[\frac{L_i D_i}{Q_i} - W \right] \tag{5}$$

where:

ℓ_I = the investment constraint Lagrangian multiplier.

ℓ_W = the workload constraint Lagrangian multiplier.

Because the functions are convex (7:77), the solutions to the first order conditions are optimal. Thus, the

Lagrangian function is differentiated with respect to Q_i, R_i, ℓ_I and ℓ_W, and the following 2n+2 equations in 2n+2 unknowns are solved simultaneously, where 'n' is the number of items.

$$Q_i = \left[\frac{2 L_i D_i \left(\ell_W + L_i E_i \right)}{\ell_I P_i} \right]^{1/2} \tag{6}$$

$$\sum_{0}^{R_i} f_i(x) = 1 - \frac{\ell_I P_i Q_i}{L_i D_i} \tag{7}$$

$$\ell_I = \sum_{i=1}^{n} \frac{L_i D_i B_i}{2 \left[I - \sum_{i=1}^{n} S_i \right]} \tag{8}$$

$$\ell_W = \frac{1}{W} \left[\ell_I \sum_{i=1}^{n} \frac{P_i Q_i}{2} - \sum_{i=1}^{n} \frac{L_i^2 D_i E_i}{Q_i} \right] \tag{9}$$

where:

E_i = the partial expectation of demand, which is the dollar value of backorders.

B_i = the probability of stocking out.

S_i = the dollar value of safety stock.

The simultaneous equations are solved iteratively, beginning with small values of R_i and Q_i. As each iteration is completed, the aggregate results are checked against the two constraints. If either of the constraints is violated, the process is completed; otherwise, the values of R_i and Q_i are incremented and the process is completed.

Demand Data.

The data set used for this research is comprised of item demand history for an eighteen month period, for 7,478 consumable items from England AFB. Of those items, 1,336 are classified as critical, with a Stockage Priority Code (SPC) of 1. The data is the same used by AFLMC in the inventory models comparison study (2:10).

Performance Measures

The model is an expected backorders minimization model; therefore, expected backorders will be the main performance measure used for comparison of results from the modified versions of the model. The equation for expected backorders (equation 1) has already been given in the model description. Average on-hand inventory investment, number of requisitions, total variable costs, and service levels will also be used as supplementary, supply oriented, measures. To provide another (non-supply oriented) performance measure, an availability rate measurement will be used, based on the measurement used in the Logistics

Management Institute (LMI) Aircraft Availability Model (AAM), which computes stockage policies for repairable items. Each item's contribution to aircraft availability is calculated:

$$a = \left[1 - \frac{EXPBAC_i}{F * QPA_i} \right]^{QPA_i} \qquad (10)$$

where:

$EXPBAC_i$ = expected backorders per year, for item i.

QPA_i = quantity per application (number of this item on each aircraft in the fleet).

F = fleet size.

Total aircraft availability is calculated:

$$A = \prod_{i=1}^{n} \left[1 - \frac{EXPBAC_i}{F * QPA_i} \right]^{QPA_i} \qquad (11)$$

where:

n = number of critical consumable items per aircraft.

An availability measure applies only to critical items i.e., those consumable items which can cause the grounding of an aircraft. In the context of this research, the availability measure will be an artificial one used solely for judging the relative performance of the model versions. The QPA information required for the AAM computation is not available for consumable items, so an artificial QPA value will be substituted for each item. The figure used will be constant by item throughout the research, thus making the availability measure suitable for use as a tool for comparison. However, the absolute availability measure will be of no operational significance because of the artificial QPA.

Aggregate Constraint Analysis.

To show the sensitivity of the model to changes to the aggregate constraints, a number of runs will be conducted with incremented constraint levels. Both constraints will be incremented, in various combinations. An increase in the average on-hand investment constraint will allow higher stock levels and more frequent reordering of both critical and non-critical items, resulting in a decrease in expected backorders for both categories. The results of a change in the workload constraint are not so obvious. More frequent orders of smaller amounts will decrease the value of on-hand inventory, and may result in fewer expected backorders. During preliminary testing of the model, the investment constraint was the first constraint violated each time, while the workload constraint was rarely approached. By reducing the slack in the workload, some improvement in the performance of the model may be possible.

Unit Cost Analysis

Because the model's objective function is constrained by an on-hand inventory investment constraint, the model will compute stockage policies which result in low backorder figures for low cost items, whereas higher cost items will have stockage policies which result in higher backorder figures. For this reason, one suggestion put forth by the AFLMC for improving the model's critical item performance is to set the unit cost of all critical items at an artificially low level, thus making critical items, as a group, less expensive and subject to more favourable treatment within the model. The unit costs of the critical items must be readjusted to their correct levels before the aggregate inventory investment is compared to the constraint. The desired effect of the unit cost adjustment is to increase the proportion of the investment amount which is allocated to critical items. An obvious effect of this action must be an increase in the number of backorders for non-critical items. The acceptable balance between the backorder levels of the two categories is a management prerogative.

In this research, the model will be modified to demonstrate the effects of the changes in artificial critical item unit cost. The modification will result in two passes through the model. The first pass will establish an investment level and individual item stockage policies for critical items. The second pass will compute individual stockage policies for non-critical items. The investment and workload constraints for the second pass will be determined by subtracting the critical item levels of investment and workload from the original constraints. The model will be run a number of times, with a different cost adjustment factor for critical items in each run. The effect of the size of the cost adjustment, in terms of expected backorders and availability, will then be evident.

Identification of High Backorder Items

The analysis of the sensitivity of the model to changes in the aggregate constraints and critical item unit costs concentrates on aggregate aspects of the model i.e., the modifications to the model are intended to apply to all critical items equally. Another approach will be taken which will attempt to identify an individual item's characteristics which may influence the model's performance for that particular item. Individual item data for critical items will be examined to determine if any one type or class of item has relatively high expected backorders. An "item profile" will be established for those items which generate disproportionate numbers of backorders. Because the unit cost and demand rate are the only two variable inputs (order and ship time is fixed at 31 days for each item), the profile will be a function of those two variables. The profile will then be used to segregate high backorder, critical items from the remainder of the 1,336 items. Unit cost and demand rates will then be treated as functions of component design. A decrease in unit cost may be possible with a redesigned component, while a reliability improvement resulting from redesign will be reflected in a reduction in the demand rate for the item. The consequences of a redesign will be illustrated by running the model a number of times, with different combinations of unit cost and demand data for the high backorder items.

This process will be an extension of the analysis of the model's sensitivity to change in the unit cost of critical items. The analysis will be expanded to include the sensitivity of the model to change in the unit costs and demand rates, both singularly and in combination. Also, the changes will not be made across all critical items, but only to those identified as being high backorder items. Thus, the characteristics of an item with twenty backorders expected per year will be analyzed, while an item with 0.5 expected backorders will be unaffected. There are a number of implications for the inventory manager if one class of items is found to be causing a disproportionate number of backorders.

1. The group of items are a part of a weapon system, the availability of which is adversely affected because of the items'

disproportionate backorders figures.

2. There is an associated cost with the adverse effect, either in terms of reduced readiness or additional investment to improve readiness.

3. An economic life cycle decision may be to improve availability and reduce inventory investment by identifying the problem components, and offering the contractor incentives to reduce unit costs (through technological improvements in the production process) or improve reliability.

The decision can be based on the type of analysis which will be conducted on the model, and reported on in Chapter IV.

IV. Results and Findings

Aggregate Constraint Analysis

During the AFLMC comparative study (2), the model was run with a 7,478 item data set, as previously reported. The results of that study were replicated, and used as a baseline for the examination of the effects of constraint changes on the critical item performance of the model. Multiple runs were made with the constraints incremented above and below the baseline constraints. The results of these runs, in Table I, highlight the need for discussion of the behaviour of the model, and its practical applications.

The figures in Table I illustrate a characteristic of the model which makes it difficult to systematically adjust the model's inputs to achieve a desired output. The model arrives at a solution at the first iteration after one of the constraints is broken. In essence, the constraint is more of a guideline because it is not strictly adhered to. In all cases during this research (involving hundreds of model runs), the investment constraint was always the one to be exceeded. Therefore, the model always recommended investment levels higher than the constraint figure. For example, the baseline run of the model was constrained to an average on-hand inventory value of $1,139,009, and 16,943 orders for the year, the same levels used by the AFLMC in their study (2:10). e model recommended levels of constraint by $17,446, or 1.5%.

TABLE I

MODEL RESULTS WITH INCREMENTED CONSTRAINT VALUES

Constraints	Average On-Hand Inventory	Orders	Total Variable Costs	Expected Backorders	
	$	#/year	$	Critical	Other
1,139,009 16,943	1,156,455	12,437	445,254	957.45	2608.29
1,195,960 (+5%) 16,943	1,292,297	14,971	474,321	427.00	889.24
1,252,910 (+10%) 16,943	1,315,306	14,494	476,923	402.19	805.17
1,082,059 (-5%) 16,943	1,132,184	13,274	443,384	1042.49	2808.30
1,025,108 (-10%) 16,943	1,088,316	16,435	447,576	1159.31	3332.06
1,139,009 17,790 (+5%)	1,153,151	12,725	445,401	955.29	2617.23
1,139,009 18,637 (+10%)	1,151,609	13,020	445,703	927.08	2615.33
1,139,009 19,484 (+15%)	1,148,484	13,346	446,174	935.12	2620.77
1,139,009 16,096 (-5%)	1,161,414	12,094	445,201	953.44	2599.24
1,139,009 19,484 (-10%)	1,166,499	11,707	445,081	944.85	2601.54

The average on-hand inventory investment was then increased by 5%, to $1,195,959, with the order constraint remaining at 16,943. The model's solution recommended an investment level of $1,292,296, and 14,970 orders. The investment constraint was exceeded by $96,337, or about 8%, while the number of orders was below the constraint by about 12%. Further, the investment level of $1,292,297 in the second run exceeded the baseline investment level of $1,156,455 by 11%, even though the investment constraint for the second run was increased by only 5% of the baseline level. The behaviour of the model after constraint changes was unpredictable.

The model approaches its solution by repeatedly increasing the reorder points and quantities, and simultaneously solving equations 6 to 9 at each iteration. The process halts when one of the constraints is violated. The stockage policies for the final iteration generate the minimum number of backorders for that iteration's levels of investment and workload. Each of the model's iterations prior to the constraint violation provides an optimum solution for that iteration's investment and workload levels, each of which is below the constraints. Therefore, an acceptable solution may be found in one of the iterations prior to the final iteration. For example, the second of three iterations in the run with a 5% increase in the on-hand inventory constraint recommended a solution with an investment level of $1,174,894 and an annual orders figure of 12,218. The investment level was about 1.8% below the constraint. The expected backorders figure was considerably greater than for the final iteration (881.1 versus 427.00), but no constraint was violated.

The point of this discusson is that the model will not always automatically arrive at a solution which is entirely acceptable. Whereas a 1.5% investment constraint violation in the baseline run may be acceptable, the 8% excess in the following run may be unacceptable. If the constraint is an absolute maximum, the most acceptable solution will lie somewhere between the results of the model's second last and final iterations. A solution which does not violate either of the desired limits can be obtained by re-running the model with constraints at a level below those levels. As experienced during this research, such "fine tuning" may involve a substantial number of extra runs of the model.

Given that the model's solution may require additional processing, the results shown in Table I can be examined to judge the effects of the constraint increments on the model's critical item performance.

The most obvious result, as expected, was the substantial decrease in expected critical item backorders when the investment constraint was relaxed. Of greater interest, however, is the fact that the model decreased critical item backorders when the workload constraint was relaxed. Not only was a decrease in backorders possible, but the average on-hand inventory investment also decreased, by almost $5,000. The decrease in expected backorders halted near the 10% relaxation in the workload constraint. The halt in the decrease is probably attributable to the fact that as the number of order cycles increases, the risk of exposure to backorders increases.

The 957.45 expected backorders of the baseline run represent a critical item service level of 97.1%. The ten percent relaxation of the workload constraint resulted in 927.08 expected backorders, and a service level of 97.3%.

A small improvement in the model's critical item performance was possible with a slight increase in the number of requisitions, suggesting that such improvement may be available with other data sets.

Unit Cost Analysis

The analysis of the effects of an artificial cost reduction for critical items began with multiple runs of the model, using the complete data set of 7,478 items. On each run, the unit cost of each critical item was reduced to a certain proportion of its correct unit cost. Initially, the reduction factors were 0.5, 0.6, 0.7, 0.8, 0.9 and 1.0. The factor was fixed for each run. The cost factor of 1.0 i.e., no reduction in unit cost, was included to replicate earlier results, and verify that the model operated as intended. The model was modified to compute all stockage policies in one run, using two passes. In the first pass, the model computed stockage policies for the artificially priced critical items. The non-critical item policies were computed in the second pass, constrained by the investment funds and number of orders remaining after the first pass. The results of the run are shown in Table II.

The first point for discussion is the problem created, once again, by the model's iterative process. As shown in the table, each run resulted in a substantially different average on-hand inventory constraint, making accurate comparison of the results difficult.

The differences between the investment levels are generated during the second pass of the model, when the non-critical item stockage policies are computed. The problem can be overcome by adjusting the investment constraint for the second pass, so that the combined investment for critical and non-critical items satisfies the total investment constraint. Since this study is concerned primarily with critical items, the model was not re-run to match the investment levels of the runs. However, the effect of such action would be to increase the number of non-critical item backorders for the runs with investment levels currently above the original constraint, and decrease the number for those runs with investment levels below that constraint.

For instance, the final two iterations for some of the

TABLE II

MODEL RESULTS WITH COST REDUCTION FACTORS

Constrained to $1,139,009 and 16,943 orders.

Cost Reduction Factor	Average On-Hand Inventory	Orders	Total Variable Costs	Expected Backorders	
	$	#/year	$	Critical	Other
0.5	1,161,872	13,640	448,910	237.83	4287.64
0.6	1,152,531	13,635	447,402	281.3	4137.99
0.7	1,142,266	13,638	446,174	339.61	4041.44
0.8*	1,136,587	13,647	445,026	376.49	3991.83
	1,211,767	15,549	455,529	376.49	1617.75
0.9*	1,130,193	13,664	444,237	425.39	3937.21
	1,206,730	15,619	460,406	425.39	1576.36
0.94*	1,110,800	13,414	441,142	884.10	3567.72
	1,191,432	15,757	459,788	884.10	1365.85
0.95*	1,110,477	12,922	441,100	890.79	3565.83
	1,191,643	15,264	459,756	890.79	1364.49
1.0*	1,109,616	13,423	441,047	957.45	3498.23
	1,190,226	15,669	459,436	957.45	1343.26

* Final two iterations shown. See text for details.

runs are shown in Table II. The constraints for the run were the same as used in the previous section, so the results of the run with no cost reduction were already known. The figure of 957.45 for expected critical item backorders was obtained, but the second pass of the model did not produce a figure close to 2618.29 as the number of non-critical item backorders. Instead, the final two iterations produced figures which bracket the desired result. The number of non-critical item backorders for an average on-hand inventory value of $1,139,009 is between 3498.23 and 1343.26 backorders, and can be obtained by re-running the second pass of the model in isolation, with adjusted constraint values. As suggested by the AFLMC, a reduction in the unit cost of each critical item did result in a decrease in the total number of expected critical item backorders, at the expense of the number of non-critical item backorders. The cost reduction had the desired effect of increasing the proportion of the investment constraint allocated to the critical items. The proportion rose from approximately 30.9% for the model run with no cost reduction to 38.4% for the run with a 50% cost reduction. The number of expected backorders fell 75.2%, from 957.45 to 237.83. The effect on non-critical items was to increase the number of expected backorders by 1,669 (approximately 63.7%), even with a $5,000 increase in the average on-hand inventory value ($1,156,455 to $1,161,872).

As can be seen from Table II, the number of expected critical item backorders decreased markedly when the cost reduction factor was incremented from 1.0 (no cost reduction) to 0.9 (a 10% reduction). A reduction of 532 backorders, or 55.7%, was possible with a 10% unit cost reduction. The number of non-critical item backorders increased by 1,319, or 50.4%. The effect on total expected backorders was a 22% increase from 3,575.74 to 4,362.6. To determine why such a large drop in expected backorders resulted from a small reduction in the unit price of the critical items, the model was run several times with cost reduction factors between 0.9 and 1.0.

As explained earlier, the model is run for one pass with discounted values for each critical item unit cost. From that pass are computed the critical item stockage policies. A second pass computes the non-critical item stockage policies, using the resources remaining from the first pass as constraints.

For cost reduction factors above 0.93, the first pass of the model resulted in the investment constraint being broken in the second iteration. For cost reduction factors of 0.93 and below, the reduction in unit costs was substantial enough to "trick" the model into doing three iterations. As also explained previously, on successive iterations, the model's recommended investment level may be slightly below, and then substantially above, the constraint. However, the iterations will cease only after the constraint is broken. Such is the case with the considerably lower backorders figures for runs with cost reduction factors below 0.94.

The table shows the combinations of critical and non-critical item backorders for a series of cost reduction factors. A larger cost reduction will result in a smaller number of critical item backorders. The balance between the two groups of backorders must be decided upon by the inventory manager. A cost reduction factor can be used to modify the model to produce a level of backorders consistent with local policy.

Identification of High Backorder Items

A number of screening runs of the model with the complete data set resulted in a list of nineteen critical items, each with an expected backorders figure of ten or greater. The expected backorders total was 422.67, or 44.1% of the 957.45 backorders for the entire critical item set of 1,336 items. The details of the nineteen items are listed in Table III. Because the unit cost and daily demand rate are the only two variable inputs, each of the two factors, or a combination of the two, was expected to be a contributing influence to the model's performance for the high backorder items.

Examination of the data set revealed that item #5592, which has the highest daily demand rate of the items in

TABLE III

HIGH BACKORDER ITEMS

Item No.	Expected Backorders	Unit Cost	Daily Demand Rate
68	24.4313	1070.00	0.10909
1001	11.8955	6.89	2.79455
1276	10.3170	114.26	0.20727
1727	37.7331	167.00	0.59091
1784	10.6412	379.21	0.10182
2493	40.8987	40.92	1.35273
3624	11.8032	68.18	0.27818
3701	12.8291	108.54	0.24364
3993	25.6850	855.90	0.11818
5024	11.4035	89.00	0.25818
5258	36.6545	209.84	0.48727
5592	20.4683	2.50	16.60727
6202	13.5548	46.63	1.22182
6500	14.0900	20.00	0.82545
6739	10.0348	393.43	0.09636
6927	14.6746	79.76	0.35818
7040	55.8451	202.26	0.83636
7394	15.6047	128.29	0.28182
7426	44.1408	357.58	0.54000

Table III, also has the highest demand rate of any of the 1,336 critical items. Nine items in the set have a daily demand rate of greater than 3.0, and only two of those have a figure above 10.0. However, item #5592 is the only one of the nine which appears in the list of high backorder items, so demand rate alone did not appear to be a major contributor to an item's expected backorders.

The highest priced item in Table III is item #68, with a unit cost of $1,070. It ranks thirty-third on the list of high priced items in the entire set. Of the thirty-two items with higher prices, twelve have stockage policies of (1,2) i.e., re-order one when there is one remaining in stock. The other nineteen items have policies of (2,3), (3,4) or (4,5) i.e., re-order points of two, three or four and re-order quantities of one. Of the fifty-four items priced at $800 or above, only items #68 and #3993 do not have stockage policies of (1,2), (2,3), (3,4) or (4,5). Item #68's policy is (5,6) and item #3993's is (5,7). So, although the unit costs of items 68 and 3993 are among the highest in the set, their stockage policies are different from those of the other high priced items and, although the two items do not have the highest unit prices, their backorder figures are among the highest. Therefore, unit cost alone is apparently not a major contributor to the number of backorders an item generates.

The combination of unit cost and daily demand rate was then examined. Of the five items with the highest backorders, four have unit costs and daily demand rates which, when multiplied together, give a product of greater than 100. The fifth item's product is slightly below 100. This fact was taken as an indication that high backorder items may be identifiable by the product of their cost and demand rate figures. The relevant figures for the ninete n items were calculated; sixteen of the nineteen had products which exceed twenty. This figure was then applied as a screen to all the critical items in the set, with the result that some high cost, low demand items were found to have similar products. As previously discovered, high cost alone is not a great influence on the model's performance, so an additional screening criterion was introduced. Eighteen of the nineteen items in Table III have daily demand rates greater than 0.10, so the two screening criteria were set at:

1. multiplicative product of unit cost and daily demand rate greater than, or equal to, twenty;
2. daily demand rate greater than, or equal to, 0.10.

The resulting list of seventeen items included fifteen of the original nineteen items, plus two additional items. The seventeen items are listed in Table IV.

The item profile is described above, although arbitrary, is representative of the high backorder items because it includes the top ten, and fifteen of the top

TABLE IV

PROFILED CRITICAL ITEMS

Item No.	Expected Backorders	Unit Cost * Daily Demand Rate	Daily Demand Rate
68	24.4313	116.73	0.10909
538	6.3064	20.70	0.12909
1276	10.3170	23.68	0.20727
1727	37.7331	98.70	0.59091
1784	10.6412	38.64	0.10182
2493	40.8987	55.36	1.35273
3701	12.8291	26.44	0.24364
3993	25.6850	101.15	0.11818
5024	11.4035	22.98	0.25818
5258	36.6545	102.26	0.48727
5592	20.4683	41.53	16.60727
5661	9.2565	20.07	0.21818
6202	13.5548	56.98	1.22182
6927	14.6746	28.57	0.35818
7040	55.8451	169.17	0.83636
7394	15.6047	36.15	0.28182
7426	44.1408	193.10	0.54000

TOTAL 390.4446 = 40.78% OF ALL EXPECTED CRITICAL ITEM BACKORDERS, FROM 1.27% OF THE CRITICAL ITEM POPULATION.

nineteen. The seventeen items are responsible for 390.44 of the expected 957.45 critical item backorders. The importance of the item profile is that a high backorder item can be identified as one which requires additional management attention.

Analysis of the Effects of Profiled Items

Component re-design, as a result of Air Force incentives, was briefly discussed in the previous chapter. Re-design of a component by a contractor could result in either lower unit cost, improved reliability (reflected in a lower demand rate), or a combination of the two. Re-design of the complete set of 1,336 critical items in this study may not be possible, but re-design of the seventeen items responsible for many of the backorders is more feasible.

Table V shows the model results for a number of runs, each with a discounted value for either unit cost, daily demand rate, or both, for the seventeen high backorder items. Only the demand history for the 1,336 critical items was used for this portion of the study. For approximately the same inventory investment, and fewer orders, a decrease in the number of backorders was possible in each case. Availability also improved with the reductions in unit cost and demand rate for each of the high bckorder items. Table VI shows an alternative way of measuring the effects of the unit cost and demand rate changes. With a given set of constraints, and no changes to unit cost or demand rates,

TABLE V

MODEL RESULTS WITH DISCOUNTED UNIT COSTS AND DEMAND RATES

Constrained to $351,656 and 3135 annual orders.

Change	Expected Backorders #/year	On-Hand Inventory $	Orders #/year	Availability
No Change	1,241.82	350,466	2,697	.285
UC* 0.9	1,196.56	349,954	2,604	.298
DDR* 0.9	1,154.24	349,606	2,605	.312
UC and DDR * 0.9	1,126.40	350,620	2,599	.329
UC* 0.8	1,128.96	350,447	2,483	.320
DDR* 0.8	1,063.12	349,674	2,490	.342
UC and DDR * 0.8	963.60	351,521	2,289	.379

1,241.82 backorders are expected to be generated by the model's stockage policies for the 1,336 critical items. By changing the costs and demand rates to simulate the effects of a re-design of the seventeen high backorder items, equal performance levels can be achieved with lower investment levels. An increase in the number of orders is required in each case, but the workload is still well below the original constraint.

TABLE VI

MODEL RESULTS WITH DISCOUNTED UNIT COSTS AND DEMAND RATES

Comparable Performance with Reduced Investment Levels.

Change	Expected Backorders #/year	On-Hand Inventory $	Orders #/year
No Change	1,241.82	350,466	2,697
UC* 0.9	1,241.63	346,034	2,735
DDR* 0.9	1,240.23	342,343	2,875
UC and DDR* 0.9	1,236.52	338,902	2,898

V. Conclusion and Recommendations

Conclusion

This research has shown that the critical item performance of the model achieved during the AFLMC inventory system comparison study (2) can be improved upon.

The first method of decreasing the number of critical item backorders involved relaxation of the workload constraint. Only a modest improvement was possible, but it was an improvement nonetheless; it was achieved with a decrease in on-hand inventory. However, an increase in the number of order cycles and a decrease in on-hand inventory raises the risk of an item's exposure to to backorders, and the effect of relaxed workload constraint is soon negated. This simple method can only be expected to produce modest improvements in the model's critical item performance.

An additional improvement in critical item performance was possible with the use of artificial critical item unit costs. A discounted cost effectively increases the proportion of total inventory investment allocated to critical items. Using this method, a substantial reduction in the number of critical item backorders was generated, but at the expense of non-critical item backorders. The proportion of investment funds allocated to each of the two classes of items is a local management decision which can be supported by the model.

The "item profile" approach to critical item management showed that a small group of critical items was responsible for a disproportionate number of backorders. A number of model runs simulated the effects of improved component reliability (as reflected in lower demand rates) and cost reductions. Such changes are possible when incentive schemes are offered to contractors to improve the design of their components. The incentive schemes can be financed by the savings in the inventory system.

The behaviour of the model in arriving at a final solution has been commented on a number of times in Chapter IV. The model's final solution may not be totally acceptable because the model arrives at a solution after a constraint has been violated. Additional effort may be required to obtain a solution which does not violate either constraint. However, the model requires only modest computer processing time, and an inventory manager's familiarization with the model's algorithm should keep the additional effort to a minimum.

Recommendation

Minimal critical item backorders is a more operationally oriented supply objective than minimal variable costs or maximum fill rates because the importance of the items is recognized, and priority is given to those items which can cause an aircraft grounding. Availability measures have recently been developed which directly measure a repairable item's contribution to a weapon system's availability. Requirements determination can then be made on the basis of maximizing availability. Consumable items have not been included in the availability modelling efforts. Consumable items are not all managed on an individual item basis, as are repairable items; nor is the same type of data collected for consumables as for repairables. For instance, the quantity of each item on an aircraft is not recorded for the Air Force's critical consumables, although such information is necessary for an availability calculation to be made.

However, some of the requirements of an availability model can be met for consumable items. The aggregate model provides an backorder figure which is a requirement of the availability models in development. With expanded data collection for consumable items, the availability goal could very well be applied to consumable items as well as repairables, and provide the Air Force with an operationally oriented approach to determining requirements for all aircraft components. Research in this area would be of great benefit.

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A 1984 Air Force Logistics Management Center (AFLMC) study compared the Standard Base Supply System (SBSS) inventory models to ten alternative models. The AFLMC report concluded, in part, that an aggregate inventory system which minimizes backorders, subject to investment and workload constraints, better suits the operational needs of the Air Force than does a system which minimizes total variable costs. The AFLMC aggregate model was based on the Gardner-Dannenbring Two Lambda Aggregate Inventory Model, which does not discriminate between those consumable items which are critical to a mission and those which are not. This study investigated means of improving the model's critical item performance.

Considerable improvement was made possible by setting artificially low critical item unit costs, thereby increasing the proportion of funds allocated to critical items, but this improvement was at the expense of the model's non-critical item performance. Additionally, the model's critical item performance was marginally improved by reducing the workload slack in the model's solution. High backorder items, responsible for disproportionately large numbers of backorders, were identified by an "item profile" of unit cost and demand rate. The benefits of cost reductions and lower demand rates for the high backorder items (simulating the effects of component re-design) are demonstrated.

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