RESOURCE ALLOCATION TECHNIQUES FOR LOGISTICS MANAGEMENT

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1. INTRODUCTION

BACKGROUND

The United States Air Force has provided The RAND Corporation with a unique opportunity to study a logistics sytem in detail and to develop improved cost-effective management techniques. Three major factors have made this opportunity unique: (1) a relatively consistent and generous level of Air Force funding over a 15-year period; (2) a broad charter from the Air Force to investigate problems that RAND feels are important to the client; and (3) a close personal working relationship with Air Force personnel at all levels.

This paper describes a portion of the RAND logistics effort in resource allocation during the past six years. The objective is to demonstrate that the family of models discussed here (six in all) is applicable to other military services, to hardware contractors who are serious about integrated logistics support (ILS), and to non-military users such as the airlines. It appears that some of the models and many of the research techniques are even general enough to be used by medium-sized companies engaged in manufacturing and distribution.

The models themselves might be described as supply related, but in the broadest sense to include maintenance and operations. They address the problems of asset management including what and when to buy, where to place materiel, and where and when to repair.

Each model runs on a computer, but the computer time is kept to a minimum because each model is analytic; none use simulation. The models

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are all normative in the sense that they can analyze alternative support postures. For example, it is possible to assess the impact of shorter resupply times due to the C-5A aircraft, or to evaluate the logistics implications of different deployment options.

The models have a common ancestor known as the base stockage model (BSM), developed at RAND about five years ago. The BSM optimizes budget allocation across a group of recoverable or reparable spare parts used at one air base. During a six-month test at Hamilton Air Force Base, the BSM produced the following results. Even with a 20-percent reduction in budget, the fill rate (defined as the fraction of spare part demands immediately satisfied by base supply) was improved from 83 to 94 percent. Furthermore, the incidence of non-operationally ready aircraft attributable to the test items was reduced 32 percent when compared to the six months prior to the test.

Subsequently, in a field test at George Air Force Base, investment was reduced almost 46 percent with no degradation in fill rate or increase in the number of non-operationally ready aircraft.

The potential dollar savings possible using the BSM and its variants are enormous, since the Air Force procurement of spares alone approaches one billion dollars annually. Consequently, in the Advanced Logistics System now being designed at Air Force Logistics Command Headquarters, the policy innovations scheduled for earliest implementation are those in the stockage area. These policy changes are based on the RAND research described below.

The models are in various stages of test and acceptance by the Air Forces of Canada, Japan, Norway, Sweden, Great Britain, and Germany, as well as by commercial interests.

RESEARCH DEVELOPMENTS

Before describing the models, a few general comments are in order. The models are mutually consistent since they are based on the same body of mathematical theory. Technical details for each one can be found in the corresponding reports listed in the reference section. This body of research includes several important breakthroughs by the RAND staff, enabling the construction of the models. These include the following:

1. Extensions of the queueing theory literature generalizing the assumptions of Poisson demand [2].
2. The first practical formulation of a two-echelon problem where the stock levels at the several bases and supporting depot are jointly optimized over a group of items [5].
3. A highly efficient computational technique for finding the Lagrange multiplier in large-scale resource allocation problems [7].
4. A practical method for finding a set of Lagrange multipliers in multiple constraint problems [3].
5. A Bayesian procedure that capitalizes on early demand data leading to significantly better decisions for items with low or erratic demand patterns--the majority of items [13,14].

II. THE MODELS

Figure 1 depicts the family of integrated support models. The order of presentation, from top to bottom, corresponds roughly to the time sequence in which the models would be applied through the acquisition process.

SCAM (source-coders cost analysis model) is used in early acquisition to determine the appropriate mix of support resources at bases and depots.

METRIC (multiechelon technique for recoverable item control) optimizes the allocation of a procurement budget across a group of items and computes, by item, both the appropriate base stock levels and depot stock levels.

MINE (multi-indenture NORS evaluator) relates the procurement budget for spares to an operational measure of performance such as the number of aircraft not operationally ready due to lack of spares (NORS). This provides a tool for justifying a budget request or for taking a budget and dividing it appropriately into resources for each of several smaller programs.

RTM (real-time METRIC) takes the available assets of an item and makes optimal decisions about where and when to ship.

RPM (repair priorities model) provides a priority system to the repair facility indicating the best sequencing of items.

WRSK (war reserve spares kit) determines the additional spares necessary to support contingency operations.

SCAM (Source-Coders Cost Analysis Model)

One of the first decisions to be made during provisioning of components to support end items is determining (1) whether the component should be classified as a reparable item (able to be repaired) on the basis of economic considerations and (2) if so, what the level of repair should be, i.e., base or depot, or some combination of the two. In the United States Air Force this activity is called source and maintenance coding and is carried on prior to and apart from the requirements process. SCAM was designed as an aid to personnel who must make such decisions.

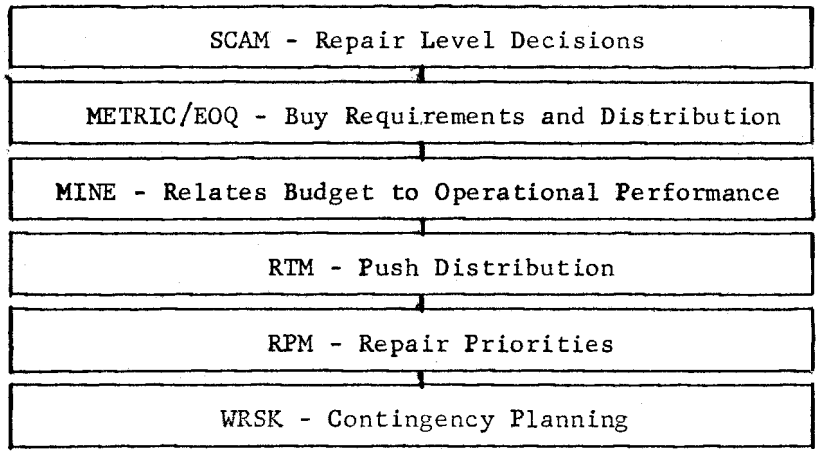

Fig. 1--Integrated Support Models

The decision process requires that both conditions of use and support costs be considered when assigning the source and maintenance codes. When it is determined that a part might be recoverable, the coders must then consider the repair alternatives, repair at base only, repair at depot level only, some repair at both levels, and finally no repair at all. To determine the optimal alternative, the resource requirements of each must be estimated and their costs aggregated for comparison and evaluation. SCAM is an automated costing model that develops total costs for comparison. The key to its utility is that it provides cost estimates that represent total resource requirements for each alternative for a specified level of performance. Through the use of optimal stock leveling techniques of the METRIC type, the model will compute the stock level required to meet the performance objective (backorders) for each maintenance posture. Given the stockage objectives, the model then aggregates the costs of the stock, equipment, transportation, repair, labor, training, facilities, and miscellaneous support required to operate each posture. These costs can be computed for a complete variety of base and depot structures for a range of programs.

The data requirements for model operation are available to coders making evaluations under current guidelines. SCAM was designed so that all data elements can be varied, and it thus can produce useful cost

estimates even when parameter estimates are uncertain or widely variable.

METRIC (Multiechelon Technique for Recoverable Item Control)

METRIC is applied to a base-depot supply system where a unit failing at base level has a probability r that it can be repaired at the base according to an arbitrary probability distribution of repair time, and a probability 1-r that it must be returned to the depot for repair according to some other arbitrary distribution. In the latter case the base levies a resupply request on depot. Since METRIC deals with recoverable or reparable items that usually cost over $50 apiece and that usually have a yearly base demand of less than ten, the appropriate policy is one-for-one replacement; there is no batching of repair or resupply requests. In our Air Force application, any demand that cannot be met immediately is backordered; however, the model can be easily restructured to handle applications where this excess demand goes to another supplier.

The model computes optimal stock levels at each base and the supporting depot for a group of recoverable spare parts in accordance with a budget or performance constraint. To our knowledge it is the first stockage technique for more than one echelon of supply to be proposed as a practical, implementable management system. The model can be used to determine the time-phased buy requirements; it can also be used to set distribution stock levels for each base and the depot based on the total assets of an item. In the distribution mode, the operating stock levels are computed periodically, and then resupply requests levied on the depot are satisfied on a first-come, first-served basis except when an aircraft is grounded for lack of the part. Consequently, the distribution system may operate in a decentralized manner where the bases "pull" material in accordance with their periodically computed levels, or in a centralized manner where the depot "pushes" material.

Since METRIC is the linchpin for our family of models, it seems appropriate to describe why the research was undertaken. When we began to look at the recoverable item stockage problem some years ago, we found three major areas that could be improved. In the first place, official policy did not utilize all the important parameters. For example, unit cost was not considered. Yet with a limited budget and

random demand it is not feasible to stock to the same depth on a $50,000 item as on a $50 item even though they have the same demand history. If the absence of either item can cause a not-operationally-ready aircraft, it is appropriate to stock more units of the low-cost item and place greater emphasis on expedited repair and lateral shipment for the high-cost item.

A second area for improvement was demand prediction. Because recoverable items have low, erratic demand at base level, the issue rate technique (where observed demand is divided by the time period) does not provide an adequate basis for demand estimation. We developed an application of Bayesian analysis. The Bayesian technique does not specify a single number as the issue rate technique does, but rather it specifies a series of demand levels with associated probabilities of their occurrence. From a practical standpoint the Bayesian technique extends the range of items stocked. The items that formerly had zero stock levels and now have positive levels are typically lower cost items that have a substantial probability of moderate demand, though their average issue rate is predicted as low.

The final area for improvement was in management decisionmaking. We felt that a cost-effectiveness curve should be generated to show the maximum performance attainable at any budget, or equivalently, the minimum budget required for any level of performance. This procedure should be contrasted with the traditional approach in inventory theory of estimating the cost of a backorder and holding cost, and then computing stock levels as a function of this cost ratio. What is the point of using such a cost ratio if the resulting stockage decisions exceed the available budget? Or if the resulting level of performance is unacceptably low?

EOQ (Economic Order Quantity Model)

Items managed under METRIC require tight management control, usually because the items are costly or are in critically short supply; all other items should be managed under the Economic Order Quantity (EOQ) model. EOQ items are generally low cost and can be reordered in batches. Some of the EOQ items, however, may be recoverable.

The EOQ model optimizes the allocation of a fixed budget across a group of items at one base. Or, more generally, it computes a series of equal performance curves as a function of the number of orders placed per year and the average inventory investment. Since the model computes a reorder point and a reorder quantity for each item, it is more complicated than METRIC, for which the reorder quantity is always one; it is less complicated than METRIC in that it addresses a single base rather than a complex of bases and the supporting depot. From an economic point of view, a multiechelon EOQ model probably does not make sense due to the low item costs, even if it were mathematically tractable. This is not only because of the computation costs, but also because a multiechelon model requires an extensive and costly data collection system.

MINE (Multi-Indenture NORS Evaluator)

METRIC avoids arbitrary cost estimates for holding inventory and backorders by producing a cost-effectiveness curve for investment cost versus total backorders at all bases. The manager can then select an appropriate cost or effectiveness target. To provide the manager with some insight in target selection, the MINE model has been developed to deal with demand at a single base.

MINE evaluates the expected number of aircraft not operationally ready at a random point in time because of supply (NORS). The model was developed for application to the F-111 aircraft for a multi-indenture problem, where demand on a first-indenture line replaceable unit (LRU) eventually causes second-indenture demands for one or more modules that are components of the LRU. As in METRIC, each LRU or module may have a probability of being base reparable and a probability of being depot reparable. We assume that part shortages are consolidated by cannibalization to minimize the number of NORS aircraft. Since the model is evaluative in nature, the inputs include item stock levels as well as item demand rates, average repair times, and resupply times.

An optimization model to determine stock levels that minimize the number of NORS aircraft subject to a budget constraint would be preferable to the evaluation model. An optimization model is not mathematically

tractable, however, because the criterion function is not separable into independent item calculations. Calculations using F-111 data indicated that if the METRIC model were used to optimize stock levels, the resulting NORS rate would be within one percent of the minimum NORS rate achievable with the same budget.

RTM (Real-Time METRIC)

RTM complements METRIC in a centralized or "push" system for recoverable item distribution. Instead of computing steady-state stock levels as METRIC does, RTM is a real-time decisionmaking model that uses current asset information and parameter estimates. No periodic updating is necessary because RTM is automatically updated continually. RTM does away with the base level concept. Decisionmaking takes place when serviceable spares are shipped from the depot to the bases based on the current "need" of a base and the current "reluctance" of the depot.

Results indicate that on high-demand items (greater than 1 per month), RTM can achieve a 30-percent reduction in backorders over that possible with a distribution system using base levels computed by METRIC. RTM shows little or no improvement with low-demand items.

An extremely important consideration is how well a decision rule performs with imperfect information (the realistic situation). When imperfect information (specifically, poor demand estimates) is introduced, RTM's relative advantage is significantly increased.

RTM can also be used with regional supply bases, a third, intermediate echelon of supply. This method applies especially to items with worldwide usage, and reaps much of the benefit that can be obtained via lateral supply between bases. The triple echelon method (depot, regional supply base, satellite base) is more complex than the base-depot system, but is a significant further improvement when applicable.

The computer program for RTM is much simpler than that for METRIC distribution, and the annual computer time for a group of items is estimated to be substantially less. This latter fact may be somewhat surprising in that RTM calculations must be made daily whereas METRIC may be recomputed only once a quarter.

An additional advantage of RTM is that it can handle the distribution problem for a family of items with limited interchangeability. In this case, the decision about whether to ship a master item to satisfy a demand for a limited interchangeable on which there is no stock must take into account the stockage position on other interchangeables. Also, RTM contains a lateral supply rule that determines when to make shipments between bases.

RPM (Repair Priorities Model)

In the distribution process the optimal decisions on one item are independent of any other item (unless the item is interchangeable) since the investment money has already been spent. However, in the requirements process, either buy or repair, items are competing for resources. RPM is a variant of RTM which computes system "need" for each item of a group over a planning period. The system's need for an item is the sum of the corresponding base values. To compute the need of repairing one, two, or more units of an item, we recompute the system need assuming that the on-hand balance is increased by the corresponding amount. It turns out, not surprisingly, that the need to repair the $k+1^{st}$ unit of an item is always less than the need to repair the k^{th} unit.

The outcome of this calculation is a ranking that specifies in order of decreasing importance that we should repair, say, a unit of item 4, a unit of item 2, and a unit of item 1, a second unit of item 2, and so on. The shop scheduler making up the repair plan for the next period attempts to repair those items with the highest priorities subject to the availability of reparable carcasses and appropriate skills. The technique is not directly applicable to items with a significant repair setup cost, but such items are relatively rare in our experience with Air Force items. There is, of course, a significant learning curve effect that influences the time to do repair, but this does not alter the validity of our model. Even in cases where the repair setup costs must be considered, it is not difficult to modify the priority scheme in an appropriate manner.

WRSK (War Reserve Spares Kit)

It is often the case that a set of stock levels must satisfy more than one type of programmed activity. For example, the stock levels of an Aerospace Defense Command base must support the peacetime flying program, but they must also be capable of supporting a high level of activity for a short period of time in the event that the United States is attacked. Furthermore, during such a period the logistics posture for these aircraft will be drastically different since the aircraft may be operating from dispersed sites with reduced maintenance capability and no depot resupply.

Another example is the Tactical Air Command where there is a normal flying program requirement as well as a deployment mission.

In the past, the stock to support these additional missions has been computed independently, ignoring the effects of pooling. Furthermore, in the interest of simplicity, the basis for computing the additives has been quite unrealistic; most Tactical Air Command mobility kits were computed on the assumption that there would be no resupply for thirty days and then full resupply afterwards, though planners are hard put to identify any contingencies, past or anticipated, conforming to this pattern.

We have developed a War Reserve Spares Kit model to assist in planning for the types of contingencies described above. One would first use the METRIC and EOQ models to compute buy requirements for the normal program. Then the WRSK model focuses on a single base and the set of stock levels determined above for the group of items. Based on the stock level for each item, WRSK computes the probability that there will be zero, one, two, ..., n, serviceable units of the item on the shelf when the contingency occurs. Then WRSK determines the optimal allocation of additional budget to support the contingency. The criterion of meeting the contingency may be expressed in several ways including maximization of the probability of mounting a specified number of sorties in a specified period. The criterion may include the restriction that mass sorties are required (at least x aircraft must be flown on each mission).

It is important to note that the WRSK model uses the repair times and capabilities, resupply assumptions, if any, and general environment

of the contingency. Thus it provides the vehicle not only for joint optimization of resources, but also for a much more appropriate representation of the types of contingencies that can be expected to occur.

III. CONCLUSION

We have described a family of related cost-effectiveness models for logistics planning and support. Though they have been developed and described in an Air Force context, we believe that they are relevant to a much larger audience. In today's military it is highly probable that future budget constraints will force exploitation of cost-effectiveness techniques to enhance the support of combat capability in the face of declining budgets. The models described were designed to meet this challenge.

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