# LOGISTICS MODELS: EVOLUTION AND FUTURE TRENDS

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## I. INTRODUCTION

History and doctrine recognize the key role of logistics in warfighting. However, only since World War II have logistics models been a key element in the planning and operation of support functions. Operations research methods that have been applied to support problems include: linear and dynamic programming; networking and queuing techniques; inventory, reliability, and decision theory; simulations (both man-machine and machine); and statistical models. In many cases these methods were initiated and evolved because of the needs of the military support area.

The number and complexity of weapons systems have grown tremendously since World War II. Modern technology has brought with it enormous changes in communications, transportation, materials, and data processing. The very nature of warfare has changed in terms of rapidity of attack, severity of weapons effects, increased territorial scale, and complexity of management requirements. Logisticians will rely more and more on models to deal with the complexities of procuring, maintaining, and transporting military material, facilities, and personnel. Models

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predict the requirements for support, evaluate the effect of alternative support plans on warfighting capability, and project the readiness of the support system to go to war.

Support modeling is sweeping in its application to:

- Forecasting resource requirements.
- Purchase, stockage, distribution, and data handling for spare parts, ammunitions, fuel, food, medical supplies, and construction materials.
- Transportation system design and utilization for peacetime support and strategic mobilization.
- Design of weapons systems for maintainability and reliability.
- Maintenance management policies including inspection, replacement, and workload scheduling.
- Communication, including the design of message and data transmission systems.
- Maintenance and repair facility location and layout.
- Personnel and training requirements for maintenance of weapons systems.

This chapter will discuss generally (and incompletely) past and current logistics models in several of these areas and point out that:

1. The logistics support functions have been rich domains for model development and have been at the forefront of certain methodological developments.
2. Despite the sophistication of many of the methodologies, there are important aspects of military logistics problems that have yet to be modeled adequately.

3. Although there has been some recent progress, much remains to be done with respect to the modeling of logistics support in the context of the real mission of the military--readiness and sustainability of the operational forces for and in wartime.

## II. LOGISTICS MODELS--THE INTERSECTION OF FUNCTIONAL AREAS

### MODELING METHODOLOGY, AND MEASURE FUNCTIONS

Logistics models can be viewed as the intersection of one or more of the various functional areas of support, one or more of the methodologies of operations research, and measurement functions as illustrated in Figure 1.

In many cases, several different methodologies have been applied to single functional areas. More significantly, there has been a trend toward models that combine several functional areas, permitting much needed tradeoff analysis. The earlier models were driven by measure functions that dealt with how well a particular logistics function was

Functional Area

- o Maintenance
- o Supply/inventory
- o Transportation
- o Communication
- o Other (procurement, basing, facility location and layout, etc.)

--- The Logistics Model ---

Methodology

- o Simulation
- o Mathematical programming
- o Network methods
- o Decision methods
- o Statistical and probability methods
- o Other (heuristics, production functions, etc.)

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Measure Functions

- o Individual function measures--e.g., fill rate, equipment utilization
- o Cross functional peacetime measures--e.g., operational ready rates
- o Cross functional wartime capability measures--e.g., combat capable aircraft available to fly as a function of time

Fig. 1--The Logistics Model

performed. Many were measures of internal efficiency rather than system effectiveness. As models began to integrate several functional areas, the measure function properly focused on more general or system wide effects. The problem with the more general overall objective function was that it usually dealt with system performance in peacetime. Recently there has been movement toward measures that attempt to reflect warfighting capability, but this is still a major area for improvement.

The following illustrations will describe some of the logistics support problems, methodologies applied, and some issues that remain.

## MAINTENANCE

Modelers have given considerable attention to several important aspects of maintenance: replacement and inspection policies, reliability, and workload scheduling and planning.

### i. Maintenance replacement and inspection strategies.

The basic problem is to determine when to inspect and replace components of weapons systems that are subject to failure. It is desirable to perform this inspection and possible replacement as infrequently as possible because of the cost of inspection and spare parts and the unavailability of the weapon system during maintenance. Letting the system run until failure, however, may be undesirable because of increased cost of maintenance, possible hazardous operation, and unpredictability of failure time (especially during wartime).

Most of the work has been done on simple (nonredundant) system preventive maintenance models, which attempt to reduce down time of the equipment or minimize maintenance cost to achieve a given level of protection from failure. Generally, these models assume that:

- Time to system failure is unknown, but some aspects of the lifetime probability distribution are known.
- Maintenance regenerates the system.
- Maintenance actions are independent.

To illustrate the varied methodologies applied to these problems consider that: Bellman (1955) applied dynamic programming to determine optimal replacement policies under the above assumptions. Barlow and Hunter (1960) applied a decision-theoretic approach to determine optional preventive maintenance policies; more recently, Arrow, Levhari, and Sheshinski (1972) used a production function approach for the replacement problem. Wagner, Giblis, and Glaser (1964) illustrated the use of mathematical programming for the age replacement problem. A recent and fairly complete survey of models by Sherif and Smith (1981) shows more than 500 articles and books on the subject.

Most results describe optimal policies in terms of the nature of the failure distribution and the way it changes in time (increasing failure rate, etc.). A few papers describe procedures for unknown distributions. Cohen (1972) described a process of controlled inspection interval extension for this case.

A number of aspects of this problem require further development and refinement of the modeling. The objective must include the possible effect of failure or decreased capability in wartime. This means, among other things, that the nature of the measure function must change and that fluctuating utilization and value over time must be explicitly considered. Also, the failure distributions of wartime damage and wear due to unique wartime use must be considered in addition to normal projections of failure from incorrect utilization. Most models do not adequately represent the complexity of modern weapon systems. The skill of personnel to diagnose and the ability of test equipment to isolate system failures in addition to 'black box' failures must all be jointly considered. Additionally, experience with modern weapon systems indicates that maintenance induced failures and the inability to pinpoint causes of problems produces a heavy workload and causes "removals" that are not the result of any inherent failure characteristic of the component. This raises as a major issue, pervasive across all aspects of maintenance and supply, the usefulness of mean time between failure as an indication of demand rather than mean time between removal. Finally, the interaction of replacement policy and stockage should be considered. All of these factors greatly increase the complexity of the model and constrain the choice of methodologies.

ii. Reliability

The problem is to design reliable and maintainable weapon systems by using modular components, redundancy, and components, frequently with unknown reliability. In most models, reliability is measured in terms of the probability that the system will be operable at a given time; the design problem is to achieve a given level of reliability at minimum cost in components.

Most of the work in this area is stochastic and descriptive, generating basic rules for reliable designs. Barlow and Proschan (1975) present a consistent theory of reliability and life testing in their excellent book. Others, such as Gross and Kamins (1967) have described the application of statistical techniques to empirically determine reliability changes in complex weapon systems. A few papers have described the optimal design of reliable systems using mathematical programming approaches. Kettelle (1962) described the least cost allocation of reliability investment using a dynamic programming algorithm. Jacobsen and Arunkumar (1973) applied nonlinear mathematical programming to maximize the expected lifetime of series and parallel systems.

This area of maintenance also has considerable need for improved modeling to deal with such issues as the interaction of reliability with supply, maintenance replacement, and measures of wartime capability. A special area of concern is the optimal improvement of current system reliability--that is, the determination of what components and elements of design of a weapon system to improve to increase capability and reduce cost (including supply and munitions costs). This area must also emphasize the possible wartime use of the system to assess both cost and effect of different levels of reliability.

### iii. Workload Scheduling

Scheduling problems or problems of sequencing abound in all aspects of military planning. In the maintenance function the problems of scheduling work as it arrives in a shop (workload scheduling), and planning the sequencing of work requiring multiple tasks and equipments have received special attention. The well-known flow shop problem has n jobs of various duration for m machines, procedure requirements for processing, and usually a flow time, due date, or machine utilization objective. This by itself is a very difficult combinatorial problem, which many modelers have studied with only limited success. Generally, only the two-machine problem has a known solution, although results for more complicated problems have been stated. Conway, Maxwell, and Miller (1967) characterize the flow shop scheduling problem and solution approaches to it. Maxwell (1969) applied simulation to assess various types of rules, and many articles such as an early one by Johnson (1954) describe rules of sequence.

Workload scheduling increases the complexity by including the random generation of demands for processing. In the military this randomness is associated with the random failure of weapon system components as they are used. Most of the successful modeling for this problem has been with simulation (see Miller, 1973, for example) and special network techniques such as GERT (Pritzker and Hopp, 1966) and Q.GERT (Pritzker, 1967).

A criticism that can be made for almost all models developed for this problem is that the flow time, utilization, and due date objectives are inadequate measures, particularly when the scheduling is for components of weapon systems whose ultimate purpose is warfighting. In general, deterministic N job M machine models have little relevancy to military maintenance. Military models need to examine decisions about priority repair and expedited repair in the face of stochastic demands. There may be N jobs but seldom more than one (or two) machines in military models. The degree of mission essentiality and criticality of the components must be included. For example, when adequate spare components exist, the need for immediate repair of an item may not be as high as for one with no spares. A component that will degrade mission capability only slightly will have less priority than one with high essentiality. Priority repair, a necessary aspect of workload scheduling in the military, is mostly ignored in current scheduling models.

## SUPPLY AND INVENTORY ANALYSIS

Multi-echelon inventory analysis has dominated the modeling work in this area. The problem is to determine ordering, inventory, and distribution policies for two or more interrelated supply or production facilities. In the military these represent depot repair facilities, intermediate repair shops, and the inventories associated with each. Although the basic effect of the policies is on availability of weapon systems, more intermediate measures--such as the probability of satisfying demands for components and the expected number of components backordered--have generally been used. Most models of this process make assumptions about the nature of demands--whether they are deterministic or stochastic, whether they are stationary or nonstationary, whether demands not satisfied immediately are lost, and whether demands arise from a single type of component or multiple types. The inventory review process is assumed to be either continuous or periodic and the components may or may not be repairable.

The spare parts problem and maintenance problems are intimately related. Sufficient spare parts can allow weapons systems to operate while components are being repaired. Flexible priority in maintenance can quickly repair weapons systems when spares are short. Generally, multi-echelon inventory models consider the maintenance and transportation of components (the converse is not usually true for maintenance models), although the information used (average repair time, location of repair, and average transportation time) is usually minimal.

The multi-echelon problem is of extreme interest to the military because of the influence component shortages have on weapon system capability and because the majority of logistics resources (manpower, depots, test equipment, transportation, etc.) are included in it.

Several authors have developed models for this area:

- Zangwill (1966) described a deterministic approach and characterizations of solutions for a multi-product, multi-facility production and inventory problem.
- Veinott (1969) recognized the network interpretation of this problem.

- Sherbrooke (1968) applied marginal analysis and the use of Lagrange multipliers to determine optimal supply policies.
- Muckstadt (1973) who extended the Sherbrooke work for indentured components (subcomponents of components).
- Kotkin (1978) developed an heuristic algorithm for the multi-echelon indentured item supply problem.
- Hillestad and Carrillo (1980) extended the Sherbrooke and Muckstadt work for non-stationary demand processes.
- Clark and Scarf (1960) applied dynamic programming to the periodic review multi-echelon problem.

Another aspect of the supply/inventory problem includes the distribution of inventory to meet the time dependent and mobility requirements of the military. Miller (1968) used simulation to investigate alternative real-time distribution rules for components shipped from depots to airbases. Landi (1967) used mathematical programming to determine optimal prepositioning rules for spare parts for military transport aircraft.

The multi-echelon inventory models typically treat the sources of repair and capability to repair as known elements of the problem. The Level of Repair Analysis (LORA) problem complicates the models by letting these be decision variables as well. Fixed costs of facilities manpower, test equipment, transportation links, etc. frequently lead to large integer models. (This area is further complicated with the politics surrounding military facilities location and the commonality of facilities, equipment, and skills for some new and old weapon systems.)

The major criticism of work in the inventory/supply area for military applications is the lack of attention to objectives that emphasize weapon systems availability and capability. The use of a backorder measure does not consider the relative importance of different components of weapon systems, and does not properly reflect their availability even when all elements are essential; it does not account for the cross-cannibalization (consolidation of shortages on the smallest number of weapons systems) that commonly occurs. Other important features of actual logistics operations--such as lateral supply (borrowing components from other bases); priority repair of backordered, critical components; and priority transportation from military depots--have not been treated in most models. Wartime military operations with uncertain arrival of transportation and possible disruption of repair are ignored in most of these models as well. Most of the modeling assumes that something is known about the demand for maintenance and spare parts in terms of its expected value or probability distribution. In truth, we know very little about the failure and removal patterns of components from new weapon systems during wartime. Inventory/supply models should be designed to reflect this uncertainty when generating optimal stockage policies.

## TRANSPORTATION

Basically, the transportation problem is to design a network of routes or carriers to move the materials and personnel of war. The overriding aspect of this problem is to create a transportation system that can respond in a timely manner to varied mobilization requirements. The cost to create such a transportation system and maintain it in peacetime brings in economic considerations and the tradeoff between time and network capacity. (The capacity of military transportation is generally described in ton miles per day--that is, how many tons can be moved how many miles per day.)

Transportation problems during and after World War II sparked the development of that special class of network algorithms called transportation algorithms. Dantzig (1962) and Ford and Fulkerson (1954) provided early developments in these algorithms. The special case with the military time objective was called a "bottleneck" transportation problem, and Hammer (1969) and Garfinkel and Rao (1971) developed special algorithms for it. Fulkerson and Dantzig (1954) used integer mathematical programming to include additional real constraints in tanker scheduling. Others resorted to simulation. For example, Nolan and Mastroberti (1972) simulated an entire airlift operation to understand the quantitative need for C-5A transport aircraft; and the Defense Department currently uses a large simulation called MIDAS to study airlift requirements and capabilities.

The use of ton miles/day as a measure of the military transportation system is inadequate for many purposes because it does not state the effect of shortfalls in transportation capacity or the effect of delays on output measures of the total support system, not just the transportation system. Since transportation is generally a key element of weapon systems support (transporting those systems, spare components for those systems, and maintenance personnel), it should be measured in terms of the capabilities of those systems. Models must consider the effect of losses and degradation of transportation on those systems. Furthermore, the value of priority transportation for certain commodities in a multi-mode, multi-commodity transportation system for wartime support must be measured at the weapon system. An example of a model that attempts to relate the performance of the transportation function to relevant system-wide output measures is discussed by Berman et al (1982). The interaction between the transportation and other logistics functions and their impact on sortie generation capability over time is dealt with explicitly. Tradeoffs between more spares and more transportation, or more transportation versus more weapon systems can be performed directly.

## COMMUNICATION

Most modeling work in the communication area has been done on the synthesis problem--designing communication trunks and switching networks for given capacities at minimum costs. Problems of special interest in military communications include message criticality, high reliability requirements, the potential loss of trunks and switching centers, and message security. Kalaba and Juncosa (1956) described a linear programming approach to synthesis and message routing and suggested the use of weighting functions for critical messages. Gomory and Hu (1964) recognized the applicability of various network approaches to the problem. Cady, Lientz, and Willsworth (1974) described experiments in communication networks to determine the tradeoff of economic efficiency through centralization and vulnerability.

## OTHER FUNCTIONAL AREAS

The logistics areas described above represent only a fraction of the military problems where operations research models are needed and have been usefully applied. Facilities location and facilities layout for effective maintenance and reducing vulnerability of weapon systems have been addressed with varied mathematical programming algorithms. Various forms of centralization or decentralization problems in supply, maintenance, and other support functions have received attention over the years. (Typically, the military have an economic incentive to centralize and span of control and vulnerability incentives to decentralize. Since the former is more important in peacetime and the latter in wartime, the tradeoffs between the two have not always been fairly considered.)

Procurement problems in terms of bid evaluation, phased procurement of support materials, facilities expansion, planning, and budgeting are very big problems requiring and frequently using the models of operation research.

Clearly, the functional areas of logistics support have been fruitful ground for the development of modeling methodologies, and many models have contributed to the effectiveness of the logistics functions. Still (as we have briefly indicated), much remains to be done to expand the scope and realism of those models within the functional applications; and, of course, there is the continuing desire to get more integration of models between functional areas. Frequently, models ignore military objectives and constraints in favor of peacetime economic objectives or intermediate measures of the particular function being examined. The next section gives some historical perspective on this issue and discusses the evolution that models are undergoing for a more direct consideration of the influence of logistics on wartime capability.

# III. HISTORICAL TRENDS AND THE NEED TO REFOCUS THE LOGISTICS MODELING EMPHASIS AND SCOPE

## MODELING EMPHASIS AND SCOPE

Since World War II and up to the early 1970s, the primary emphasis on defense was strategic deterrence. The de-emphasis of tactical conventional capability because of the nuclear umbrella caused much of the logistics concern to be peacetime support of the forces. The long period of peacetime activity for the military, the reduction in real defense appropriations, and the increasing cost of sophisticated weapons systems motivated logistics modeling to look for cost minimization within peacetime performance constraints. Logistics, becoming increasing costly and yet loosely related to operational performance (most models, as illustrated in the previous section, used intermediate objectives associated with the specific functional areas), was highly vulnerable to military budget cutting, even within the defense establishment. The effect on warfighting capability if $100M less of spares were purchased was simply not apparent. The effect of not having ten aircraft or 100 tanks was more intuitively obvious.

The result of this economic emphasis and lack of distinct relationships to operational performance led to models around peacetime efficiency. Structures and policies were based on least cost peacetime alternatives. Arguments for centralization and decentralization of maintenance and supply were generally based on peacetime economic considerations rather than potential wartime support requirements.

Visions of tomorrow's wars include a very dynamic environment, entirely mobile threats, potential for high vulnerability, and generally a great deal of uncertainty. Wars may be fought anywhere on the globe. Nuclear weapons may be used in sustained operations. War may be just conventional or combined conventional and nuclear. The objectives, constraints, and structures of logistics support models must now deal more directly with the dynamics, uncertainty, and mission objectives of warfare.

Clearly, support requirements are likely to be more dynamic in wartime than in peacetime. The failure rates of weapons systems, availability of maintenance during a deployment, and surges in weapons systems activity rates will place different requirements on the support structure than the peacetime activity. Muckstadt (1980) shows, for example, that the spare parts requirements for a surge of activity are incorrectly approximated with the stationary inventory models currently in use. Lippiatt et al. (1981) showed that priority repair would clear a bottleneck on an aircraft carrier, whereas approximations with a steady-state queuing result predicted an infinite queue. In that case, the question was not whether the maintenance facility was overloaded but how quickly the overloading became apparent at the weapon systems under wartime activity rates.

New logistics models must consider the uncertainty of tactical wartime support requirements. The models must provide robust answers to support requirements when the scope, scale, and type of operational activity is only an educated guess. The uncertainty regarding losses and damage to support systems and about such weapon system characteristics as failure rates, mission effectiveness, and wartime maintenance requirements are key issues. The support environment itself may not function anywhere near as well as peacetime operations. (Modern military supply systems are almost totally dependent on large centralized computer systems with supporting computer systems at each base. Capability after mobilization when the computer support is lost may be seriously degraded.)

Support objectives in wartime are different from those in peacetime. Efficiency, quality of life issues, and costs will take a back seat to mission effectiveness. Models tuned to wartime logistics support will recognize that support is provided for maximum effectiveness of the weapon systems and forces supported.

Finally, because future tactical warfare may be considerably different from previous wars, models based on past views of wartime support requirements should be rethought. More capable weapons (in payload and accuracy) and increasing vulnerability of support make support disruption an important consideration. A great ability to inflict damage may mean a short, intense conflict, increasing the requirements for carefully calculated initial support. Further, the sophisticated tactical weapon systems currently planned and in use require different kinds of support in terms of complex test equipment, skilled technicians, and high reliance on communications and computers.

Logistics models are beginning to accommodate these new views. The work on dynamic multi-echelon inventory systems by Muckstadt (1980) and Hillestad (1981), the evaluation of support in a theater of war under battle damage conditions provided by Emerson's TSAR-TSARINA models (1982), the Berman et al. (1982) use of wartime models to investigate theater transportation systems, and the U.S. Air Forces development of War Reserve Spares Kits based on measures of aircraft availability rather than supply backorders point are only a few of the recent developments in this direction.

## IV. SOME IMPORTANT REMAINING ISSUES IN LOGISTICS MODELING

Military modeling areas are merging and should continue to do so. For example, battle management models need to consider logistics support (particularly in the case of damage and losses). Weapon selection models must become highly sensitive to the support requirements. (Requirements for sensitive, complex test equipment may be inconsistent with the probable environment of the weapon system.) Manpower models need to show the influence of manpower on the supportability of weapons, and tradeoffs between personnel skills and design of complex weapon systems need to be understood.

The drive for more operationally oriented performance measures for support models must continue. Weapon systems availability is a start but it is certainly desirable to consider mission capability, mission effectiveness, etc., as well.

There should be more effective use of good support models in the ongoing management of logistics. We must move from the bean counting approach of current readiness reporting to using models to predict force capability to go to war as a result of current logistics states. Implementation issues and the management structure affecting model use continue to be important.

## V. CONCLUDING REMARKS

We have presented only a sample of the functional areas and logistics support models, but it should be clear that logistics has been and will continue to be rich territory for operations research models. Mathematical programming, stochastic analysis, simulation, and other approaches have certainly made important contributions to military logistics. The models are evolving toward the wartime support aspects of logistics and more relevant measures of military performance. Finally, as weapons systems and support requirements become more sophisticated and complex there are important issues requiring more integration of military modeling areas. Examples of the wider application of these newer models are for studying basic, general decision areas such as tradeoffs between short term and long term goals--i.e., between readiness and force modernization, or the allocation of relatively fixed dollars among competing but interrelated demands (people, test equipment, spares, transportation).

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