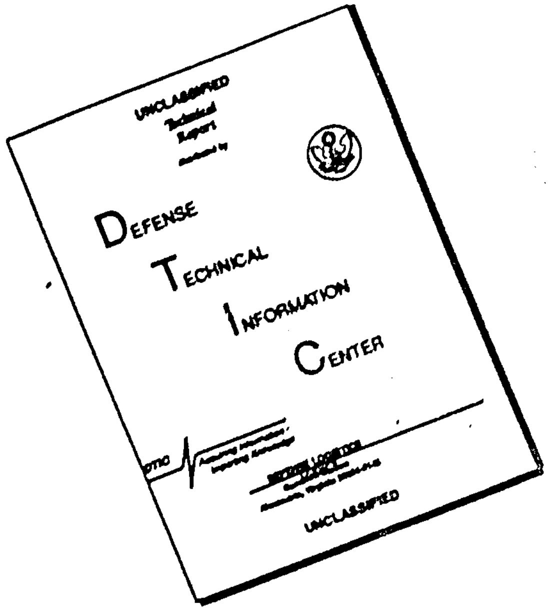
OPTIMIZING FORCE DEPLOYMENT AND FORCE STRUCTURE FOR THE RAPID DEPLOYMENT FORCE

THESIS

James C. Cooke
Captain, USA

AFIT/GST/OS/84M-7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THESIS

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Master of Science in Engineering

James C. Cooke

Captain USA

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Preface

The topic of optimizing a strategic mobility force was generated by the Army War College, Carlisle, Pennsylvania. LTC William T. Murphy, USAF, of the Army War College faculty, was very helpful in defining the problem.

Special thanks go to my academic advisor, LTC Ivy Cook, who gave me the latitude to work independently, while making numerous pertinant suggestions. I am also indebted to my reader, LTC Palmer Smith, who not only made excellent suggestions but was extremely helpful in guiding me through the intricacies of response surface methodology. I also wish to express my heartfelt gratitude to my typist and friend, Marietta Gress, for her endless patience in transforming my chicken scratching into a readable product. And of course I have unbounded thanks for the love and support of my wife, Kathleen, and four sons, who in their own way put as much work as I did into this effort.

James C. Cooke

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Abstract

This paper describes a goal programming approach to modeling the rapid deployment of combat units which offers decisive advantages over any current methodology. It accounts for both intertheater and intratheater airlift, and can be used to optimally plan movement schedules for predetermined forces or optimally choose and move a force from a list of available units and airlift resources to meet specified goals. Both methods are demonstrated, showing that the goal programming model minimizes wasted resources and accomplishes desired goals both faster and more exactly than the current interservice operating system. The model developed for demonstration uses 212 variables and 136 separate equations. In addition, a flexible response surface methodology is used to generate a full parametric sensitivity analysis, resulting in the reduction of a fully computerized and intricate large scale programming model to an equation programmable on a hand-held calculator, with minimal error. A demonstration is presented comparing relative advantages of C-5 and C-17 aircraft procurement, in a proposed addition of 50 aircraft to the current airlift fleet, with simultaneously varying airport capacities and deployment distances.

I. Introduction

This thesis was developed in response to a perceived need to approach the deployment of combat forces using a total system methodology, rather than the present method of separate mission/service optimization studies. The model developed in this research effort is a multiobjective optimization which addresses intertheater movement, intratheater movement, and deployable unit capabilities.

Background

In 1980, the United States government identified a requirement for a capability to move large conventional (non-nuclear) ground forces to any location within a broad geographic area centered on Southwest Asia. Therefore, it formed the Rapid Deployment Joint Task Force (RDJTF), now redesignated the Central Command (CENTCOM). This force consists of the 82nd Airborne Division, the 101st Airborne Division (Airmobile), the 24th Infantry Division, two Ranger battalions, and Air Force, Navy and Marine forces. The RDJTF Army units are all forces which facilitate air transportability.

Although CENTCOM was developed in direct response to a perceived threat, the Air Force has insufficient aircraft resources to support the full and rapid deployment of CENTCOM assets. The Army, in its deployment planning, can consider only the current inventory of Military Airlift Command (MAC) assets. When planning a deployment, therefore, critical decisions must be made as to how best to use limited air transport. The basic decision must key on increasing the combat potential available to the ground commanders at the risk of reducing the sustainability of the already deployed force. Combat potential is a complex and currently largely subjective index of the fighting capabilities of the force, based on deployed troops, tanks, and artillery. Sustainability is the continued ability of a force to fight in the event its supply line is interrupted by either enemy actions or natural means, such as weather. Sustainability is provided both by supplies and by combat support units such as maintenance companies.

Examples of failure in both deployed combat potential and sustainability can be demonstrated by historical example. One example is from World War II when the Soviet Union conducted brigade-sized airdrop operations near German armored units. The armored units quickly eliminated the relatively low combat potential the parachutists represented. In another example, sustainability was demonstrated in the loss of the German Sixth Army at Stalingrad. A large, powerful force was defeated because of insufficient and improperly distributed supplies. At the end, the still powerful Sixth Army surrendered, showing low morale and an inability to engage some targets due to lack of ammunition.

The U.S. Army must plan its deployment of forces to avoid both of these extreme cases. Currently scenario war plans are developed by operations analysts, who determine what forces they believe are required and by what date for a given scenario. Logisticians then calculate required supplies to support the force, using tabulated data. Given this data, the transportation officers attempt to move the required force packages by the required dates. If this is deemed impossible, the force planners either extend the required due dates or reduce the planned force.

The implementation of this process has resulted in Under Secretary of Defense Chayes reporting a requirement for between 50 and 150 C-5A equivalents in order to meet urgent national security needs (Ref 10:30). Limited airlift assets prevent the Army from moving everything it requires to respond to a major threat at a single time. Therefore, decision makers must be able to evaluate, at each point in time, how best to use the forces and resources available. This should be done by incorporating into the process the reduction of airlift resources caused by each force unit's "tail", the logistical requirements of the force.

Although this is a critical consideration for U.S. planners, research to date has addressed the problem only peripherally. The U.S. Army War College 1983 list of "strategic issues...most relevant and urgent for the army to study" (Ref 3:23) specifically identifies the issue of sustainability and strategic mobility as an unsolved research area. Col. Dale [illegible] Chief of the War College [illegible] Operations and [illegible]ning group; LTC. Murphy, [illegible] to the Doctrina[illegible]d Force Issues group of the War College

Military Strategy department; and Mr. J.E. Trinnamen, head of Mediterranean studies for the Strategic Studies Institute, have all separately proposed that immediate research be conducted on this topic (Ref 3:26-18).

Problem

There is presently no methodology which determines how the interactions of unit weight, combat attributes, logistics needs, and airlift resources can be jointly optimized. Because of this, there is currently no system to determine, analytically, the optimal force mix or the incremental advantage in deployed power attainable by an incremental change in airlift resources.

Research Objective

The primary objective of this research effort is to determine a methodology by which to optimize combat power delivered to a theater during a specified time, within acceptable levels of force sustainability. The use of this methodology is demonstrated through implementation of a small-scale model. The objective measure of merit is a methodology which simultaneously incorporates unit weights, requirements, combat power attributes, resources, and in-theater constraints to find global optimal solutions, and allows sensitivity analysis of the interrelationships in order to determine relative worth of the airlift resources.

Scope

1. With the emphasis on rapid deployment, this stu
will address only air-deployed, air-supported units. Th
close presence, in a crisis, of logistics ships or Marir
Amphibious units is fortuitous, but cannot be relied upc
with current worldwide commitments.

2. Only the case of CENTCOM deploying into a singl
friendly airfield capable of supporting strategic airlif
will be developed.

3. Once deployed into theater, the standard supply
consumption rates will be used.

4. This study will incorporate only Air Force airc
and designated Civilian Reserve Air Fleet (CRAF) to move
CENTCOM assets.

5. This study will not cover any attrition modelin
forces leadihg to decreased supply requirements.

6. Sustainability will be kept as a constant measu
across the entire deployed force. That is, all forces,
unsupplied, would run out of all supplies at the same ti
This is assumed as a logical result of proper logistical
plannning, as it wouldn't be acceptable, in combat, to r
out of ammunition but have ten days food on hand, or vic
versa.

Assumptions

1. The posture-related combat supply requirements

listed in Army Field Manual 101-10-1 and Army Supply Bulletin 710-2 relates the best expectations of Army logisticians and is assumed to be accurate.

2. Combat power as a variable can be given a definitive value in a set scenario for a given type unit, and the utility of all deployable units, in relation to each other, can be rank ordered. Although quantifiable values for the abilities of each type of unit are difficult to determine, experts in the field of operations planning should be able to quickly, accurately, and subjectively rank order the relative unit desirability (Ref 9, 21).

3. Aircraft moving units may be cross-loaded with more than one unit. A linear trade-off relationship is assumed between different categories of cargo. Therefore, if an aircraft is filled to 50% of its oversize carry capacity, it can still add up to 50% of bulk carry capacity.

4. An Aerial Port of Delivery (APOD) exists which has a ground link to the area of force employment, and at least one secondary airfield exists in the area of the deployed force location.

5. Free (no transportation cost) aircraft POL is available in unlimited quantities at the airfields. This is a common assumption and will be repeated here. If this is eventually not the case, the sorties available may be reduced or the cargo capacities changed.

6. The air cargo weight of a unit can be completely expressed in terms of outsize, oversize, and bulk cargo, and

these categories are independent of the aircraft hauling the cargo.

Methodology

The overall objective of this study is to develop a methodology to maximize combat power delivered to a theater as a function of time. This can be broken into two subordinate and equally important goals: maximize the combat power delivered, and minimize the time it takes to deliver it. Constraints, which could be expressed as goals, because variance from them is allowable but undesirable, are the following:

1. Keep a certain fixed or minimum ratio between combat and combat support units.

2. Keep unit sustainability, as reflected by percentage of required supplies delivered, at a fixed level.

3. Maximize the anti-tank strength, defensive frontage or firepower of the deployed force.

4. Maximize utilization of Air Force airlift assets, in tonnage and allowable cubage.

Constraints which are absolute are the following:

1. Outsize cargo will fit only outsize capable aircraft. Oversize cargo will fit on outsize capable aircraft or on oversize capable aircraft. Bulk cargo will fit on all cargo-carrying aircraft.

2. A deployed unit consumes supplies at a fixed rate

for its given state, related to its combat posture.

3. There is a limit on the number of each type of aircraft available.

4. There is a limit on the number of sorties the Aerial Port of Delivery (APOD) can service.

5. CRAF, C-5, and C-141 aircraft can only land at the APOD. C-17 and C-130 aircraft are capable of direct delivery, or of landing at the APOD. C-141's can direct deliver airborne units and supplies by airdrop, or land at the APOD.

6. Unit sustainability has a floor. United States National Command Authority will not build up force strength at the expense of letting troops already deployed run out of ammunition or food.

7. Supplies delivered to the APOD for front-line forces must be trucked or airlifted to the combat forces at the front.

Once the model is mathematically formulated, it is evaluated as to the combat power per unit time it delivers to the theater of operations. This measure of effectiveness is tested over several scenarios, varying APOD capacity, distance from APOD to the front, and the available aircraft force mix. Finally, a determination is made as to whether this attempt at modeling the problem of delivering combat power offers advantages over current processes.

Pictorially, the model is as shown in Figure 1.

Format

Chapter II of this paper provides a description of complexity and realism issues associated with force employment models, followed by a brief review of currently used models. Prevailing assumptions and approaches are addressed.

Chapter III provides a brief description of the available means of modeling to approach the problem and shows why goal programming is selected. Additionally, it describes briefly the underlying mathematical preliminaries of the goal programming formulation.

Chapter IV addresses the underlying assumptions of the model approach, and describes model parameters, both inputted and computed.

Chapter V presents the development of the model, including the constraint set and the goal formulations. Each constraint set is accompanied by a description of its use and applicability.

Chapter VI addresses the model options which can be developed by the inclusion of additional variables and constraints.

Chapter VII provides a numerical example with a generated scenario.

Chapter VIII presents a discussion of sensitivity issues and model stability. This is extended to an analysis of the benefits to be gained by expanding the analysis of a single model run to the generation of a flexible response surface based on a feasible ranging of the critical variables.

Chapter IX demonstrates the interrelationship of five key variables by use of a multiple analysis of variance, and then generates a flexible response surface using a fractional factorial minimum bias design based on a cube plus star plus center point second order surface. The relative worth of each response surface variable is explored over its range, and a simple estimation of trade-off points between two airlift aircraft developed.

Chapter X presents the conclusions of this research as to whether the explored methodology has valid applications for military modeling, and presents observations which are a result of the model output.

II. Literature Review

In reviewing pertinent literature, this research investigated two separate areas: the deployed unit attributes and requirements (both movement and logistical supply), and current strategic deployment models available to fulfill the research objectives. The first portion of this literature review develops the unit attributes and requirements. The final portion reviews existing deployment models.

Unit Attributes

1. Available models to analyze combat potential

Many attempts have been made at modeling Army combat power, most utilizing Lanchester equations (Ref 33). Lanchester equations are large mathematical models which relate small unit combat and all its variables to a system of differential equations. These models utilize low level tactical engagements and then aggregate these engagements for increasingly higher level units. The models are sensitive to small variations in tactical deployments (Ref 45:36).

An alternative, the Historical Evaluation Research Organization (HERO) Quantified Judgemental Model (QJM) has been developed and utilized over a wide range of engagements, including the latest Mideast wars. Analysis results are comparable to or better than the results of the Lanchester-based aggregate models (Ref 15:150). This QJM model can also be used independently of enemy force structure. Although it has not yet been used for forecasting capabilities, it is capable of doing so, and of being applied to a Mideast/Southwest Asia deployed force (Ref 15:181). The QJM method, although programmed on the AFIT computer, requires an extensive breakdown of every unit, and every weapon, and ballistic data on every weapon. Its basic methodology relies on a number of generated interrelationships between input factors to obtain generalized variables. These variables are then manipulated by a quadratic equation obtained through historical factor regression analysis to determine an end result, given as an output.

The Army War College has a strategic mobility exercise, followed by a large-scale tactical exercise, which assigns values to combat units. These values were developed at the Army War College by consensus among the faculty and staff. Analysis of Delphi consensus closure techniques has revealed an extremely good correspondence between actual variable values and those estimated by a consensus formulation among knowledgeable participants (Ref 9). Since the faculty and staff are of extremely high caliber, it can be assumed that the combat values associated with the various units have a reasonable degree of validity, or at least are excellent starting values.

2. Methods of estimating Anti-Tank capabilities.

To estimate the anti-tank (AT) capability of various units, many separate studies and analyses conducted by the

Army Training and Doctrine Command (TRADOC) and the Army's TRASANA "think-tank" have been done listing the assets available and implying linear relationships between numbers of systems and unit worths in the AT role (Ref 27:26). Systems can be weighted as to their average performance.

3. Methods of estimating unit defensive ability.

The capability of a unit to man a front line, or hold a perimeter, is largely a reflection of its infantry strength, adjusted by mobility (Ref 15:150;45). This Front-Line-Trace capability, or limit on defensive frontage, is readily available in Army field manuals specific to the Army units.

Equipment restrictions on Force buildup:

An airhead is the Army technical term used to describe the perimeter of ground controlled by friendly forces during an airborne operation into a hostile country. For initial seizure by airdrop of an airhead, an airborne brigade requires over 1500 cargo parachutes and 4583 individual parachutes (Ref 46:V.2-13). There are three airborne brigades in the 82nd Airborne Division. In combat, the parachutes are largely unrecoverable, and, because of a limited number of parachutes in stock, the Army will run out of parachutes to support sustained airdrop operations. Additionally, support requirements for large scale units are normally measured in thousands of tons per day. The U.S. Army currently has only one active and two reserve quartermaster airdrop supply companies. They are capable of preparing at most 200 tons per day apiece for airdrop (Ref 19:8). Therefore, sustained operations require early establishment of an airbase for resupply operations.

To establish an airbase capable of sustaining large scale Air Force operations into the airhead will take a large number of Air Force personnel and their accompanying equipment (Ref 40). Studies of Saudi Arabia, a typical RDJTF deployment area, show that the ratio of austere (bare base, requiring maximum Air Force support and improvement) airfields to main bases is between 7:1 and 10:1 (Ref 1:5-13). Therefore, after initial delivery of combat power into a theater of operations, considerable effort must be expended to deliver and sustain airfield support personnel, a requirement which interferes with the steady increase of combat power on the ground. The delivered supplies, especially munitions (Ref 11:3), must then be transported from the new airbase to the troops, requiring a large influx of combat service support troops and their trucks. This is substantiated by Captain B. Tarnopolski, U.S. Army, in an abstract of an unpublished report quoted in DOD Log Abstract (Ref 2:175). The effect of these limiting factors on combat power during deployment has not been specifically addressed to date in any research listed with the Defense Technical Information Center (DTIC) (Ref 43).

Current Models on Logistics and Sustainability

Current research recognizes the exceptionally high vulnerability of the best plans to logistics problems. The Institute for Defense Analysis (IDA) reported "Current ground-air models do not treat logistics vulnerabilities well, if at all" (Ref 22:17).

An analysis sponsored by the U.S. Army Harry Diamond Laboratories "examined the impact of varying resupply rates on the units' ability to sustain combat" (Ref 35:ES1). This paper found that the standard artillery battalion can fire at expected rates only 12 hours with no resupply, and the daily resupply rate for the battalion is 192 short tons of ammunition (Ref 35:ES6). Similarly, the standard tank battalion can sustain itself for fuel only two days, and its daily resupply rate is in excess of 12,000 gallons, or 96 short tons of fuel per day (Ref 35:3-25). The 82nd Airborne Division, the lightest division in the RDJTF, contains three artillery battalions and one light tank battalion. The problem with transport constraints increases greatly when all supplies for all deployed units such as water, food, spare parts, and other types of ammunition and fuel are considered. The Army Field Manual (FM) 101-10-1 and Supply Bulletin (SB) 710-2 relate requirements of each unit by type of supply to combat posture, and these rates aggregate as more units are deployed (Ref 11).

Given these large requirements for continuing logistical support, it is critical that an optimal point be defined which offers the most combat power for the mission, without exceeding resupply capabilities. This point has not yet been determined (Ref 26).

Current Deployment Models

An article capturing the lessons of the BRIGHT STAR 81 rapid deployment exercise to Egypt suggested improvements in MAC load planning procedures, currently done mainly by hand (Ref 18:22). The measure of merit discussed is that "the most efficient use of airlift resources is obtained through maximum airlift loads" (Ref 18:23). HQ MAC, with the approval of HQ USAF, is developing computerized models to accomplish load planning. However, the optimization of a subgoal, efficient movement of cargo, does not necessarily imply or support optimization of the RDJTF mission, which is rapid deployment of combat power. The comprehensive nature of the problem is well described in an overview essay by Sheldon (Ref 36).

Currently, very detailed computer models exist at HQ USAF/SAGM in the Pentagon and at the Military Traffic Management Command. These models move units based on a large number of parameters and are generally efficient. Phase I of the Time-Phased Force Deployment Data (TPFDD) completes a detailed analysis of forces and supplies to be moved (Ref 31:21). This model sums all unit equipment and requirements, in accordance with the units' priorities. MAC planners may begin movement of a unit in advance of the RDD (Required Due Date) in accordance with its best aircraft utilization mandate (Ref 26). As shown by Levin and Friedman, "It is fairly common practice to separate the decision problem into two separate stages in battle situations where the command of the support units has to plan according to the demands of the fighting units. This may, of course, lead to a suboptimal overall solution; very seldom, however, are the decisions made simultaneously. As in many other military problems, the deployment of support units is solved as a cost-effectiveness rather than a cost-benefit problem" (Ref 28:41).

Although the interface between the intertheater delivery airfield and the front line where the combat strength will be deployed is critical, to date no model is available which interrelates the intertheater/intratheater problem for the Air Force assets. This makes it currently impossible to obtain an analytical estimate of the relative worth of various aircraft types in the CENTCOM deployment scenario, or to estimate an optimal force mix for airlift resources (Ref 30).

A Congressionally Mandated Mobility Study (CMMS) examined lift requirements through four scenarios, three dealing with the employment of forces in Southwest Asia, and one dealing strictly with NATO. The study assumed in all cases that:

1. Adequate fuel would be available at all enroute bases.

2. Reception ports and airfields (APODs) were adequate to process all personnel and cargo moved to the theater.

3. Basing and overflight rights were granted by all

allied and normally friendly countries.

The conclusion was that current mobility forces "were not able to meet the lift requirements of any of the scenarios" (Ref 27:30).

The study also showed that a timely response (rapid) force was up to four times as effective as a similar force delivered later, and that "direct delivery of material to forward airfields" conferred a 7% to 15% productivity advantage based on time made up by reduced intratheater movement (the units were then not required to move forward from the APOD to the deployment area) (Ref 27:32). However, this finding is predicated largely on assumption number two. If in fact the reception port or airfield is constrained by parking space or by material handling equipment, then aircraft which can fly only to the reception APOD will be limited in delivered sorties, whereas aircraft capable of direct delivery remain unconstrained. Thus, the CMMS, because of assumption number two, underestimates the advantages gained by direct delivery. Assumption two also inherently allows an unlimited number of intratheater flights to move cargo forward, basically portraying an airfield which cannot become capacitated. Only flying hours, distances, planes and lift capabilities limit the airlift of forces. Further, the forces lifted are predetermined, so that there is not an optimal force response, unless coincidentally. The study dealt solely with the question of how fast a given set of units could be moved to a given area.

The aircraft Loader Model is currently used by the J-4. Given the complete physical description and weigh all cargo to be moved, and the physical limitations and numbers of all planes available, it estimates the numbe airlift aircraft required to perform a stated transport mission (Ref 33:17). A month is required to acquire th data; one man-day is required to analyze the output. T is no attempt to determine if the load chosen was optim just an attempt to estimate the fewest sorties required move the force, using numerical analysis.

The Airlift Loading Model (ALM) performs a similar function, but uses simulation. Currently used by the A Force Assistant Chief of Staff for Studies and Analysi takes only one man-hour to evaluate the results. Howev is strictly a one-sided model which loads forces, and t is no interaction with the deployed units' needs, transhipment, or attributes (Ref 33:21).

The AMPS (Air Movement Planning System) is an anal model which plans, diagrams, and manifests individual aircraft loads of equipment and personnel for movement C-5, C-141, and C-130 aircraft (Ref 33:25). It is used the U.S. Army Logistics Center.

ATLAS (A Tactical, Logistical and Air Simulation) another analytical model. Ground forces are scheduled arrival, logistics inputs establish supply requirements air inputs provide performance, vulnerability and other on aircraft and airbases. The model output varies, but measure of merit is Forward Edge of the Battle Area (FEBA) movement, which in turn is a function of firepower, terrains, and posture. It requires 2-4 months to acquire the base data and one month to input the data in model form. Its principal users are the U.S. Air Force Special Studies Division, the Studies, Analysis and Gaming Agency (SAGM), the Organization of the Joint Chiefs of Staff, and the U.S. Army Concepts Analysis Agency. The model is not an optimization routine, but determinative, which reveals the probable system output response to given input data. Firepower scores for the opposing forces (the "combat power") are assumed to be linearly additive with no interactive or enhancement coefficients. This model is used over 600 times per year (Ref 33:44).

The POSTURE model, developed in the early 1970s by the General Research Corporation, solves for the maximum capability of a mobility fleet subject to a given set of transportation restrictions. A typical representation ranges from 500 rows, 2000 columns to 2000 rows, 10,000 columns, and takes between forty minutes to one hour of CPU time on an H15 6080 computer. In order to optimize, vehicles are fractionalized and unit integrity is not maintained. POSTURE relies on a predetermined time-phased deployment list of units, and therefore, is solely concerned with mobility (Ref 33:243), using a transportation algorithm.

There are three models extant which attempt to close units by means of airlift to an Aerial Port of Debarkation

(APOD) in the most efficient manner possible. MACE (Military Airlift Capability Estimate) is an analytical model which uses general planning data (not specific data on every piece of unit property, such as used by ALM) to estimate large-scale troop and cargo movement closure times. It makes no attempt to move the most needed units first, just to minimize aggregate closure time. It is used about 75 times a year by the Organization of the Joint Chiefs of Staff (OJCS) J-4 (Ref 33:202). RAPIDSIM (Rapid Intertheater Deployment Simulator) simulates both the deployment of combat units and their required supplies to a theater. All units moved have a predetermined order of movement priority, and the transhipment problem from the APOD forward to the front is not addressed. The same organization aa above uses this model 260 times a year (Ref 33:261). The OJCS J-4 also uses SITAP (Simulator for Transportation Analysis and Planning). This is formulated as a transportation model. The network formulation allows weights to utilization and blockages in the defined network, but requires a predetermined demand ordering for cargo movement (Ref 33:309).

The Army's Concepts Analysis Agency uses the TRANSMO, a computerized, analytical model which determines arrival time of U.S. forces to overseas theaters. The model determines deployment schedules with specified lift assets, or designs a lift system to meet the required deployment schedule. Its inputs include troop strengths, resupply rates, lift vehicle capacities, and general scenario characteristics such as port restrictions and distances between ports (Ref 33:365-366).

The models described here all fail to meet the objectives of the research for several reasons.

1. They are response oriented in that the desired units and order of units to be deployed is predetermined.

2. Although some address supplies for deployed forces, they fail to solve the problem of transhipping the supplies to the combat units forward of the APOD, or to incorporate the effects of the intratheater problem on APOD port capacity to receive intertheater shipments.

III. Modeling Approach

The problem of modeling a contingency force deployment is subject to inevitable trade-offs between total realism and practical use. Two broad types of models are available, simulation and analytical optimization, and both have been separately employed in the construction of various existing air movement models. Both these methods attempt to capture, as best as possible, the essential elements of the problem. If a problem cannot be solved as it is exactly, one seeks an approximating problem "close to the original" which can be solved. The exact solution of the approximating problem is potentially - but unfortunately, not necessarily - an approximate solution to the exact problem (Ref 48:275). This chapter will discuss the criteria and methodology trade-offs which led to the choice of interactive sequential goal programming as the preferred methodology for the developed model, and the selection of a flexible response surface based on regression analysis as the preferred means of investigating the sensitivity of the model to parametric changes.

Simulation

The larger portion of available models representing force deployment utilize simulation techniques. Simulation models have considerable appeal to non-technical managers, because the actions flow sequentially and a rapid check can be made as to the level of simulation detail. Simulation models consider one alternative and evaluate a given plan based on the given scenario. The generated solutions do not identify alternatives and provide limited insight to the underlying trade-off relationships within the model. In a large scale simulation, actual differences in worth of competing resources can be dominated by the stochastic variance of the final solutions (Ref:8). A simulation provides the flexibility to iteratively and manually alter parameters, but it never compares solutions or attempts to optimize. Therefore, simulation results in feasible solutions, which approach "good" through careful use but can never guarantee "best". Because of these reasons, analytical optimization was chosen.

Formulation as a Transportation Model

This problem could be formulated as a transportation problem using all integer expression, and using each plane-cargo combination as a link between nodes which represent airports (Ref 17). An effort to create a formulation of this type was briefed at the 1983 MORS conference, dealing only with efforts to further optimize cargo delivery, without recourse to simulation (Ref 24). The disadvantage, though, is that the number of link-node combinations is very large, and it would be difficult to express the tonnage delivered in terms of combat units without recourse to gross aggregation, which would not serve the purposes of this thesis.

Formulation Through Dynamic Programming

A "Dynamic Programming Approach to Resource Scheduling under Constraints" was offered by David Tyburski (Ref 47). It uses the general form of the recursive relationship

$$f_n(X_n) = \min_{D_n}[r_n(X_n,D_n) + f_{n-1}(t_n(X_n,D_n))]$$
$$n = 2,3,\ldots,n$$
$$f_1(X_1) = \min_{D_1} r_1(X_1,D_1)$$
$$n = 1$$

with the transition function tn finding the optimal decision at each stage based on performance at the previous stage. A separate transform would have to be written for each type of cargo, and a dependency relationship formulated for each type of unit among the types of cargo. Although a feasible methodology, the recursive nature of dynamic programming requires initial knowledge of the ending state. With a program set up using the interservice approach of current models, to optimize delivery of given units (and, correspondingly, tonnage) in a given time, this would be an excellent approach. However, the goal of this thesis is to both force delivered and means of optimize delivery, i.e., do as much as possible, not just optimally match a given predetermined response.

Formulation by use of Linear Programming

The methodology of linear programming is well proven. When set up as a system of interrelated linear equations, the problem becomes readily solvable by a number of LP algorithms. A key criteria, however, is the requirement to insure that the expressed relationships are in fact linear over their domain.

This problem can be addressed by partitioning the problem in such a way that the nonlinear function can reasonably be expressed as piecewise linear, without serious degradation. For the nonlinear relationship of combat power to time of deployment, for example, the time can be broken into subsets which allow the combat power to be placed in the objective function with separate variables, each representing a time segment of the timed response, with each having a different coefficient. If the partitioning of the independent variable is sufficiently small, the errors induced by this forced linearity of a curvilinear response are negligible (this is similar to arguments for the calculus of differences).

The responses desired from this model, however, are not merely dependent on a single objective function, but rather on a series of desired objectives, or goals.

Goal Programming

Another method of achieving a solution set would be to formulate the problem as a generalized multiple objective linear program (GMOLP), allowing mixed-integer solutions (Ref 20,25). The immediate advantage of this method is that it avoids the problems of strictly formulated integer programming, although it doesn't guarantee an efficient solution set until the entire problem is solved. The theory behind this method is well proven, and several commercial programs exist, available for employment, such as the IBM MPSX370-MIP (Ref 42,44).

Since the basic problem is to emphasize combat power delivery, the use of GMOLP would have to be modeled to force this occurrence. Three methods are available to do this: prioritized goals, weighted goals, and intervals around the goal.

Prioritized goals will insure that the primary objectives are fully satisfied in order of rank, never satisfying a lower goal at the expense of a higher one. This would accomplish the objective, but it may drive several lower ranked goals to large values of underachievement. A major difficulty is in setting the objective value of a high ranked goal - if it is too high, the lower ranked goals have no impact on the solution set. This result is demonstrated graphically by Ignizio (Ref 21:397-399).

Weighted goals are a good alternative to the problems posed by prioritized goals, because the goals are satisfied simultaneously in accordance with their importance. A major difficulty, however, is in determining the comparative weight of conflicting priorities, especially when goals have incommensurable units. Minor errors in these weights invalidate the model results, and it is difficult to find competent authority to state, categorically, that anti-tank capability of the deployed force is exactly 1.2 times as important as the defensive frontage of the force.

An interval around the objective goal could be established, which would avoid both the problems in weighting the goals and the problem of specifying too high a goal in prioritization (Ref 21:402). The interval would, instead of an objective goal, specify minimum and maximum acceptable values around the desired goal. This has the advantage that, if the solution set is feasible, no goal will be unacceptably underachieved. However, because of the problem under consideration, it is likely that with this method the measure of combat power delivered, the most demanding factor, would always be driven towards the lower acceptable edge of the interval. This is exactly the opposite to the purpose of this study.

A further problem with GMOLP is that various goal levels must be investigated to insure that the "best compromise" solution is found. But, since this search investigation process is not a formal part of the GMOLP, truly optimal solutions may fall in the intervals between the searched states. Zeleny and Cochrane, summarized by Masud and Hwang, found "that the a priori specification of goals and their ranks can result in a solution which may not be 'nondominated'" (Ref 29:391).

Sequential Goal Programming

Sequential goal programming is a lexicographic approach to goal programming. Using an objective formulation of strictly commensurable units, the first goal is maximized (or minimized) subject to a determined constraint set. The optimal response returns the highest value this goal can ever take on. If this response is less than the desired goal, the desired goal is unachievable. The objective formulation is appended to the constraint set as an additional constraint, with the right hand side being either less than or equal to the maximum attainable response, depending on whether the desired goal is either less than or greater than the achievable response. This will ensure consistency in the constraint set. The next goal formulation is subsequently maximized (or minimized). The advantage of this methodology is that the goal set is piecewise evaluated, and full sensitivity ranging (right hand side ranging and objective coefficient ranging) can be explored for each goal as it relates to the constraint set and to higher priority goals (Ref 29). However, this approach still shares with GMOLP the problem of finding the "best compromise" goal which is fully achievable and gives the overall best response.

Flexible Response Surface Theory

Examining a model's solutions dependent on a single goal can be accomplished by use of standard objective coefficient ranging techniques, with multiple runs giving a full spectrum of the sensitivity of the solution to the goal-weighted interrelationships between variables. Similarly, right hand side ranging for resource input parameters or higher ranked goals defines the model's range within the optimal response. To explore the full range of responses dependent on multiple parametric changes in order to explicitly define parametric relationships would require a factorial design which could, even within a reasonable range of interest, require an infeasible number of model runs.

> "The single parameter sensitivity technique... has three major disadvantages. First, only one parameter can be varied efficiently at a time. Secondly, this measure provides no numerical measure or ranking of the importance of a parameter to the end solution. And, thirdly, no information is provided about the interrelationships between the important factors under study." (Ref 38)

A fractional factorial response surface attempts to map the entire response surface of systems with a small number of factors. Using least squares regression analysis to fit a response surface to a fractional factorial design will insure the minimization of the sum of squared deviations of the observed responses from the predicted responses. The great advantage of this type of analysis is that it reduces a large model response to a single equation, programmable on a hand calculator, whose maximum error is minimized to the value of the maximum bias estimator returned by the regression. With a proper design, we are guaranteed independence of coefficients due to orthogonality. Therefore, two alternative parametric changes may be directly compared, and if the response of one, minus possible maximum error, is greater than the response of the second alternative plus maximum possible error, then it can be said categorically that alternative one dominates alternative two. This assumes both the alternative sets were entirely within the bounds of the calculated response surface.

A similar approach using a fractional factorial design could be achieved to investigate the entire goal subset, assuming that goal achievement levels were continuous. However, since the goals would still be incommensurable, presumably lexicographic, and probably nonseparable (i.e., the achievement of one goal would enhance, in some way, another, thereby providing a non-singular moment matrix), some method must first be developed to either partition and normalize the separate goals, or to meld several response surfaces to a single response. Research work to maximize a response defined by a response surface subject to a constraint from another response surface is currently in progress (Ref 39).

The problem of this research is to develop a methodology which allows joint optimization of the attributes of combat power and airlift resources, subject to numerous constraints, and a system to reflect advantages in deployed power caused by an incremental change in airlift resources. The use of sequential goal programming to reflect the impact of multiple goal requirements on an intertheater-intratheater mobility/force model will allow optimization of the response. A flexible response surface built on the reactions of the model to parametric changes in airlift resources will not only provide a sensitivity analysis of the response, but a direct analytical estimate of the relative worth of airlift resources and trade-off points between competing systems under the given scenario. Both the optimization process and the response surface will demonstrated.

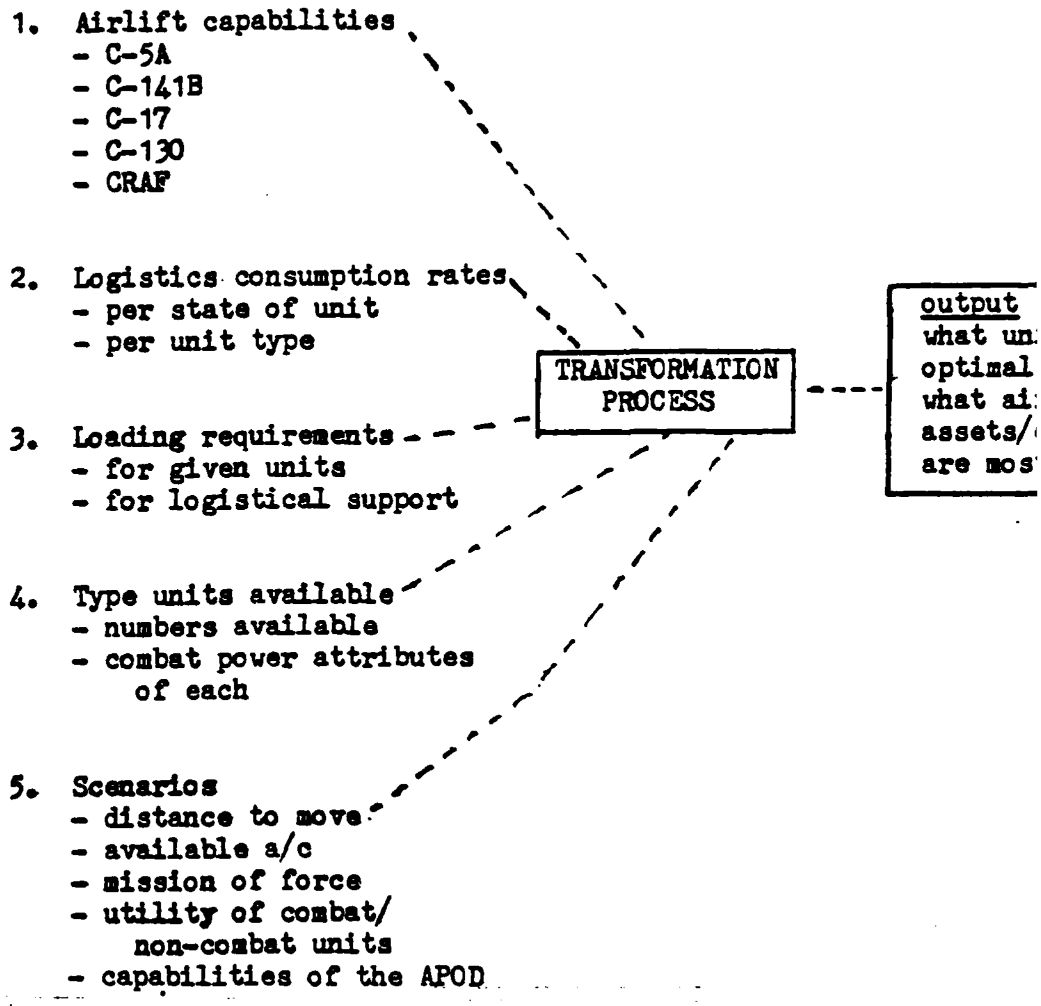

1. Airlift capabilities
- C-5A
- C-141B
- C-17
- C-130
- CRAF
2. Logistics consumption rates
- per state of unit
- per unit type
3. Loading requirements
- for given units
- for logistical support
4. Type units available
- numbers available
- combat power attributes of each
5. Scenarios
- distance to move
- available a/c
- mission of force
- utility of combat/ non-combat units
- capabilities of the APOD
TRANSFORMATION PROCESS
output
what un
optimal
what ai
assets/
are mos

Figure 1

IV. Problem Description and Model Parameters

The problem is simply defined as how to construct an analytical model which incorporates strategic mobility, intratheater mobility, logistics factors, and the elements of combat power. In general, the more combat power an Army unit has, the more it conflicts with the strategic mobility requirements.

Each of the four factors related here are made up of a number of elements. This chapter describes the underlying assumptions of the model. Additionally, model parameters are identified. Those which are not self-explanatory are described in detail.

Strategic Mobility

The factors which comprise strategic mobility have been intensely investigated. Huge models and simulations such as the MAC M-14 simulation model incorporate spares, wingtip clearance on parking ramps, mechanic and crew availability, and a host of other elements (Ref 26). Other models, primarily concerned with loading such as the Aircraft Loader Model, use allowable cabin loads for aircraft, exact dimensions of equipment, stacking heights, and many other pieces of data input (Ref 33:17). The critical elements of strategic mobility were delineated by Major James Crumley in research submitted to the Air Command and Staff College in May 1980 in partial fulfillment of graduation requirements

(Ref 12).

He determined that aircraft size could be described in three terms: outsize capable, oversize capable, or bulk capable (Ref 12:3). Aircraft could also be described as airdrop capable and/or short field capable (for direct delivery).

The problems of crew availability, spares, and maintenance per flight hour are described as subsumed into the UTE (Utilization) Rate, which is a "planning concept that reduces airplane operating rates, on a system-wide basis, to a single figure expressed in daily flying hours" (Ref 5:99). UTE Rates are mission-oriented so that intratheater UTE rates are generally less than intertheater UTE Rates for the same aircraft.

At the cargo handling ends of the flight route, critical elements deal with the port capabilities. Loading and unloading an aircraft takes a finite amount of time for ground-delivered cargo, so that "turn" times for aircraft are important. Because most airfields are limited in parking ramp space, this turn time has a direct impact on the sortie generation rate of the airfield. The unloading and turn time are affected by the material handling equipment and handling personnel available at the port (Ref 12:21;36:21). "Shortages in any of these areas, as well as even short-term distribution problems, can lengthen ground time and reduce flying hour capability" (Ref 12:21). Because of the parking limitation, the limitations imposed by the material handling equipment and personnel availability form an absolute constraint on the number of cargo sorties throughput by the airfield.

The strategic mobility mission, then, can be described by a series of factors. The outsize, oversize and bulk cargo delivered are a function of the number of aircraft flying missions and their respective outsize, oversize, and bulk cargo limitations. The number of mission-capable strategic airlifters is a function of the number of aircraft of all types available at any time, the UTE rate for those aircraft, and the distance in flying hours from loading to unloading the cargo. The number of missions acceptable at the airfield is a function of the airfield parking space and the turn time for the aircraft. The turn time for the aircraft is a function of the material handling equipment and personnel available, with a predetermined minimum (optimmal) ground time.

The strategic mobility of direct delivery aircraft is not limited by available APOD space. Since there are in general far more airfields capable of receiving direct delivery capable aircraft than there are strategic airlifter capable airfields (Ref 1:5-13), the parking and turnaround constraint is basically unlimited.

Intratheater Mobility

Intratheater mobility by air is represented by the same factors as the intertheater mobility airlift. However, intratheater mobility can also be accomplished by means of ground transportation. Units capable of self-movement can move by ground, if required, to the location of employment from the APOD. Items or units not capable of self-movement must be moved by external intratheater transport. For the wholly military scenario, this devolves to moving by intratheater aircraft or transportation units, or both.

Intratheater aircraft, while not limited at the delivery end, conflict at the APOD with strategic aircraft for the resources of parking space, material handling equipment, and service personnel. Transportation (truck) units do not compete for these resources, but they and their fuel must first be delivered to the theater.

Logistics Factors

Every deployed unit consumes supplies of varying types at varying rates. While units which are based at the APOD receive their supplies directly from strategic airlift, forward based units need their supplies delivered. Most units have a self-contained logistics tail capable of ground movement of a constrained number of ton-miles. After this point they require logistical assistance from intratheater mobility assets, or direct delivery of their supplies.

Another aspect of logistics is the "tag-along" service support or combat service support to combat units ratio. Doctrinally, American units move with a given "tooth-to-tail" ratio, with each combat unit being supported by a given force of Headquarters, supply, and service/maintenance personnel.

Presently, logistics models assume a "straight slice of the pie" for each sub-element of a larger element, which reasonably approximates the modern "task-organized" combat force readied for deployment. This model, when possible, will follow this approximation.

Deployable Unit Attributes

The assignment of a value of "combat power" is a valuation which is only useful as a general approximation of worth, and changes with the environment and the objective (Ref 23). Therefore, not only does the broad valuation of combat power need to be reflected, but also several of the specific attributes which contribute to this value.

Some of the more separable elements of combat power are the anti-tank capabilities of the given unit and the unit's ability to hold and defend a linear portion of terrain against attack. The anti-tank capabilities can be expressed as a function of the number and type of anti-tank weapons systems in the unit, and the defensive capability can be assumed as the unit's doctrinally assigned defensive frontage. A third "specific" measure of combat capability is a unit's firepower, which can be approximated by the tons of ammunition per day it consumes.

Deployable units can also possess several other critical attributes. Fighter aircraft, deployed at the APOD, conflict with transport aircraft for parking space. Airlift Control Elements, once deployed (ALCE), enhance the capability to unload, service, and turn airlift aircraft. Transportation assets such as medium truck companies or helicopter groups are capable of moving many ton-miles of logistical supplies, freeing air transport from the intertheater role. However, all these conflict with the primary goal of moving combat units, because the last two types have no combat power, and tactical aircraft cannot hold ground.

The deployable units possess attributes which act to minimize their deployment and lead to goal conflicts. These are their attendant outsize, oversize, and bulk cargo shipment requirements, their supply needs once deployed, and ancillary support units which must be moved in some proportion to the combat units. There are also doctrinal restrictions on the employment of units in greater than certain ratios to other units, such as combat support to combat units.

Scenario Bounds

Each separate scenario is likely to have a discrete solution. The elements which would change the solution, even given constant valuations for all the above parameters, are distances, time periods, and changing values over time.

Critical distances to be expressed are the distance to be flown from the staging base to the APOD and the distance to be flown from the APOD to the front. These distances affect the number of missions capable of being flown, given an average speed of the aircraft. The distance from the APOD to the front is particularly critical, since ground combat units delivered to the APOD do not contribute to the measure of deployed combat power until they are capable of being utilized for combat. Also, a large distance between these two critical areas is likely to put a high premium on air-delivered logistical supplies, whereas for short distances from the APOD, trucks would be favored.

The time period of interest is also of critical importance. Obviously, a one-day response to a problem area will drive surge rates of aircraft and put no valuation on logistics transportation units. However, a twenty-day response can be expected to value a high average rate of aircraft movement and will deploy ALCE units early in order to capitalize on their accruing advantages.

The last external influence which changes the response of the other elements is the changing values of force over time. A Congressionally Mandated Mobility Study (CMMS) has quantified the intuitive analysis that a reasonably sized force early is worth more than a large force later. This relationship is not a straight line curve, and is in fact likely to change from one political/military situation to another. On a very long term or non-critical basis, force value from day to day might approximate a constant value, such as in a Reforger exercise. For other situations, the value curve of the unit over time should be elicited from decision makers before attempting to optimize delivery of forces, using surrogate worth trade-off measures.

Input Parameters

The input parameters will be broken into three sections - those dealing with aircraft which describe the aircraft capabilities and limitations, those related to deployable units available to the planner, and those which bound and formulate the scenario.

For a generalized model, each aircraft is described by its capability for every mission and cargo. This allows rapid refinement of the model to express additional capabilities of specific aircraft, instead of requiring a re-expression of the entire model. Required input parameters for aircraft are summarized in Table 1.

Deployable units are likewise each described for all attributes, although some interactions may be zero. Deployable units are also subdivided into five classes of units:

1. Those which engage in ground combat and can be airborne delivered.

2. Those which engage in ground combat and cannot be airborne delivered.

3. Those which are tactical fighter units and compete at the APOD for parking space.

4. ALCE units which possess material handling equipment and personnel, which result in a quantifiable improvement in airfield sortie generation rates.

5. Transportation units which move supplies between the

APOD and the front.

Other required input paramters, such as combat power, AT strength and front line trace capability, can be subjectively assessed by means of a Delphi closure or can be analytically expressed as some function of the weapons systems assigned to the unit.

A summary of required input parameters for deployable units is expressed in Table 2.

The third set of parameters is the set which makes the solution set specific to the scenario. This set is summarized in Table 3.

These input parameters will be used by the model to delineate the interrelationships of developing force projection, strategic mobility, intratheater mobility, and logistical resupply through or over an APOD to a deployed destination.

AIRCRAFT INPUT PARAMETERS

(for each aircraft)

outsize cargo tonnage capability

oversize cargo tonnage capability

bulk cargo tonnage capability

number of personnel moved with outsize cargo

number of personnel moved with oversize cargo

number of personnel moved with bulk cargo

number of personnel moved with no other cargo

Block speed of aircraft

UTE rate on intertheater mission to an APOD

UTE rate on intertheater mission to direct delivery (forward airfield)

UTE rate on intertheater mission to airdrop

UTE rate on intratheater mission

Ground time for aircraft on each mission

Availability rate for aircraft type (fleetwide)

Attrition factor for aircraft on each type of mission

Material Handling Equipment (MHE) needed to service aircraft (pallets)

Table I. Aircraft Input Parameters

UNIT INPUT PARAMETERS

(for each unit)

outsize tonnage

oversize tonnage

bulk tonnage

number of personnel

Defensive frontage

Anti-tank strength

Combat power

Supply consumption rate

Number of pallets unloaded per day by the unit

Airborne capability

Number of this type unit available

Ton-mile lift capability

Movement speed, nautical miles/day, for scenario

Unit designation as combat/combat support/other

% of APOD space any aircraft in the unit will occupy

Table II. Unit input parameters.

SCENARIO PARAMETERS

1. Airfield

   Number of each type aircraft which would capacitate the park space of the airfield.

   Material Handling Equipment (MHE) prepositioned at airfield in terms of 1000 pallets per day capability.

2. Distances

   Distance between the U.S. and the APOD (DUSAPD).

   Distance between the APOD and the front area (DAPDFT).

3. Decay curve for Timliness versus Response, portraying the advantages of quickly closing forces to the deployable area in terms of a combat power multiplier.

Table III. Scenario input parameters.

V. Model Development

This chapter shows the development and construction of the goal constraints which form the ordered set of objective functions. Three of the developed force parameters are time insensitive, but one, force projection of combat power, is non-linearly variant with time. The coefficients and interactions over time of the goals are explicitly defined, and the state constraints which make the goal constraints competitive are developed for the generalized case from singular expressions.

Variable parameters and factors

Since this chapter is primarily concerned with the mathematical development of the proposed model, it is essential to begin with a common basis for variables, subscripts, and multipliers used throughout the equations. These are summarized here:

Variables used:

Xi,j,k,d: where the variable takes on values depicting the number of delivered plane loads.

Uy,m,d: where the variable takes on values depicting the number of units deployed.

Rd: the desired response or goal, by day d.

Ha: handling capability of the APOD for pallets existing pre-deployment. Hf is analogous at the forward airfields.

Period: a defined period over which the UTE rate i

applicable.

Sd: representing supplies transhipped on day d frc

APOD forward.

My: the movement time taken by a unit to move from

APOD to the front by ground transport.

Subscripts used:

a: the APOD

Cy: representing a combat unit or combat support u multiplier, combat type y units have a Cy of 1, noncomb type y units have a Cy of -1.

d: representing days in the deployment phase. d ta values from 1 to D, the total number of days in the air deployment before seapower linkup.

f: the field, or non-APOD airports closer to the f

i: representing the ith type of plane. i takes on from 1 to I, the total number of types of airplanes.

j: representing the jth type of mission. j takes v from 1 to J, the total number of mission types.

k: representing the kth type of cargo. k takes on from 1 to K, the total number of types of cargo.

m: representing the mode of delivery, where m take values from 1 to M.

y: representing the yth type of unit. y takes on v from 1 to Y, the total number of types of units.

Multipliers used:

$\alpha_{i,k}$: giving the cargo capacity of the ith aircraft type carrying k type cargo.

$\beta_{y,k}$: giving the tonnage to move of the yth type unit in k type tonnage.

γ_y: giving the number of fighter planes assigned to unit type y in terms of the percentage of the APOD they occupy.

θ_y: giving the front line trace capability of unit type y to defend, in kms.

$\epsilon_{u,k}$: standardization factor for MHE needed to unload plane type i with cargo type k.

λ_y: giving the firepower (or steady statecombat power) of type y units.

Φ_y: giving the anti-tank power of unit type y, expressed in equivalent TOWs.

ω_y: giving the supply consumption rate for unit type y.

δ_y: giving the ton-mile capability for lift of supplies for unit type y.

Γ_y: the limiting number of units of type y available.

Ω_y: the airborne capability of the yth unit. This is a 0-1 factor.

Ψ_y: the number of pallets that a unit of type y can unload at the APOD in a day, in addition to previous APOD capabilities.

σ_y: giving the speed of the yth type unit.

σ_i: the block speed of the ith type plane.

V_i: the average availability rate of plane type i

$t_{i,j}$: giving the ground time for aircraft type i on mission type j.

$Z_{i,j}$: giving the attrition factor for loss rate of aircraft type i on mission type j.

Num_i: the number of planes of type i in the model.

PRK_i: the number of planes of type i which can park at the APOD, if the APOD was solely devoted to that type of plane.

Intense(d): a factor which scales the model basis of required supply to another supply usage factor. Its dependence on the d day reflects that this scaling can change over time.

V_d: giving the multiplier effect for arrival at the front on day d.

$UTE_{i,j}$: the UTE rate of aircraft type i on mission type j.

DAPDFT: the Distance between the APOD and the FronT.

DUSAPD: the Distance between the US and the APOD.

The repetitious use of these symbols will greatly enhance the reader's ease in understanding the model.

For the implementation of this model in the thesis, the following ranges were allowed for the subscripts:

i: from 1 to 6. 1=C5A, 2=C17, 3=C141, 4=CRAF (cargo type C747), 5=CRAF (passenger type C747), 6=C130H.

j: from 1 to 4. 1=Delivery to the APOD, 2=Direct delivery to the front area, 3=Airborne delivery, 4=Intratheater transhipment.

k: from 1 to 5. 1=outsize cargo tonnage, 2=oversize cargo tonnage, 3=bulk cargo tonnage, 4=personnel, 5=supplies (considered to be bulk-sized).

d: from 1 to 20. This is considering that after D+20, shipborne cargo becomes a factor and this model, as is, is no longer valid.

m: from 1 to 2. 1=delivered to the deployable area, with minimal travel time required. 2=delivered to the APOD, travel time dependent on distance to the front and unit speed.

y: from 1 to 8. 1=Airborne units of the 82nd Airborne Division. 2=HQ units for the Brigades of the 82nd. 3=Air Assault units of the 101st Airmobile Division. 4=Artillery units of XVIII Airborne Corps Artillery (155mm). 5=Mechanized battalion Task Forces (2mech, 1armor) of the 24th Mechanized Division. 6=F16 Fighter Squadrons (18 UE). 7=Airlift Control Elements (ALCE) of the U.S. Air Force. 8=Medium Truck Companies of the XVIII Airborne Corps Support Command (COSCOM).

Goals

If all the combat attributes of a force were mutually reinforcing, there would be no choice problem for the strategic planner - the more units delivered, the better the results. Unfortunately, such is not the case. Units which can project a great deal of combat power in one area, such as aircraft squadrons, usually have little worth for equally important missions, such as holding terrain. Any scenario usually requires two or more types, or attributes, of combat power, as well as the requirement to react quickly. The objective of this program methodology is to develop a plan which:

1. meets all the requirements or specified goals based on force attributes.

2. after meeting these goals, attempts to maximize specific force attributes towards a specified limit or as far as possible.

Since the achievement of all the minimum goals is very much more desired than maximization of any one aspect of combat power, and since these minimum goals can themselves be ordered, iterative sequential goal programming is appropriate.

Goal programming notation represents each equation as an equality, and any surplus results in a surplus variable p, whereas any underachievement results in a slack variable n in the equation. Therefore, the equation:

[$y \geq 4$] would be rewritten to $y-4 \geq 0$

and then to $y-4-p=0$

A similar solution can be attained for equations of the less than or equal to form, such that

$y \leq 4$

becomes

$y-4+n=0$

This convention will be followed throughout this chapter.

The variables chosen to reflect aspects of combat power are defensive frontage (front line trace or FLT), anti-tank (AT) capability, and firepower. These variables do not change with time; a unit's capability remains the same regardless of deployment time. The variable which does change with time is combat power, or potential force, of the deployed unit. This is the perceived potential, to implement the concept that a small force in the right place can be up to four to six times as effective as the same size force later, which was a finding of the 1981 Congressionally Mandated Mobility Study (Ref 27:30). Using this fact, we can formulate that

$$\sum_{d=1}^{D} \sum_{y=1}^{Y} \phi_y U_{y,r,m,d} \geq R$$

or

$$\sum_{d=1}^{D} \sum_{y=1}^{Y} \theta_y U_{y,r,m,d} \geq R$$

This shows that, over the period d, the sum of all the unit capabilities in the particular attribute ϕ or θ of all units closed to the combat area should equal or exceed the desired capability. The concept of "closed to the combat area" is an important one, because these specific attributes are of no use to the ground commander unless they can be employed. These specific attributes are then distance and speed dependent: the distance they need to travel between the APOD and the combat area divided by their daily movement speed gives the time they need to move to the combat area after delivery to the theater. A unit in theater on the limiting day but not available for employment wouldn't count. This adds to the value of direct delivery, especially in areas where major airfields are scarce.

Using the subscript m for mode of delivery, with m=1 being directly delivered units and m=2 being units delivered to the APOD, we have, defining $\frac{DAPDFT}{\sigma_Y}$ = My, with d'-My equal to the nearest non-negative integer,

$$\sum_{Y=1}^{Y} \sum_{d=1}^{d'} \phi_Y U_{Y,1,d} + \sum_{Y=1}^{Y} \sum_{d=1}^{d'-M_Y} \phi_Y U_{Y,2,d} \geq R_{d'}$$

for the anti-tank capability response on any day d'.

A typical goal would be verbally expressed as a need for the capability to hold ten kilometers of front line trace by D + 5, and this could be formulated

$$\sum_{Y=1}^{Y} \sum_{d=1}^{5} \Theta_Y U_{Y,1,d} + \sum_{Y=1}^{Y} \sum_{d=1}^{5-M_Y} \Theta_Y U_{Y,2,d} \geq 10$$

In this simple illustration it is evident that all units directly delivered to the combat area would be available to hold combat frontage, as well as all units delivered to the APOD which could move to the combat area by D + 5. However, units arriving at the APOD on day D + 4 would not be useful to satisfy this goal if they took two days to deploy forward.

Because lexicographic goal programming is an extended linear program, it will attempt to satisfy one goal at a time, and if the stated goal is underachieved (it cannot be achieved within the time period given), a goal program will move to the next goal without prejudice. That is, underachievement of a high order goal does not preclude satisfaction of a lower order goal. Therefore, a goal programming model should reiterate force goals across a band of days, on the presumption that, if the goal is impossible to achieve as stated, it still needs to be filled before other goals. In the example above, this can be done by keeping the goal level of ten kilometers of front line trace constant and allowing the period to expand to six, seven, and eight days. This will require an additional three goals to ensure lexicographic preemption of other goals until this goal is fully attained. In this circumstance, if the model cannot deploy sufficient units to defend the frontage by day five, it will attempt again to do so on subsequent days. The effect of additional goals is only on computer run time; the additional goals are redundant once the goal objective has been met.

The mathematical goal formulation of the time dependent variable of combat power is similar. The actual effect of response times on perceived combat power must be estimated, either by elicited responses from scenario area experts or from known curves generated by simulations. These curves are typically curvilinear with rising decay over time. For each day of deployment, a multiplier can be estimated from this curve, and incorporated into our model. Thus

$$\sum_{y=1}^{Y} \sum_{d=1}^{d'} \nu_d \lambda_y U_{y,1,d} + \sum_{y=1}^{Y} \sum_{d=1}^{d'-M_y} \nu_d \lambda_y U_{y,2,d}$$

$$= \text{combat power}_{d'},$$

is a valid expression for our model. This term allows a unit with an arbitrary combat power of four, delivered on day four, to be worth less than two units worth a value of two, delivered on day three.

With the great concern for short-term combat power deployment, a natural response would be to repeatedly maximize the goal of deployed combat power for successive days. However, the lexicographic ordering of goals for days 1, 2, 3, 4...would result in an optimal response for day 1, an optimal response for day 2 given day 1 occurrences, and so forth. This is not necessarily optimal. An end case can be shown which is obviously suboptimal - a successive maximization of combat power only, which rapidly results in an APOD converted to a fighter-bomber base and only marginally capable of receiving more deployed units. This case may be an optimal response for the first few days, but for a deployment period of twenty days it is not a preferred response. For this situation, a weighted response will best suit the uses of the model, showing an equal or varied valuation of the ability to develop combat power over more than one time period. These objectives are competitive because they are each to be optimized per se, so that they restrain each other over a limited alternative set (Ref 49:322). By making goals members of the same goal set, an efficient solution is obtained which avoids the problem of suboptimality.

Bounding Constraints

The constraint set developed here acts to constrain the levels of potential goal achievement. The factors which impact on goal achievement have already been described in Chapter IV, and this section will formulate them into mathematical expressions.

Aircraft Limitations: The first set of constraints on strategic deployment relate to aircraft. There are two types of constraining factors, those dealing with aircraft availability, and those dealing with the fleetwide average utilization rate. They will be handled in turn.

1. This set of constraints bounds aircraft SORTIES by the number of available airframes. It is assumed that a single aircraft can make 1 intertheater round trip and be prepared for a second one every 1.5 days, but could make 5 intratheater trips every day (at maximum surge turn rate). Similarly, the number of possible intratheater round trips is limited to five times the total airframes available. Then for day 1:

$$\sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,1} + .2 \sum_{k=1}^{K} X_{i,4,k,1} \leq NUM_i * V_i$$

Thus, if all type (i) aircraft began an intertheater round trip, the number of sorties would be limited by the number of available aircraft. For day 2:

$$.5 \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,1} + \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,2} + .2 \sum_{k=1}^{K} X_{i,4,k,2} \leq NUM_i * V_i$$

showing that, on the average, half the planes which flew intertheater missions on day 1 were not ready to fly in support of day 2. This series is generalized for day d′ (an intermediate point between d=1 and D) to

$$.5 \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,d'-1} + \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,d'} + .2 \sum_{k=1}^{K} X_{i,4,k,d'} \leq NUM_i * V_i$$

When the effects of attrition (mission specific) are incorporated, it serves to reduce the number of planes in the fleet, for a given multiplier (loss rate) times the number of missions of that type flown. Therefore,

$$.5 \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,d'-1} + \sum_{j=1}^{3} \sum_{k=1}^{K} X_{i,j,k,d'} + .2 \sum_{k=1}^{K} X_{i,4,k,d'} - \sum_{d=1}^{d'-1} \sum_{j=1}^{J} Z_{i,j} X_{i,j,k,d'}$$

$$\leq NUM_i * V_i$$

This set of constraints results in one equation for each type aircraft for each day d, or a total of I*D constraints.

2. This set of constraints bounds aircraft sorties by the fleetwide expected utilization (UTE) rate. The computed

parameter for this set of equations standardizes the different utilization rates for different missions into an expression in a single utilization rate. Since nearly all aircraft considered are capable of intertheater airlift to an APOD, we can use this expression as a baseline.

The utilization rate gives the fleetwide average for flying hours per day per aircraft. Thus, for three aircraft, a UTE Rate of four can be achieved with one aircraft flying twelve hours per day or all three aircraft flying four hours per day, or any linear combination of these. The utilization rate is generated over a finite period of time, such that surges and recoveries average to a rough constant. The UTE Rate, therefore, can be manipulated to give the expected number of available flying hours within a given time period. From these flying hours, knowing the distance traveled and the aircraft block speed, it is possible to calculate the number of loaded sorties of which the aircraft fleet is capable during the time period for the given mission.

Expressed mathematically, this is

$$Period * UTE_{i,j} * NUM_i * \sigma_i / (2 * DUSAPD)$$

The factor 2 is included because each aircraft must fly both ways, but the return trip doesn't deliver to the deployment theater.

The period times the utilization rate for the mission times the number of airframes gives the total number of flying hours available. Twice the distance for the mission, divided by the block speed, gives the flying hours required to generate a loaded sortie. This number of hours divided into the flying hours available gives the number of sorties available during the time period.

To convert aircraft of the same type flying other missions to an equivalent number of sorties for this mission, a simple ratio change is required. The effective flying hours available are expressed by $(\frac{UTE_{i,l}}{UTE_{i,j}})$, which, since the U.S. to APOD mission usually has the highest UTE Rate, tends to make each other type of sortie more costly. However, the ratio $\frac{D(other)}{DUSAPD}$ must also be incorporated, and, for the large change between intertheater and intratheater distances, this more than counterbalances the other ratio, which shows a lot more sorties are available in the intratheater mode versus the intertheater mode, using strictly flying hours. This is exactly as expected. However, where the distances are roughly equivalent, such as a direct delivery, and the UTE rates for the same aircraft in the two missions is not (because of sparse facilities or other reason such as increased wear and tear), then the model reflects that direct delivery sorties are relatively more expensive to aircraft than sorties through an APOD. This, also, is as expected.

Aircraft which are optimized strictly for intratheater transport, such as the C-130, cannot be related by UTE rate to the intertheater mission, and therefore, must be separately expressed, with their total available sorties directly dependent on intratheater distances.

Since it is incorrect to expect an "average" to be a limit every day, a period must be assumed. Taking 5 days for a viable period over which to expect an average UTE rate response we can write, for one type aircraft i,

$$\sum_{d=d'}^{d'+5} X_{i,j,k,d} \leq (5)\ UTE_{i,j} * NUM_i * \sigma_i / (2 * DISTANCE)$$

Since the UTE Rate is particular to the mission, if rewritten

$$\sum_{j=1}^{J} \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,j}} X_{i,j,k,d} \leq (5)\ NUM_i * \sigma_i / (2 * DISTANCE)$$

or

$$\sum_{j=1}^{J} \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,j}} X_{i,j,k,d} + \eta = 5\ NUM_i * \sigma_i / (2 * DISTANCE)$$

it is generalized, although the value of n, the slack variable expressing leftover potential in the equation, is now clouded, and cannot be read directly. The period is used as a moving average, first for days 1 to 5, then days 2 to 6, etc. The general expression, including attrition which is mission specified and will reduce the aircraft base of the UTE rate, is

$$\sum_{j=1}^{3} \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,j}} X_{i,j,k,d} + \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,4}} \left(\frac{DAPDFT}{DUSAPD}\right) X_{i,4,k,d} - \sum_{j=1}^{J} \sum_{d=1}^{d'+4} Z_{i,j} X_{i,j,k,d}$$

$$+ \eta = 5\ NUM_i * \sigma_i / (2 * DUSAPD)$$

where DUSAPD is the intertheater distance, while DAPDFT is the intratheater distance. There is one constraint for each i and for each period, which would give (D-Period+1)*I constraints.

Airport Limitations. The next set of landing constraints deals with the traffic limitations an airport places on strategic mobility, both in terms of ramp parki space and in terms of material handling equipment.

1. This set of constraints imposes limitations on traffic through a reception airport due to ramp parking space. Expressing the capacity of the airport in terms c exclusive use for each type of aircraft, the model assume linear trade-off relationship which closely approximates reality. For example, if an airport is capable of parkin fighters or 12 C-130's, it assumes that the airport is a capable of parking simultaneously 24 fighters and 6 C-130 This is an approximation accurate for any airfields excep very small ones with end-point solutions to parking limitations, where one large aircraft blocks taxiways or runways for any other flights; however, APODs will not normally be chosen at minimally capable terminals.

The computed parameter for this set of equations is calculate the parking space-time taken up by each aircraf it is optimally unloaded and serviced enough to move off APOD. Using the factor PRKi which gives an indication of many of a single type aircraft can use the APOD at a sing point in time, and the factor tij, it is possible to determine how many sorties of this type of aircraft may b generated through the APOD in a single day, with ramp par space the constraining limitation. Mathematically,

$$\frac{t_{ij}/24}{PRK_i} \leq 1.$$

This is a way of stating that if an aircraft takes up, for example, one sixth of the parking space and takes one eighth of a day to get off the APOD, then only 48 of these aircraft can process through the APOD in a single day. The factor "24" converts the ground time per plane from hours to days. The one on the right hand side equates to 100%, since essentially we have converted aircraft sorties into a factor which gives the percentage of a day-space they occupy on APOD.

Since fighter planes, if based at the APOD, must be assured of a spot whatever the time, the equation representing the tactical fighter units is

$$\sum_{y=1}^{Y} \gamma_y U_{y,z,d} \leq 1$$

which means that no more fighter aircraft may be assigned than the airfield has space for parking, and assumes a linear relationship between parking spaces. For example, if an APOD could park 24 F-111 or 36 F-16, then the APOD could park 12 F-111 and 18 F-16 simultaneously, and be capacitated. Of course, this extreme solution would mean that the APOD had been converted into a fighter base, and so is not a likely solution, just an end-point illustration.

Given the amount of a type airlifter which can park, the max airfield sortie capability is determined by the aircraft's turn time, under the best of circumstances.

Therefore,

$$\sum_{j=1,4} \sum_{i=1}^{I} \left(\frac{t_{ij}/24}{PRK_i}\right) X_{i,j,k,d} \leq 1$$

which limits the sorties of those missions which move through the airfield. With this formulation, an airfield which could park 12 C-141's, which required 3 hours ground time apiece, would be capable of through putting 12/(3/24) = 96 C-141's a day, if only C-141's were using the port.

Since, however, fighter planes based at the APOD must always have a reserved space, the parking space limitation becomes

$$\sum_{i=1}^{I} \sum_{j=1,4} \left(\frac{t_{ij}/24}{PRK_i}\right) X_{i,j,k,d'} + \sum_{d=1}^{d'} \sum_{y=1}^{Y} \gamma_y U_{y,2,d} \leq 1$$

There is one of these equations for every day d of the model, for each APOD, so that with our single APOD model this adds a total of D constraints.

2. This section describes the limitations imposed by the material handling equipment which is available at the APOD. For each type of aircraft, there is a normalizing factor which relates the aircraft to a standardized requirement for material handling equipment, based on the number of pallets the aircraft can carry, and the ease of servicing the aircraft. Each APOD also has a fixed capability, Ha, to handle a given number of standard planes.

Lastly, each Airlift Control Element (ALCE) and its ancillary port improvement package has the capability to unload another given number of standard planes. The amount of planes moving through the APOD must not be greater than the capabilities at the airport to unload them. Therefore

$$\sum_{i=1}^{I} \sum_{j=1,4} \sum_{k=1}^{K} \epsilon_i X_{i,j,k,d'} - \sum_{d=0}^{d'-1} \sum_{y=1}^{Y} \Psi_y U_{y,2,d} \leq H_a$$

The service units which close on any day through the day before the one in question use their joint capacity to unload (or load) planes which arrive at the APOD on day d.

Similarly, to constrain the offloading of direct delivery aircraft, we have

$$\sum_{i=1}^{I} \sum_{j=2,4} \sum_{k=1}^{K} \epsilon_i X_{i,j,k,d'} - \sum_{d=0}^{d'-1} \sum_{y=1}^{Y} \Psi_y U_{y,1,d} \leq H_f$$

There is one constraint for each day for the APOD and the forward airfields, resulting in 2*D constraints.

Unit Limitations. The number of units available naturally limits the number which can be shipped, for each type of unit. This is expressed by

$$\sum_{d=1}^{D} \sum_{m=1}^{2} U_{y,m,d} \leq \Gamma_y$$

for each unit type y, which adds Y constraints.

Shipment of Units. Units can be shipped into theater by three types of airlift missions (j=1,2,3) and can arrive in two modes (APOD or at the front), depending on the delivery method. This section will deal with the similar expressions for all three mission types sequentially.

1. The first mission is delivery to an APOD. All deployable aircraft units and ALCE units are constrained to be delivered to an APOD. Other units may be delivered there.

Every unit is described in terms of outsize, oversize, and bulk tonnage, as well as the number of unit personnel. For a given unit to close, the complete amount of outsize, oversize, and bulk tonnage, plus personnel, must be moved. For each category of weight, the amount moved to the APOD in a given day is equal to the sum of all deliveries in that category to the APOD. Therefore, for j=1,

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,1,k,d} - \sum_{y=1}^{Y} \beta_{y,k} U_{y,2,d} \geq 0$$

On a given day the tonnage delivered must meet or exceed requirements for a given unit in order for that unit to close. Pd,K represents surplus tonnage of type k delivered by day d.

However, if no unit closes or if there is excess tonnage delivered, it is considered an advance delivery for the next unit. This holdover tonnage is also represented by the surplus variable, Pd,K. Pd-1,k then comes to represent the total surplus tonnage in cargo type k in the days preceding the one presently under consideration. As the time period extends, therefore, it is evident that this equation becomes

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,r,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \beta_{y,k} U_{y,2,d} - P_{d,k} = 0$$

There is one constraint for each day and cargo type, adding D*K constraints. And this series of equations fully describes the shipment of units to the APOD.

2. The shipment of units directly to the front is covered next. Similarly to the APOD shipments, the relationship is given by

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,2,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \beta_{y,k} U_{y,1,d} - P_{d,k} = 0$$

As above, this adds a constraint for each day and cargo type, and so adds D*K constraints.

3. Airborne units are handled in the same manner, with interactions allowed only between airdrop capable aircraft (j=3) and airborne capable units (where Ωy=1). This is shown by the equation set

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,3,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \Omega_y \beta_{y,k} U_{y,1,d} - P_{d,k} = 0$$

This equation is repeated for every day and cargo type, adding another D*K constraints.

Supplies. The delivery of units to the overseas area in order to meet goal objectives automatically imposes an additional set of constraints - that of keeping supplies at a stabilized level. There are three levels of supply constraints. One insures that enough supplies are sent intertheater to meet all deployed unit needs. Another set insures that enough supplies are distributed to the front to meet the needs of the forward deployed units. The last set insures that sufficient supplies are on hand at the APOD to meet the needs of units based at the APOD. These will be discussed in turn.

1. The class of supplies is a separate one, k=5. For this model only one class of supply was addressed, as an aggregate need. More detailed representation, if needed, could be gained by adding additional variables. Since supplies are considered only bulk cargo, each additional type of supply adds only one variable.

Very much the same as the shipment of unit cargo, the need for intertheater supplies can be represented

$$\sum_{j=1}^{3} \sum_{i=1}^{I} \alpha_{i,5} X_{i,j,5,d} - \sum_{y=1}^{Y} \sum_{m=1}^{2} \omega_y U_{y,m,d} - P_{d,5} = 0$$

The excess delivered one day is carried forth to the next, so that

$$\sum_{j=1}^{3} \sum_{i=1}^{I} \alpha_{i,5} X_{i,j,5,d} + P_{d-1,5} - \sum_{y=1}^{Y} \sum_{m=1}^{2} \omega_y U_{y,m,d} - P_{d,5} = 0$$

for each day D, adding D constraints. The factor j varies from one to three, so that any means of intertheater delivery is considered.

2. The series of constraints to insure supplies at the front are presented next. Each unit not based at the APOD generally units other than fighter squadrons, ALCE units and transportation units (truck and helicopter), is considered to consume its supplies at the front, regardless of its mode of delivery. Supplies can be delivered to the front through direct delivery (j=2), through airdrop (j=3), through transhipment by air (j=4), or through transhipment by deployed unit. The last capability requires an additional factor computation. All units have input parameters concerning the ton-miles per day which they are capable of hauling, which is a common measure of performance. For combat units, this parameter is set to 0, reflecting their capability to move supplies in the rear of the corps rear area. To determine, then, how many tons can actually be transported per day, the expression

$$\frac{\delta_y}{2 * DAPDFT}$$

must be calculated. Again, similar to the first set of computed parameters, the factor 2 represents a dead-head return trip to pick up more deliverable cargo. Supplies delivered directly to the front this period, plus supplies transferred by air and truck between the APOD and the front this period, plus supplies at the front which are surplus from last period, minus consumption this period, equals surplus for this period. This can be mathematically expressed:

$$\sum_{j=2}^{4}\sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} + \sum_{y=1}^{Y}\sum_{m=1}^{2} \frac{\partial_y}{(2*DAPDFT)} U_{y,m,d-M_y} + P_{d-1,s} - \sum_{y=1}^{s}\sum_{m=1}^{2} \omega_y U_{y,m,d} - P_{d,s} = 0$$

However, the unconstrained use of the term $\partial_y U_y$ could lead to the "creation" of supplies in the model. Therefore, letting Sd equal the supplies transhipped during d, which must be less than or equal to the capacity of the transhipment "pipeline", we have:

$$S_d \le \frac{\partial_y}{(2*DAPDFT)} \sum_{y=1}^{Y}\sum_{m=1}^{2} \partial_y U_{y,m,d-M_y} + \sum_{i=1}^{I} \alpha_{i,s} X_{i,4,s,d}$$

Also, the term Sd must be less than the amount left over at the APOD, which we will deal with later.

Now the supplies at the front can be expressed as:

$$\sum_{j=2}^{3}\sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} + S_d + P_{d-1,s} - \sum_{y=1}^{s}\sum_{m=1}^{2} \omega_y U_{y,m,d} - P_{d,s} = 0$$

If it is desired to investigate the results of a buildup leading to conflict after a given period of time, while still supported by air, the supply consumption rate of the combat units can be premultiplied by a time dependent factor INTENSE(d), which will scale the supply tonnage consumption to the appropriate level. This would also need to be done for the previous set of constraints.

This would result in a final formulation of

$$\sum_{j=2}^{3}\sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} + S_d + P_{d-1,s} - \sum_{y=1}^{s}\sum_{m=1}^{2} \text{Intense}_d\, \omega_y U_{y,m,d} - P_{d,s} = 0$$

and

$$\sum_{y=1}^{Y} \sum_{m=1}^{2} \frac{\delta_y}{(2*DAPDFT)} U_{y,m,d-M_y} + \sum_{i=1}^{I} \alpha_{i,s} X_{i,4,s,d} - S_d = 0$$

for each day d, giving 2*D constraints to the model.

3. Supply of forces stationed at the APOD is addressed here. Again, supplies delivered must equal or exceed unit requirements. Because of the availability of APOD - capable aircraft as opposed to direct delivery capable aircraft, it is assumed that supplies will move, if required, from the APOD forward, but there will be no requirement for supplies to move from the front back towards the APOD. Besides consumption, there are two ways in which supplies can leave the APOD - transhipment by air or shipment by a deployed transportation unit. Since forward units must be supplied, if there are insufficient direct delivery means for supplies, the transhipment of the supplies will require increasing assets as the number of deployed units increases. Without truck units, this supply movement problem would soon utilize so much APOD capacity for intratheater transhipment by air that further units would be hindered in deployment. Therefore, truck and helicopter logistics transportation units, although offering no direct combat power, are automatically moved by the model at optimum points in order to further the goal objectives of deploying combat units.

The supply situation at the APOD is that supplies to the APOD in period d, plus surplus supplies at the APOD from period d-1, minus consumption by units at the APOD, minus transhipment forward, equals the surplus supplies at the APOD in period D. Since no one is allowed to starve, this surplus must always be non-negative. Therefore, we can express the mathematical relationship:

$$\sum_{i=1}^{I} \alpha_{i,5} X_{i,1,5,d} + P_{d-1,5} - \sum_{y=5}^{8} \sum_{m=1}^{2} \omega_y U_{y,m,d} - S_d - P_{d,5} = 0$$

The summation of the units is made here from 5 to 7 because it is assumed that the fighter squadrons, ALCE, and transportation units draw their supplies at the APOD.

This set adds one equation for each day d, for a total of D constraints.

Unit Linkages. Unit linkages can describe either ceilings or floors on deployment of certain units in relation to other units. A typical ceiling would be on the deployment of combat support arms such as artillery, requiring a minimum number of combat units to be deployed before more follow-on artillery. This can be shown as

$$\sum_{y=1}^{Y} \sum_{m=1}^{2} c_y U_{y,m,d} \geq 0$$

which keeps combat designated units in at least a 1:1 ratio with combat support units. The designation of units $U_{y,m,d}$ between combat and combat support is made for each type y, and C_y is positive 1 for combat units, negative 1 for non-combat units, or zero for units which the commander designates as non-involved, such as the ALCE. This would add one constraint.

Another typical unit linkage is a floor, which mandates deployment of a certain type unit given that other units are already deployed. This is most common in the relationship between combat units and combat service support units, such as headquarters.

A ratio of at least 1 headquarters per 5 battalions could be shown as

$$\frac{cmbt}{HQ} \leq 5 \rightarrow cmbt \leq 5\ HQ$$

$$cmbt - 5\ HQ \leq 0$$

However, in the start-up case, this would require, essentially, headquarters to arrive before the combat units, in order to satisfy the integer relationships, or even with non integer units, to begin partial deployment with the headquarters unit. A better expression is the interval limitation, such as

$$cmbt - 3\ HQ \leq 2$$

which allows up to 2 combat units to deploy before a HQ unit, and allows one HQ unit to control up to 5 combat units. It also allows 2 HQ units to control 3 or 4 units each, and forces a third HQ only before the 9th combat unit is deployed, if an integer solution technique is employed. For a current 9-battalion division, this is exactly in line with doctrine and practice.

This type of constraint would add one constraint for each link between combat units and other types of units.

Unit Abilities

A last set of equations bounds the problem due to particular unit abilities, such as that of the rigger companies which limit airdrop resupply to the capacity of the rigger companies to prepare supplies for airdrop. This can be expressed:

$$\sum_{i=1}^{I} \alpha_{i,s} X_{i,3,s,d} \leq (\text{rigger capability})_d$$

the daily maximum capability of the rigger companies. With surplus capability carried forward, the equation is then:

$$\sum_{i=1}^{I} \alpha_{i,s} X_{i,3,s,d} - m_{d-1,s} - (\text{rigger capability})_d + m_{d,s} = 0$$

This adds one constraint for each day d, for a total of D constraints.

Summary

The model as depicted consists of the constraints:

PLANES

$$.5 \sum_{j=1}^{J} \sum_{k=1}^{K} X_{i,j,k,d'-1} + \sum_{j=1}^{J} \sum_{k=1}^{K} X_{i,j,k,d'} + .2 \sum_{k=1}^{K} X_{i,4,k,d'} - \sum_{d=1}^{d'-1} \sum_{j=1}^{J} Z_{i,j} X_{i,j,k,d'}$$

$$\leq NUM_i * V_i$$

for each aircraft type and day.

UTE Rate

$$\sum_{j=1}^{3} \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,j}} X_{i,j,k,d} + \sum_{d=d'}^{d'+5} \frac{1}{UTE_{i,4}} \left(\frac{DAPDET}{DUSAPD}\right) X_{i,4,k,d} - \sum_{j=1}^{J} \sum_{d=1}^{d'+4} Z_{i,j} X_{i,j,k,d}$$

$$+ \eta = 5\ NUM_i * \sigma_i / (2 * DUSAPD)$$

for each aircraft type and period.

PARK SPACE

$$\sum_{i=1}^{I} \sum_{j=1,4} \left(\frac{t_{i,j}/24}{PRK_i}\right) X_{i,j,k,d'} + \sum_{d=1}^{d'} \sum_{y=1}^{Y} \gamma_y U_{y,2,d} \leq 1$$

for each day.

MHE

$$\sum_{i=1}^{I} \sum_{j=1,4} \sum_{k=1}^{K} \epsilon_i X_{i,j,k,d'} - \sum_{d=0}^{d'-1} \sum_{y=1}^{Y} \psi_y U_{y,2,d} \leq H_a$$

$$\sum_{i=1}^{I} \sum_{j=2,4} \sum_{k=1}^{K} \epsilon_i X_{i,j,k,d'} - \sum_{d=0}^{d'-1} \sum_{y=1}^{Y} \psi_y U_{y,1,d} \leq H_f$$

for each day.

AVAIL UNITS

$$\sum_{d=1}^{D} \sum_{m=1}^{2} U_{y,m,d} \leq \Gamma_y$$

for each deployable unit.

Ship to APOD

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,1,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \beta_{y,k} U_{y,2,d} - P_{d,k} = 0$$

for each day and cargo type.

Ship Direct

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,2,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \beta_{y,k} U_{y,1,d} - P_{d,k} = 0$$

for each day and cargo type.

Abn Ship.

$$\sum_{i=1}^{I} \alpha_{i,k} X_{i,3,k,d} + P_{d-1,k} - \sum_{y=1}^{Y} \Omega_y \beta_{y,k} U_{y,1,d} - P_{d,k} = 0$$

for each day and cargo typ

Theater Supplies

$$\sum_{j=1}^{3} \sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} + P_{d-1,s} - \sum_{y=1}^{Y} \sum_{m=1}^{2} Intense_d \, \omega_y U_{y,m,d} - P_{d,s} = 0$$

for each da

Front-Line Sup.

$$\sum_{j=2}^{3} \sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} + S_d + P_{d-1,s} - \sum_{y=1}^{5} \sum_{m=1}^{2} Intense_d \, \omega_y U_{y,m,d} - P_{d,s} = 0$$

$$\sum_{y=1}^{Y} \sum_{m=1}^{2} \frac{\delta_y}{(2 * DAPDFT)} U_{y,m,d-m_y} + \sum_{i=1}^{I} \alpha_{i,s} X_{i,4,s,d} - S_d = 0$$

for each da

APOD Supplies

$$\sum_{i=1}^{I} \alpha_{i,s} X_{i,1,s,d} + P_{d-1,s} - \sum_{y=6}^{8} \sum_{m=1}^{2} \omega_y U_{y,m,d} - \sum_{y=1}^{Y} \sum_{m=1}^{2} \frac{\delta_y}{(2 * DAPDFT)} U_{y,m,d}$$

$$- \sum_{i=1}^{I} \alpha_{i,s} X_{i,4,s,d} - P_{d,s} = 0$$

for each da

• Links

$$\sum_{y=1}^{Y} \sum_{m=1}^{2} c_y U_{y,m,d} \geq 0$$

for each unit link.

Min # of HQ

$$cmbt - 3HQ \leq 2$$

for each link.

UNIT ABILITIES

$$\sum_{i=1}^{I} \alpha_{i,s} X_{i,j,s,d} - \eta_{d-1,s} - (\text{rigger capability})_d + \eta_{d,s} = 0$$

for each modeled constraint.

GOALS-TIME INVARIANT

(FLT)

$$\sum_{y=1}^{Y} \sum_{d=1}^{d'} \theta_y U_{y,1,d} + \sum_{y=1}^{Y} \sum_{d=1}^{d'-M_y} \theta_y U_{y,2,d} \geq R_d$$

at least one for each goal.

(AT)

$$\sum_{y=1}^{Y} \sum_{d=1}^{d'} \phi_y U_{y,1,d} + \sum_{y=1}^{Y} \sum_{d=1}^{d'-M_y} \theta_y U_{y,2,d} \geq R_d$$

at leasat one for each goal.

Goals-Time Variant

(combat power)

$$\sum_{y=1}^{Y} \sum_{d=1}^{d'} \nu_d \lambda_y U_{y,1,d} + \sum_{y=1}^{Y} \sum_{d=1}^{d-M_y} \nu_d \lambda_y U_{y,2,d} = R_d$$

one or (more) for each goal.

The total number of variables contributed by the aircraft will not exceed i * j * k * d; however, since many i, j and i, k combinations for different i aircraft are nonexistent, the number of variables is usually considerably less. The number of variables from the deployable units are Y*M. However, restrictions on deployments, such as requiring fighter units to go to the APOD, will reduce the total to somewhat less. The number of constraints from the equations series, in order, is

I*D+(D-Period+1)*I+D+D+Y+D*K+D*K+D*K+D+2*D+D+#links+#goals

or (I*(2D-Period+1))+6D+Y+(3D*K)+#links+#goals.

VI. Model Options

Several means exist, within the framework of the developed model, to address complicating factors encountered in reality. Such factors include the variability over time of the available number of CRAF as the CRAF are mobilized, the availability over time of the deployable units, and the requirement for a supply buildup as a hedge against catastrophe. Also easily portrayed are the change at some period in supply usage rates due to a change in combat intensity, and the expansion of a single all-embracing class of "supply" into categories such as fuel, water, food, and ammunition. For air movement, the most dramatic model changes would occur with the incorporation of more than one APOD, and with any restrictions on intratheater delivery airstrips. All of these options will be addressed below.

Time-Dependent Availability of Forces

To portray a time-dependent availability of forces requires a change in the right hand side reflecting the appropriate period.

Since both aircraft and units have an expression relating to number of resources available per time period, the simplest way to address this is to modify the constraint limitation for the appropriate period. Changing the number of aircraft of a given type will entail not only a change in the total available per period, but also in the appropriate UTE rate constraint, since this is also based on the number of aircraft available.

Supplies

To reflect supplies as a single class is a useful simplifying assumption but underestimates the true burden of supplies management and shipping. Certain types of supplies require special handling and incur movement restrictions, such as ammunition; others require special packaging or containerization, such as water and fuel. The basic relationships developed for "supply" would remain the same, but would be reiterated for each type of supply.

A change in unit supply requirements which is expected to occur at some fixed time can be directly reflected in the supply constraint for that day or period and forward. Using standard multipliers adopted by the U.S. Army Logistics School, the values consumed from day d′ would be some scalar multiple of the tonnage consumed on day d′ - 1.

The requirement for a supply "hedge" against catastrophe can be treated as the required movement of a "linked" unit such as a headquarters, except that the supply "unit" consists solely of bulk supply cargo. There must be sufficient number of these supply "units" available so that there is never a limiting amount reached which would, of itself, stop deployment of a real unit.

More Than One APOD

Inclusion of a second APOD would add another two possible missions to the current list of three. These new missions would reflect intertheater move to APOD 2 and intratheater move from APOD 2. Units would add another node to their possible deployment; they could now be delivered either to APOD 1 or APOD 2 as well as the direct delivery mode. All factors necessary for development of one APOD would be required for the second. The inclusion of another APOD would add only a set of constraints for parking and material handling equipment at the second APOD, or 2*d constraints. However, it would add a second column for every column in the matrix for which, with one APOD, j=1 or j=4 (movement to the APOD or transhipment from the APOD), and would add another column for every column for which m=2 (mode=APOD delivery). In essence, this nearly doubles the matrix size, but it retains the logic of the original model formulation. This assumes, implicitly, that aircraft and transportation units return to their starting points. To be able to cross-service aircraft and transportation units, the model would have a geometric increase, so that for two APOD, a four-fold increase in matrix size is necessary.

VII. Scenario

To investigate the uses of goal programming and the developed model, a reduced force base scenario was set up as a demonstration. The results of this scenario cannot be construed as defining the actual optimal response, because of the numerous simplifying assumptions. Rather, this scenario was generated to verify and demonstrate the feasibility of the developed model, and the usefulness of goal programming to both Army and Air Force users of such a model.

Scenario Assumptions

1. No attrition, regardless of mission type.

2. Airborne delivered supplies are limited to the maximum Army rigger output.

3. The 20-day period of deployment can be reflected by 4 linked 5-day deployment periods.

4. C-5 aircraft will only perform intertheater transport to the APOD.

5. CRAF are not available until 5 days after movement begins.

6. All units are immediately available for movement.

7. Intratheater transport is limited to moving bulk cargo supplies.

8. Only minimum daily supplies are required.

9. There are 5 days ground travel time between the APOD and the deployment area.

10. Although six squadrons of C-130 aircraft were

available, the decision was made to base the tactical airlift forces at locations separate from the APOD because the ramp space and servicing required would restrict the capability of the APOD to handle strategic airlift aircraft arriving in theater.

Scenario Input

The input parameters to the scenario are given in Tables 4 - 6. The airport limitations and unit weights were obtained from reference 4. The aircraft limitations and capabilities were also taken from this reference and checked and modified by HQ, USAF/SA. Thus the C-5 UTE Rate of 5.5, suggested by Army sources, was changed to 12.5, in order to render this study acceptable to the Air Force. Other changes are similarly obvious.

The Army unit capabilities and values were taken from doctrinal publications, in the case of the front line trace. From TOE data for unit-owned TOW and DRAGON weapons systems an anti-tank power was computed, using a value of 1 for TOW systems and .5 for DRAGON systems. Combat power potential was developed from relative combat power of units as used to play a force-on-force war game at the Army War College, and the multiplier effect for time was taken from an open source revelation of the classified Timeliness versus Effectiveness volume of the Congressionally Mandated Mobility Study (title unclassified).

AIRCRAFT

A/C Type	Number	Availability	UTE RATE/MISSION Intertheater APOD/Direct	Intratheater	Airborne Delivery	CARGO TONNAGE CAPACITY Out/PAX	Over/PAX	Bulk/PAX	PAX Only	Block Speed	Load/Unload Ground Time	MIL REQ Standard Pallets	Remarks
C5	60	.8	12.5/0	9	0	65/25	60/25	80/25	320	430	3.3	36	
C17	0	.8	15.0/12.5	10	0	48/20	45/20	49/20	160	430	2.0	18	
C141	180	.8	12.5/0	10	12.0	0	21/14	25/14	110	410	2.3	13	
C130	300	.8	0/0	4	4	0	13.8/6	13.8/6	64	270	1.5	6	
CRAF 747 Cargo	30	.8	10.0/0	0	0	0	60/0	90/0	0	430	3.6	36	AVAIL D+5
CRAF 747 PAX	20	.8	10.0/0	0	0	0	0	0	364	430	2.8	36	AVAIL D+5

Table IV. Aircraft Data Used

UNITS

Type	Number	Tonnage Outsize	Oversize	Bulk	Pax	Tons Daily Supply Req	Cbt Power	AT Strength	km of Flt	# of Aircraft	Remarks
Airborne Battalion	9	0	1400	268.7	1400	149.2	4	19.5	4	0	
Airborne Battalion Headquarters	3	73	0	0	305	0	0	0	0	0	
Air Assault Battalion	9	152	990.3	574.7	1960	446	6	28.5	4	0	
Mechanized Battalion	9	2055	3885	151.7	2052	400.2	8	40.0	6	0	
155mm Artillery Battalion	3	139	1243	91.5	710	212.85	3	3.0	0	0	
F-16 Squadron	3	0	249.6	155.4	472	102.5	8	36.0	0	18	
Medium Truck Company	3	1098	405.0	270.0	250	55.7	0	0	0	0	182,000 ton miles per day
ALCE	2	176.0	2213.0	244.0	400	73.8	0	0	0	0	

Table V. Deployable Units Data.

APOD AIRPORT

Distance From U.S.:	7200nm					
Distance From Corps Rear:	200nm (5 days)					
Parking Capability:	C5:5	C17:14	C141:12	CRAF 747:5	C130:16	Fighters: 48
Initial MHE Handling Capability:	27 Sorties C747/Day (980 pallets)					

Combat Value of Units Closing in Time Period;

within First 5 days:	combat x 2.5
between 5–10 days:	combat power x 1.8
between 10–15 days:	combat power x 1.3
between 15–20 days:	combat power x 1.1

Table VI. APOD and Scenario Data

Scenario Goals

Five sets of goals were developed using two philosophies. The first two sets were designed around a goal programming methodology, where the required system response is input and the model optimizes the number, type, cargo, and destination of the aircraft moving and also the number, type, and destination of available RDF units. In this model, the optimization process itself attempts to best fill the required system goals, and the response is what units are deployed, to where, and when. The second philosophy of strategic airlift was also explored with the model, as a comparison. This philosophy represents the current practice of a non-wholistic approach to RDF goal achievement. Three typical goal sets were established as representing simplified versions of realistic requirements, and then these established goals, in terms of units to be moved and an optimal Army prioritization of those units, were sent to the Air Force assets. The model then used all Air Force assets to effect the fastest possible closure of the required units to the theater, in order of priority.

First Philosophy

The interests of the RDF force were hypothetically set as the following, which define goal set one:

1. Within the first 5 days, have the capability to defend 25 Kms of front line.

2. Within the first 5 days, deploy the anti-tank

equivalent of 60 heavy anti-tank weapons sytems (based on TOW = 1).

3. Within the 20-day period, maximize combat power deployed.

4. Within 15 days, have the capability to defend 50 kms of front line.

5. Within 15 days, move 2 mechanized brigades.

6. Within 10 days, maximize combat power deployed.

Scenario Output

For the given scenario, the result was:

Goal 1:	underachieved.	19.756 km of FLT defended
Goal 2:	achieved.	MAX capability was 145
Goal 3:	141.29	
Goal 4:	achieved.	MAX capability was 62.5
Goal 5:	underachieved.	.58 of mech bn moved
Goal 6:	74.55	

The figures to the right of the words achieved or underachieved show extreme goals. If underachieved, the number shows the response which can be achieved, if overachieved, the number represents to the force planner what slack there is in the system, so that if necessary the goals can be redefined. However, these numbers represent the slack at that stage; when the next goal is implemented, the slack from the previous goal is no longer an indicator.

The goals of the force planners were then adjusted to reverse the priorities of goals 5 and 6. The results were, naturally, the same for goals 1 through 4. The results for goals 5 and 6 were:

Goal 5: 82.72
Goal 6: underachieved. No mech shipped

Second Philosophy

A third set of goals was developed which more closely approximated the current goals given to the Military Airlift Command. These were:

1. Move one brigade of the 82nd Airborne as first priority.

2. Move one brigade of the 101st Air Assault Division as second priority.

3. Move one brigade of the 24th Mechanized Division as third priority.

4. Deploy close air support fighter squadrons.

These goals were subjected, at each stage, to a MAC goal of maximizing productivity, by minimizing the number of flights, as long as this did not increase unit closure time. The results were:

Goal 1: achieved by 5th day.
Goal 2: achieved by 10th day.
Goal 3: achieved by 20th day.
Goal 4: no fighters deployed.

Goal set 4 was developed the same as Goal Set 3, but required that an ALCE unit be moved first.

Goal set 5 was developed on the basis of sets 1 and 2. To afford an accurate comparison of the methodologies (systemized wholistic goal programming versus a service-optimized response) the units moved by goal sets 1 and 2 were taken as service preferred, but given a prioritized order of movement, as is current practice. Again, then, the MAC assets moved these units, in order of priority, to the theater. Lesser priority units were allowed to move before closure of a higher priority unit only if it did not affect the closure time of the higher priority unit. This fifth set of goals was:

1. Move one brigade of the 82nd Airborne simultaneously with one ALCE unit as first priority.

2. As second priority, close the remainder of the 82nd Airborne Division.

3. As third priority, move one brigade of the 101st Air Assault Division.

4. As fourth priority, move three squadrons of F-15 aircraft.

A comparison, for all goal sets, of forces moved can be found in Table 7.

Figures 2, 3, and 4 show graphically the impact that the varying philosophies and goal sets had on the responses among three types of responses that were of interest to the RDF commander.

Goal Set	1	2	3	4	5
Combat Units Moved by Day 5:					
Abn Bns	4.9	4.9	3	3	5.9
Air Asslt	.9	1.2	2.0	1.3	0
Artillery	0	0	0	0	0
Mechanized	0	0	.03	0	0
Ftr. Sqdn.	0	0	0	0	0
By Day 10:					
Abn Bns	6.9	6.8	3	3	9.0
Air Asslt	3.2	3.0	3	3	1.8
Artillery	0	0	0	0	0
Mechanized	0	0	.8	.75	0
Ftr. Sqdn.	0	0	0	0	0
By Day 15:					
Abn Bns	9.0	9.0	3	3	9.0
Air Asslt	3.9	4.4	3	3	3.0
Artillery	0	0	0	0	0
Mechanized	.58	0	2.2	2.3	0
Ftr. Sqdn.	0	0	0	0	1.0
By Day 20:					
Abn Bns	9.0	9.0	3	3	9.0
Air Asslt	4.3	4.7	3	3	3.0
Artillery	0	0	0	0	0
Mechanized	.58	0	3	3	0
Ftr. Sqdn.	2.6	2.6	.91	1.4	1.6

Table VII. Deployed Units Under Different Goal Sets.

Deployed — Combat Power DAPDFT = 5 Days

Time	Goal Objective	Set 1	Set 2	Set 3	Set 4	Set 5
By Day 5		59.48	62.5	52.14	44.04	45.0
By Day 10	maximize	75.44	82.72	63.81	62.27	70.2
By Day 15		116.34	122.95	66.51	69.67	109.76
By Day 20	maximize	141.29	141.29	77.89	81.67	130.48

Figure 2. Deployed Combat Power

Deployed AT Strength

Time	Goal Objective	Set 1	Set 2	Set 3	Set 4	Set 5
By Day 5	60	80.8	80.8	49.5	49.5	74.25
By Day 10		138.6	163.0	106.5	86.5	132.0
By Day 15		242.6	251.3	167.0	165	235.8
By Day 20		378.7	335.6	255.7	277.4	327.6

Figure 3. Deployed Anti-Tank Strength

Defended Front-Line Trace Span (kms)

Time	Goal Objective	Set 1	Set 2	Set 3	Set 4	Set 5
By Day 5	25	19.6	19.6	12.0	12.0	18.0
By Day 10		33.0	35.1	24.0	19.8	32.0
By Day 15	50	55.8	54.6	36.4	36.0	46.8
By Day 20		64.6	76.6	47.6	48.4	54.0

Figure 4. Defended Front Line Trace

Analysis

The reversal of end goals between sets 1 and 2 changed the selection of units and movement times to accomplish the same set of four initial goals. The overwhelming advantage of a goal programming methodology is here demonstrated. When a minor or end-point goal is changed, the model will respond in such a way as to still maintain, as a minimum, the desired or achievable levels of higher priority goals. Simulation as a technique to do the same job might need an enormous number of replications, dependent on the number of potential units for deployment. On the other hand, professional, service-insular judgement as to what units were now necessary, based on a goal change, might be very appropriate. However, there is no guarantee that the new prioritization of units delivered to MAC will result in similar unit closure times, and so an iterative "best compromise" solution must be worked out between the two services, if the current deployment philosophy is maintained.

The addition of a goal between sets 3 and 4, however, did not change the types of forces moved (it couldn't under that methodology) but did effect closure times and the deployed force results. The early movement of an ALCE unit pushed back the deployment of other forces. This result is especially evident in the first 10 days. However, the impact of the ALCE unit quickly becomes apparent with time, because the set with the ALCE (set 4) quickly overtakes and passes the set without (set 3) in every measure by the end of the deployment period. It is of interest to note that the trade-off point (where both alternatives are essentially equivalent) is between days ten and fifteen, so that if the deployment period of interest is less than ten days, deployment of an ALCE would not be advantageous.

A further interesting comparison is between sets 1 and 5. Although the 82nd is delivered (closed) to the theater much more rapidly under set 5, the measures of effectiveness under the true goals (set 1 goals) for set 5 are uniformly worse than those for set 1. This is because the airlift model responded to its service-oriented goal to close the unit as rapidly as possible, and thus delivered foot mobile paratroopers to the APOD whose value to the commander couldn't be reflected until they closed to the area of employment, in the next five-day period. The delivery of these units to the APOD ties up aircraft that in the goal-oriented model (set 1) were delivering mobile air assault units and transportation units (which reduced C-130 conflicts at the APOD and opened more parking space for intertheater transport). The requirement to push a prioritized force to closure before allowing conflict with another force's deployment was revealed as nonoptimal, insofar as proper prioritized fulfilment of the assumed RDF goals.

Model Verification

Verification implies a measure of the working nature of the model. The model in this paper has been verified by examining the output data and ensuring through hand calculations that the total outsize, oversize, and bulk cargo comprising the units moved could indeed be moved with the number and type aircraft used by the model, which is also given as output. A use of the "check" option of the Multipurpose Optimization system (MPOS), used to determine optimal solutions given the constraint set developed in Chapter 5, showed consistent primal-dual tableau convergence when operating with subroutines "revised" and "minit". Under revised, MPOS operates a revised Simplex algorithm, and under minit, it operates an alternating primal-dual simplex convergence scheme. Primal-dual convergence, which occurred for every tested case, implies that the constraint set is non-contradictory. Given that the model is correctly formulated, and using a known functional optimization package, we can be assured of model verification.

Model Validation

The issue of validation is far more difficult. There currently exist no comprehensive, multiservice, combined intra- and inter-theater models, much less optimization models of that type, with which to compare or contrast results. We also have no real world phenomenon with which to compare results, because an all-out mobilization of MAC plus stage II CRAF to rapidly move more than a division to an austere overseas base has never occurred. Given that this type of "validity", i.e., replication of real world events, is not available, we must focus on corroboration, referring to supporting documentation. At the MORS conference on 27-28 December 1983, it was stated that the present MAC force structure was limited to moving only a little more than a division to any intertheater commitment in the 19 - 20 day period before ships could close (Ref:24, OSD(PAE)). This is borne out in the developed model. Any optimism in the results of this model can be attributed to assumptions 6 and 8, for these discussed scenarios. The same type of corroboration can be alluded to with respect to the input parameters, which were based on a subset of the parameters found throughout literature concerning inter- and intra-theater airlift considerations. What parameters were neglected or subsumed (for example, spares availability into UTE rate) were done to simplify and make usable a model which could be used as a demonstration of principle. The model as developed and used for these results comprised 212 variables in 136 separate equations (constraints).

In the end analysis, the final measure of validity lies in the sensibility of the model output. All that can be said here is that the goal optimized outputs meet established goals, and for the extreme cases establish results that are impossible to imitate through preselection of forces based on professional experience, yet can easily be rationalized after the fact. A comparison of the two philosophies of force deployment, that shown in set 2 versus that of set 5, makes this point most clear. After the fact comparisons make the rationale behind the end differences in moving essentially the same force obvious, whereas before the fact all one could express was that the same force was being moved. A more appropriate approach would be to move a selected force chosen to perform certain tasks with current Air Force intertheater models, such as MIDAS, followed by intratheater support models, and compare these results to a force selected by this model to accomplish the same goals. Then using this model's forces and priority sets (RDDs), the Air Force models could be rerun to determine cross validity of this model for both Air Force and Army needs.

VIII Flexible Response Surface Theory

This chapter discusses the underlying basis for investigating the sensitivity of an LP model with regression analysis. The reasons for doing so are discussed, the theoretical background reviewed, the validity of the approach for this particular problem is examined, and the experimental design explained.

Background

The single parameter sensitivity techniques developed for analysis of linear programming algorithms are limited in that they fail to portray the interrelationships between factors. Typical right hand side ranging techniques give only a parametric span, by parameter, within which the solution is optimal, and reveal which variable will enter the basis if the analysis is forced beyond that limiting point. The number of separate runs required to fully determine the response surface of the problem increases geometrically with the number of factors and the span of each factor. To investigate the optimal response, in this model, given five factors varying over a wide range would take 20,907,909 separate runs, which is obviously infeasible. A much more feasible means of generating the same surface, in equation form, is given by a multivariate regression analysis.

Regression Analysis

Given a generalized model

$$y = f(x,\theta) + \epsilon$$

where $\theta = (\theta 1, \theta 2 \ldots \theta p)$ is a vector of p parameters to be estimated and $x = (x1, x2, \ldots, xK)$ is a vector of K variables, the settings of which determine the experimental runs and ϵ is the error term, (Ref 7:731).

it has been shown that use of a regression analysis design using the $x'x$ criteria leads to a confidence region for parametric estimation which minimizes the distance between the response surface equation and the actual response surface for any setting of vector x. What this means is that, using a proper design, an error term can be estimated which reveals the very worst, on a percentile basis of the response, that the proposed model equation is from the true model.

Using a linear program to generate the design points for the response surface, we effectively eliminate any variance error, because the model will always return the same response for a given input (as opposed to stochastic or sampling models). This means that all error in the model comes from model bias, which can only be minimized by limiting the number and scope of model assumptions.

Typical regression analysis attempts to fit an equation of linear or quadratic forms to design points of a model. A line only requires two points, but a quadratic parabolic expression requires a minimum of three points to be defined. A typical quadratic model in two variables would be

$$\text{Response} = Bo+B1X1^2+B2X2^2+B3X1X2+B4X1+B5X2$$

A standard regression package takes the data points given by the set of n vectors (X1n,X2n,Response..) and tries to fit the given equation. If the proposed model is a good fit to the data, the error term expressed in terms of standard deviations will be low and the data points will be distributed normally across the mean response surface. If the model is not a good fit, either the error term will be large or the data will not be distributed with the proposed response surface as a true mean. This can be illustrated below

Figure 5. Plotted Data vs. Response Surface

The example on the left is the plot of a bad fit (a proposed linear fit to an actual quadratic response) whereas the example on the right is a good fit of a proposed model to the actual data. The usefulness of using regression analysis to define the sensitivity aspects of a model without exhaustive model runs has been thoroughly documented by Smith and Mellichamp (Ref 38) and the copyrighted technique is used in this thesis with the Kind permission. As is stated in their summary.

> "The multiple dimensional parametric analysis technology using response surface concepts provides an expanded capability for conducting a more valuable analysis in a complex environment. It provides a picture of what is happening within the model being used for the study. It also provides insight into the relationship among the factors under study. 'What if' analysis can be conducted economically in real time without the necessity to obtain new computer outputs" (Ref 38:23).

The methodology can be used with any decision model, linear or nonlinear.

Experimental Design

Since the goal of this methodology is to provide rapid insight into the system response, three designs will be examined. One assumes a linear response, that is, a flat hyperplane in n dimensions where n is the number of variables examined. This design is of the form

$$\text{Response} = B0+B1X1+B2X2$$

a flat surface where B2 and B3 represent the slopes of the response plane along the respective axes. The second design assumes a first order response with interactive coefficients, that is, of the form

$$\text{Response} = Bo+B1X1+B2X2+B3X1X2$$

In three dimensions, this type of surface response would relate to a flat plane with a twist in it, with the degree of twist given by the magnitude of the interaction coefficient B3. The last design assumes a quadratic response of the form

$$\text{Response} = B_0 + B_1 X_1^2 + B_2 X_2^2 + B_3 X_1 + B_4 X_2 + B_5 X_1 X_2$$

In this type of surface, which is not necessarily linear along any axis, the coefficient B1 and B2 express the degree of curvature of the response suface in that axis, and the coefficient B5 again represents the twist.

Since a line can be given by two points, a minimal number of model runs are needed for those designs. But a quadratic representation requires at least three points in order to define the degree of curvature. Since the last proposed mathematical fit requires the most, a design will be promulgated based on the quadratic expression requirements and those points used also for the first two tested designs.

The minimum number of points required under numerous explored variables has been an area of research since the late 1950's. Draper and Stoneman proved that the set of possible runs can be fractionated in a factoral way across variable terms (Ref 14:186). Box and Draper showed, through mathematical proofs and a computer hill-climbing search, that a symmetric composite design called a cube plus star plus center points is the most efficient in terms of runs required to define the quadratic response (Ref 6:739). A large number of proposed designs have been published, and this thesis, with five variable factors, used the five-factor cube plus star plus center point design published by Box (Ref 6). The design is found in Appendix A. Normal notation for this design designates -1 to represent the lower limit of the individual variable, +1 to represent the upper limit of the individual variable, and zero to define a center point midway between the two.

IX Use of a Flexible Response Surface

This chapter describes the use of a flexible response surface, developed from the model, to determine the worth of an aircraft capable of both intertheater and intratheater delivery, the C-17. Because of the end goal selection, for the analysis, of maximize combat power, the response surface was eminently suited to address the sensitivity aspects and shadow prices of any of the output variables. This particular case was examined in direct response to the statement of LTC Mueh, HQ USAF/SAGM, during the last MORS conference. He stated that he was not aware of any methodology which could express the incremental advantages of a dual-capable airlifter given all the other changing parameters, or directly relate a quantitative measure of worth between that aircraft and another. This viewpoint was shared by Dr. M. Minneman, OCSD/R+E. Therefore, this case was obviously an excellent vehicle for demonstrating the worth of both an inter-intra joint optimization model and the flexible response theory as a sensitivity technique. First, this chapter discusses the underlying question and the scenario used. Second, the generation and verification of the response surface will be addressed. Lastly, the trade-offs between parameters will be demonstrated and findings discussed.

Background

In the recent past the Air Force and Congress decided to improve the capability of our strategic airlift fleet through the procurement of 50 additional C-5 aircraft. Additional progress to improve strategic airlift were the rewing of the present C-5 force and measures to improve the C-5 and C-141 UTE rate. An important contribution to that decision was made by the Congressionally Mandated Mobility Study. One of the major assumptions of the CMMS was that "reception ports and airfields were adequate to process all personnel and cargo moved to the theater" (Ref 27:30). However, due to the sparse nature of large airfields in the RDF's primary area of interest, as reported by Abbey et.al. (Ref 1:5-13), the RDF may need to deploy through a single APOD, which by itself may be many days travel from the proposed area of employment. When deploying through a single strategic-airlifter capable APOD, the requirements for supplies to be moved forward create an increasing conflict for parking space and material handling equipment between intertheater airlift and tactical airlift aircraft. This conflict can only be alleviated by moving transportation units to the theater, or by fortuitously having so large an airfield that no parking constraints emerge. Since the CMMS found an advantage in C-17 use because of its direct delivery capability, which negated the transhipment time between the APOD and the employment area, distance was obviously a large factor. Therefore, it was decided to investigate the C-5 versus C-17 decision using the variable factors C-5, C-17, APOD Size, Material Handling Equipment, and Distance. To insure the incorporation of distance as an important factor, similar to the CMMS, the response chosen as the measure of effectiveness (MOE) was combat power over time.

The current operating MAC fleet plus Stage II CRAF were made available as a scenario baseline. The APOD size parking capability was varied between 2 and 10 simultaneously parked C-5 aircraft (Ref 4:92). The Material Handling Equipment (MHE) was varied between 200 and 1000 pallets a day offload capability existing on the airfield before occupation and use or movement of an ALCE (Ref 36:21-22). This equated to 1000-5000 pallets per 5- day period. The distance between the APOD and the deployment area was varied between 0 and 10 days travel time (Ref 32:12). The C-17 and C-5 were both varied from a current number (0 and 60, respectively) to plus 50 aircraft. As the exact specifications for the proposed C-5B were not yet tested, C-5A performance specifications were used for the additional 50 C-5 aircraft. (This could be easily changed by just entering the C-5B into the model as a new aircraft, as the C-17 was.) A complete list of all the parameters entered as inputs to the model is on Tables 4, 5, and 6. Units available for movement were the same as in Chapter 7, and all were immediately available. This is a simplification, but did not affect the relative merit analysis of the two aircraft. Supplies were moved to theater equal to 1.3 times daily consumption, and the Corps

Headquarters (Forward) was required to deploy by D+10.

Generation and Verification

The model was run 41 times using the points of the design shown in Appendix A, as described in the last chapter. The data points generated were then entered to a Statistical Package for the Social Sciences (SPSS) regression analysis package, trying to fit any or all of three surface models. The abbreviations used were:

W1=C-5	W12=number of C-5 times number of C-17.
W2=C-17	W13=number of C-5 times APODSIZE.
W3=APDSZ	W14=number of C-5 times MHE in thousands.
W4=MHE	
W5=DIST	And a similar convention for all other cross-product terms.

The first model proposed was linear, of the form

$$\text{Response} = B_0 + B_1 W_1 + B_2 W_2 + B_3 W_3 + B_4 W_4 + B_5 W_5$$

which would have resulted in a five-dimensional hyperplane, with very easy trade-offs between B1 and B2, which would represent the incremental benefit to the response of C-5 and C-17 respectively.

The second model checked was first order with interaction terms, of the form:

$$\text{Response} = B_0 + B_1 W_1 + B_2 W_2 + B_3 W_3 + B_4 W_4 + B_5 W_5 + B_6 W_{12}$$

$$+ B_7 W_{13} + B_8 W_{14} + B_9 W_{15} + B_{10} W_{23} + B_{11} W_{24} + B_{12} W_{25} + B_{13} W_{34} + B_{14} W_{35}$$

$$+ B_{15} W_{45}$$

This would represent a much more complex, twisting surface, but the first partial with respect to both W1 and W2 would have given two equations, one of which would either dominate the other, or intersect where the point of intersection (or plane of intersection) would determine the crossover point between an advantage of one plane to another.

The third equation was the same as the second but added the quadratic (second order) terms

$$B_{16}W_{11} + B_{17}W_{22} + B_{18}W_{33} + B_{19}W_{44} + B_{20}W_{55}$$

B_{16} through B_{20} would define curvature rates for the surfaces with respect to that term's axis.

The generated responses can be seen in Figures 6, 7 and 8. Tables 8 and 9 demonstrate the typical response to a mean surface that reflects underdetermination of the true order of the actual response. Table 10, for the second order surface, shows the actual response conforms normally (in the sense of normal distribution) to the generated surface, with a very minimal standard deviation.

In fact, the programmed response of the package is that 99.5% of the actual response can be accounted for by the incorporation of the terms used in mathematical model three.

To verify this quadratic response as a true indicator of model response, thirteen points were generated and run through the model. Ten of these points were chosen randomly, using a vertical search procedure for numbers within the range of four parameters on columns 1-4 of the random number table in the 17th edition CRC. Three points were

```
* * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * * * * .

DEP. VAR... [illegible]1

VARIABLE(S) ENTERED ON STEP    4
DIST

MULTIPLE R      .9659 ANOVA          DF   SUM SQUARES  MEAN SQ.       F
R SQUARE        .9329 REGRESSION     4.   29350.330   7337.583   125.121
STD DEV        7.6579 RESIDUAL      36.    2111.186     58.644 SIG. .000
ADJ R SQUARE    .9254 COEFF OF VARIABILITY     6.8PCT
```

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICITY
APDSZ	7.930	.479	274.5[illegible]6	[illegible]	.71532	.42198
MHE	11.259	.957	153.474	.000	.53485	.31553
C17	.611	.077	63.744	.000	.34470	.13556
DIST	-1.133	.383	8.759	.005	-.12778	-.05025
CONSTANT	19.977	5.025	15.8[illegible]3	.000		

F-LEVEL OR TOLERANCE-LEVEL INSUFFICIENT FOR FURTHER COMPUTATION.

Figure 6. Regression Output, Assumed Linear Model

<u>MULTIPLE REGRESSION</u>

Residual Plot.

Y Value	Y Est.	Residual	-2SD 0.0 +2SD
120.450	112.752	7.698	
129.760	128.37	1.723	
101.390	97.467	3.923	
101.390	97.467	3.923	
129.760	128.037	1.723	
146.240	144.472	2.998	
81.832	81.033	.799	
81.832	81.033	.799	
147.470	144.472	2.998	
132.16	136.470	-4.310	
86.755	89.035	-2.280	
86.755	89.035	-2.280	
132.160	136.470	-4.310	
144.210	151.755	-7.545	
112.380	121.185	-8.805	
57.847	73.750	-15.903	R
95.621	104.320	-8.699	
103.810	120.754	-16.944	R
60.549	57.315	3.234	
85.076	104.750	-19.674	R
165.800	168.189	-2.389	
153.660	159.757	-6.097	
124.870	129.187	-4.317	
61.032	65.747	-4.715	
93.370	96.318	-2.948	
126.440	122.371	4.069	
99.369	91.801	7.568	
127.600	130.804	-3.204	
86.755	83.369	3.386	
141.080	138.806	2.274	
80.344	75.367	4.977	
117.901	107.886	10.814	
117.900	107.086	10.814	
138.860	133.703	5.157	
108.840	103.133	5.707	
148.660	142.136	6.524	
90.474	94.701	-4.227	
156.170	150.138	6.032	
88.781	86.699	2.082	
128.130	118.418	9.712	
128.130	118.418	9.712	

NOTE - (S) Indicates estimate calculated with means substituted
R Indicates point out of range of plot

Equation - 1st Order Linear

Numbers of cases plotted 41.

Number of 2 S.D. Cutliers 3. or 7.32 percent of the total

Table VIII.

VARIABLE(S) ENTERED ON STEP 10
W25

MULTIPLE R	.9733	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.9472	REGRESSION	10.	29801.596	2980.160	53.861
STD DEV	7.4385	RESIDUAL	30.	1659.92[illegible]	55.331	SIG. .000
ADJ R SQUARE	.9297	COEFF OF VARIABILITY		6.6PCT		

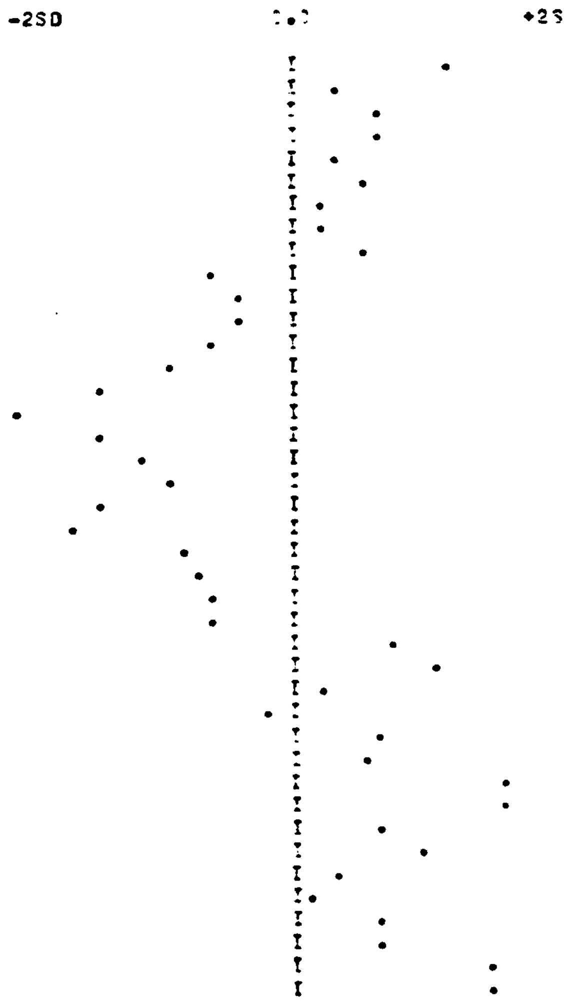
VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICITY
W34	1.171	.465	6.341	.017	.46032	.18690
W23	-.009	.037	.057	.813	-.03742	-.01190
DIST	.814	1.784	.208	.652	.09176	.03609
C17	.743	.357	4.321	.036	.44150	.17367
APDSZ	5.055	1.972	6.569	.016	.45601	.26901
MHE	7.745	3.945	3.855	.059	.34932	.20607
W45	-.434	.372	1.359	.253	-.1329[illegible]	-.05767
W35	-.093	.136	.2[illegible]	.658	-.07017	-.02213
W24	-.030	.074	.160	.692	-.06259	-.01977
W25	-.0[illegible]6	.030	.039	.844	-.02494	-.00654
CONSTANT	27.756	15.238	3.318	.079		

F-LEVEL OR TOLERANCE-LEVEL INSUFFICIENT FOR FURTHER COMPUTATION.

Figure 7. Regression Output, Assumed First-Order Model with Cross Products

<u>MULTIPLE REGRESSION</u>

RESIDUAL PLOT.



Y Value	Y Est.	Residual
120.451	112.752	7.698
129.760	128.037	1.723
101.390	97.467	3.923
101.390	97.467	3.923
129.760	128.037	1.723
146.270	144.472	2.998
81.832	81.033	.799
81.832	81.033	.799
147.470	144.472	2.998
132.160	136.470	-4.310
86.755	89.035	-2.280
86.755	89.035	-2.280
132.160	136.470	-4.310
144.210	150.269	-6.059
112.380	122.671	-10.291
57.847	72.264	-14.417
95.621	105.806	-10.185
103.810	111.389	-7.579
60.549	66.681	-6.132
85.076	95.384	-10.308
165.800	177.555	-11.755
153.660	158.870	-5.210
124.870	130.074	-5.204
61.032	64.860	-3.828
93.370	97.205	-3.835
126.440	121.634	4.806
99.369	92.538	6.831
127.600	126.468	1.132
86.755	87.704	-.949
141.080	137.143	3.937
80.344	77.030	3.314
117.900	107.086	10.814
117.900	107.086	10.814
138.860	134.441	4.419
108.840	102.396	6.444
148.660	146.471	2.189
90.474	90.366	.108
156.17	151.801	4.369
85.781	85.035	3.746
128.130	118.418	9.712
128.130	118.418	9.712

NOTE - (*) Indicates estimate calculated with means substituted
R Indicates point out of range of plot

Number of cases plotted 41.
Number of 2 S.D.outliers or 0 percent of the total

Table IX

* * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * * * *

DEP. VAR... 91

VARIABLE(S) ENTERED ON STEP 17
W11

MULTIPLE R	.9983	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.9966	REGRESSION	17.	31446.236	1849.779	401.334
STD DEV	2.1469	RESIDUAL	23.	106.009	4.609	SIG. 0
ADJ R SQUARE	.9942	COEFF OF VARIABILITY		1.9PCT		

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICITY
W34	1.264	.134	88.006	0	.49647	.20205
W23	-.009	.011	.663	.417	-.03737	-.01181
DIST	-.459	.709	.419	.524	-.05171	-.02039
W55	.127	.049	6.806	.016	.15339	.03928
C17	1.240	.142	76.343	0	.69793	.27519
APDSZ	9.436	1.412	44.654	0	.94992	.53257
MHE	23.792	2.155	121.866	0	1.07155	.63362
W44	-2.724	.305	83.317	0	-.77735	-.26130
W33	-.408	.076	28.624	.000	-.45564	-.15298
W22	-.009	.002	21.856	.000	-.27575	-.07039
W45	-.434	.107	16.311	.001	-.18264	-.05773
W35	-.083	.054	2.401	.135	-.07007	-.02215
W24	-.030	.021	1.916	.180	-.06260	-.01975
W25	-.006	.009	.472	.499	-.02490	-.00654
W13	.003	.011	.082	.777	.02596	.01392
C5	-.068	.339	.040	.843	-.03831	-.05134
W11	.000	.002	.025	.875	.02984	.02054
CONSTANT	-1.460	19.750	.005	.942		

F-LEVEL OR TOLERANCE-LEVEL INSUFFICIENT FOR FURTHER COMPUTATION.

Figure 8. Regression Output, Assumed Full Quadratic Model

MULTIPLE REGRESSION

RESIDUAL PLOT.

-2SD 0.0 +2S

Y Value	Y Est.	Residual
120.450	120.450	-.000
129.760	130.302	-.542
101.390	99.732	1.658
101.390	99.578	1.812
129.760	130.148	-.388
146.240	145.562	.678
81.832	82.517	-.685
81.832	82.056	-.224
147.470	146.331	1.139
132.160	133.115	-.955
86.755	86.055	.700
86.755	85.901	.854
132.160	132.961	-.801
144.210	140.940	3.270
112.383	113.342	-.962
57.847	63.310	-5.463 R
95.621	96.852	-1.231
103.810	108.972	2.838
60.549	57.543	3.006
82.076	84.371	-2.295
165.800	168.263	-2.463
153.660	154.448	-.788
124.870	125.652	-.782
61.032	60.217	.815
93.370	92.561	.809
126.440	126.811	-.371
99.369	97.715	1.654
127.600	126.026	1.574
86.755	87.636	-.881
141.080	141.607	-.527
80.344	81.273	-.929
117.900	118.237	-.337
117.900	118.083	-.183
138.860	139.618	-.758
108.840	107.573	1.267
148.660	146.028	2.632
90.474	90.298	.176
156.170	156.265	-.095
88.781	89.278	-.497
128.130	129.569	-1.439
128.130	129.416	-1.286

NOTE - (*) Indicates estimate calculated with means substituted
R Indicates point out of range of plot

Number of cases plotted 41.
Number of 2 S.D. outliers 1. or 2.44 percent of the total

Table X.

VALIDATION POINTS

Run	RANDOM VARIABLE	C5	C17	APODSIZE	MHE	DAPDFT	ACTUAL RESPONSE	CALC. RESPONSE	% DIFFERENCE
1		90	11	6	1	5	75.37	74.46	1.21
2		71	7	5	3	10	97.17	95.85	1.35
3		61	5	7	5	0	143.20	141.43	1.23
4		78	42	3	1	10	73.59	77.49	5.29
5		89	29	7	4	10	135.14	134.39	.55
6		79	36	8	2	0	128.75	131.19	-1.89
7		71	16	10	1	5	94.75	94.23	.54
8		99	28	3	4	5	100.43	99.35	1.07
9		94	45	2	3	5	85.18	90.99	-6.82
10		85	1	5	1	0	59.15	61.71	-4.32
	EXTREME POINTS:								
11		60	0	2	1	5	35.05	34.47	1.64
12		110	0	10	5	5	146.67	149.67	-2.18
13		110	50	10	5	5	177.70	175.52	1.22

Average Error: .08%
Average Absolute Error: 2.25%
Worst Error: 6.82%

Table XI. Validation of the Response Surface Equation specifically chosen as triplet extreme points, where it could be expected the most error would develop because these points were furthest from any used for calculation of the response surface. The results are tabulated in Table 11. The response surface equation was computerized as program add.f (Appendix 3). The average error of +.08% and the extreme error of 6.82% are an easy price to pay for a surface which estimates so closely any of 2,317,491 possible points. The model has its worst error at the extreme range where APOD size is at a minimum, and then gives an optimistic response. This can serve only to induce error (bias) in favor of the C-5, since the C-5 and not the C-17 is constrained by APOD size.

Findings

The first and most obvious finding is the net worth of additional C-5 aircraft to the net worth of additional C-17 aircraft. Using the regression step 10 results which have an R SQUARE term of 99.35, which means 99.35% of the response can be explained, the factors are shown in figure 9.

It is obvious that additional C-5 aircraft are not even in this equation. To force C-5 aircraft into the equation, we must go to the last step, where we obtain the factors shown in figure 10.

VARIABLE(S) ENTERED ON STEP 10
W22

MULTIPLE R	.9966	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.9935	REGRESSION	10.	31348.397	3134.840	461.[illegible]
STD DEV	2.6067	RESIDUAL	30.	203.848	6.795	SIG. [illegible]
ADJ R SQUARE	.9914	COEFF OF VARIABILITY		2.3PCT		

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTIC[illegible]
W34	1.264	.163	60.238	.000	.49647	.202[illegible]
W23	-.009	.013	.463	.501	-.03737	-.011[illegible]
DIST	-2.349	.418	31.561	.000	-.26446	-.104[illegible]
W55	.122	.040	9.364	.005	.14693	.037[illegible]
C17	1.132	.114	97.830	.000	.63750	.251[illegible]
APDSZ	9.389	.963	95.153	.000	.64571	.530[illegible]
MHE	21.097	1.811	135.657	.000	.95317	.561[illegible]
W44	-2.820	.248	128.953	.000	-.78738	-.264[illegible]
W33	-.417	.062	45.114	.000	-.46556	-.156[illegible]
W22	-.009	.002	34.662	.000	-.28270	-.0721
CONSTANT	6.325	5.471	1.336	.257		

Figure 9. 99.35% Response Surface

MULTIPLE R	.[illegible]3	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.[illegible]66	REGRESSION	17.	31446.236	1[illegible].77[illegible]	401.[illegible]
STD DEV	2.146[illegible]	RESIDUAL	23.	106.00[illegible]	4.60[illegible]	SIG.
ADJ R SQUARE	.[illegible]42	COEFF OF VARIABILITY		1.[illegible]PCT		

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICI[illegible]
W34	1.264	.134	[illegible].06	0	.4[illegible]547	.20205
W23	-.009	.011	.6[illegible]3	.417	-.03737	-.011[illegible]1
DIST	-.455	.70[illegible]	.41[illegible]	.524	-.05171	-.0203[illegible]
W55	.127	.04[illegible]	6.[illegible]06	.016	.153	.03[illegible]2[illegible]
C17	1.240	.142	76.343	0	.6[illegible]7[illegible]3	.2750[illegible]
APDSZ	[illegible].436	1.412	44.[illegible]54	0	.[illegible]4[illegible]2	.50251
MHE	23.7[illegible]2	2.155	121.[illegible]	0	1.07155	.5336[illegible]
W44	-2.7[illegible]4	.305	3.317	0	-.77735	-.2510[illegible]
W33	-.40[illegible]	.076	2[illegible].624	.000	-.45554	-.152[illegible]
W22	-.00[illegible]	.002	21.[illegible]56	.000	-.27575	-.0703[illegible]
W45	-.434	.107	16.311	.001	-.1[illegible]264	-.0377[illegible]
W35	-.0[illegible]3	.054	2.401	.135	-.07007	-.0221[illegible]
W24	-.030	.021	1.[illegible]16	.1[illegible]0	-.06250	-.01[illegible]7[illegible]
W25	-.006	.00[illegible]	.472	.4[illegible]	-.024[illegible]0	-.00[illegible]
W13	.003	.011	.0[illegible]2	.777	.025[illegible]	.013[illegible]2
C[illegible]	-.0[illegible]	.33[illegible]	.040	.[illegible]43	-.03[illegible]31	-.05134
W11	.000	.002	.025	.[illegible]75	.02[illegible]4	.02[illegible]
CONSTANT	-1.460	1[illegible].750	.005	.[illegible]42		

Figure 10. 94.72% Response Surface

An obvious output of this generated surface is that, if the scenario is operating at a large size but low MHE capability airfield, an increase of MHE to its maximum value (an increase of 4, to 5) can result in an objective function increase of 4 x 23.8 = 96, whereas either 50 C-5 or 50 C-17 added to the fleet can make a maximum contribution of less. Thherefore, a buy of prepositioned MHE may in some cases generate more combat power than a buy of aircraft.

Rapid use of this response surface equation can be made to find the value of the response with varying parameters. To test the effects of a buy of 50 C-5 and 50 C-17 aircraft, the response was checked at both the worst case for the C-5 and the best case, it being assumed that where the C-5 does worst, the relative advantages of a C-17 fleet will be the most, and vice versa. The generated response surface was coded and is listed in Appendix 2.

The response surface was first tested at a point where the worst possible environment existed for the C-5 - the minimal APOD size, MHE prepositioned equipment, and maximum travel distance to the front line area. It was then tested at an environment which catered to the C-5 fleet - the largest possible APOD, maximum prepositioned MHE, and minimal distance to the front. The current fleet, the current fleet with 50 additional C-5A aircraft, and current fleet with 50 C-17 aircraft have their responses tabulated in figure 11.

The primary factor to realize with these results is that the buy of C-5 versus C-17 is not in a vacuum or separately compartmented, but as an addition to the airlift fleet.

	Current Fleet	Buy 50 C 5	Buy 50 C 17	% Advantage Buy C 5	Buy C 17
Worst setting for C 5	38.0	38.08	72.5	0	90
Best setting for C 5	163.5	164.2	180.0	.4	16.2
Best airport,worst distance	140.6	141.4	165.0	.5	17.3

Figure 11. Results of a C-17 vs. C-5 Buy, Single APOD.

Additional C-5 aircraft still compete at the APOD for space and servicing with C-141, CRAF, and C-130 aircraft. However, C-17 aircraft need compete only at the forward airfields, and then only with C-130s. In fact, C-17 aircraft much reduce the overall requirement for C-130 aircraft. A regression response surface was generated, using the same data points but with the output variable C-130 usage as the response variable, and checked to find what its major component factors were. The presence of the C-17 aircraft, by itself, expressed over 61% of the response variability. The 82% response was:

$$C130 = -.558\,(C17) + .066\,W22 - .333\,W25 - .416\,W23 + 20.59\,\text{APODSIZE}$$

$$+14.45\,\text{DISTANCE} - .631\,W33 - .404\,W55 + 25.29\,\text{MHE} - 3.27\,W44 - .18\,W24 - 103.11$$

Therefore, the presence of C-17 aircraft not only enhanced delivery of combat power because of direct delivery of combat troops and supplies to the front, but also reduced the congestion of the APOD due to C-130 transhipment of supplies, before truck transportation units were delivered. Since the C-5s, in all runs, are not fully utilized because of airport size limitations, by reducing the number of C-130s required, the use of C-17s expanded the usefulness of the C-5 fleet at the expense of the C-130 fleet. The output response of the regression analysis is shown in Figure 12.

Since truck transportation units were needed in all scenarios where the travel distance between the APOD and the front was greater than zero days, another response surface was generated for the effects of the five varied parameters on truck usage (Figure 13). Although distance is the most important factor, the C-17 interaction term is next to enter the stepwise regression. Since it has a negative coefficient, more C-17s mean less need for trucks.

Because of the interrelationships of factors, to attain an estimate of the trade-off point between the C-17 and the C-5, we must take the first partial of the equation with respect to the variable, thus

$$\frac{\partial R}{\partial C5} = -.068 + 2.008\,C5 + .0021\,\text{APOD SIZE}$$

$$\frac{\partial R}{\partial C17} = 1.924 - .0182\,C17 - .0089\,\text{APODSIZE} - .0297\,\text{MHE} - .0059\,(\text{DISTANCE})$$

Entering our former limits, worst case, of APOD = 2, MHE = 1000, DIST = 10, we have the response due to C-5 as:

$$-.068 + .006\,(C5) + .0031\,(2) = -.0618 + .006\,(C5)$$

and the inflection point at which more C-5s have decreasing worth is at C-5 = .0618/.006 = 10, which is below the bounds

* * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * *

DEP. VAR... C130

VARIABLE(S) ENTERED ON STEP 13
W24

MULTIPLE R	.9561	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.8129	REGRESSION	11.	8[illegible]969.551	7360.868	12.741
STD DEV	24.1745	RESIDUAL	29.	19874.075	585.313	SIG.
ADJ R SQUARE	.7262	COEFF OF VARIABILITY		137.[illegible]PCT		

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICITY
C17	-.553	1.488	.141	.71[illegible]	-.17563	-.72961
W22	.[illegible]66	.[illegible]16	17.154	.00[illegible]	1.11719	3.0[illegible]516
W25	-.333	.115	[illegible].125	.0[illegible]3	-.79694	-2.179[illegible]
W23	-.416	.131	10.125	.0[illegible]3	-.98149	-3.26911
APDSZ	2[illegible].592	[illegible].327	6.[illegible]15	.[illegible]2[illegible]	1.[illegible]3751	6.465[illegible]5
DIST	14.453	4.948	8.532	.007	.91027	3.73144
W33	-.631	.623	1.[illegible]26	.32[illegible]	-.39445	-1.39562
W55	-.4[illegible]4	.399	1.[illegible]26	.32[illegible]	-.2732[illegible]	-.734[illegible]3
MHE	25.295	16.654	2.3[illegible]7	.14	.63723	3.97[illegible]75
W44	-3.277	2.494	1.727	.199	-.51179	-1.61[illegible]77
W24	-.1[illegible]	.262	.474	.496	-.21244	-.73759
CONSTANT	-1[illegible]3.111	52.[illegible]44	3.925	.057		

REGRESSION ANALYSIS - C130

* * * * * * * * * * M U L T I P L E   R E G R E S S I O N * * * * * * * *

DEP. VAR... TRK

VARIABLE(S) REMOVED ON STEP 17
W11

MULTIPLE R	.8532	ANOVA	DF	SUM SQUARES	MEAN SQ.	F
R SQUARE	.72[illegible]	REGRESSION	13.	15.26[illegible]	1.174	5.55[illegible]
STD DEV	.4596	RESIDUAL	27.	5.703	.211	SIG. .00[illegible]
ADJ R SQUARE	.5970	COEFF OF VARIABILITY		5[illegible].5PCT		

VARIABLE	B	S.E. B	F	SIG.	BETA	ELASTICITY
W34	.[illegible]17	.[illegible]25	.4[illegible]8	.491	.26321	.46333
W55	-.[illegible]31	.[illegible]07	21.46[illegible]	.[illegible]	-1.43648	-1.59[illegible]2
DIST	.359	.[illegible]	13.358	.001	1.56858	2.67464
W24	.[illegible]5	.[illegible]4	1.416	.244	.42[illegible]	.57499
W22	-.[illegible]	.[illegible]	.54[illegible]	.469	-.22789	-.25161
W23	.[illegible]3	.[illegible]2	1.469	.236	.45517	.62231
C17	-.[illegible]	.[illegible]23	.766	.389	-.43217	-.73692
APDSZ	-.222	.25[illegible]	.7[illegible]3	.364	-.77437	-1.98[illegible]61
W33	.[illegible]	.[illegible]	.924	.345	.43[illegible]4[illegible]	.625[illegible]6
W13	.[illegible]1	.[illegible]2	.1[illegible]9	.667	.32755	.75973
W44	.[illegible]9	.[illegible]25	.1[illegible]4	.75[illegible]	.[illegible]9661	.14[illegible]62
W35	-.[illegible]2	.[illegible]11	.[illegible]41	.841	-.[illegible]751	-.11[illegible]39[illegible]
C3	-.[illegible]5	.[illegible]15	.1[illegible]8	.733	-.[illegible]	-.63311
CONSTANT	.29[illegible]	1.411	.[illegible]42	.939		

REGRESSION ANALYSIS - TRUCK COMPANIES

of the problem and hence unreliable. The response at the same worst case point is, for the C-17,

$$1.9239 - .0182\,(c17) - .0178 - .0297 - .059 = 1.817 - .0182\,(c17)$$

The inflection point for this curve is at the point C-17 = 1.817/.0182 = 99.8 which is also beyond the bounds of the problem. So far the response surface has revealed that with the worst case of tiny airfield, minimal handling equipment, and large travel distance between the APOD and the front line, more C-5 aircraft beyond the 60 in the model are not useful, and C-17 aircraft added to the present fleet are useful throughout the studied range (50). This result has intellectual appeal, since it appears eminently sensible.

A more important, or interesting, observation is the comparative value towards increasing the response level at the "best case", which should favor the C-5. The extreme of an APOD capable of handling 1000 pallets per day (27.7 C-5 sorties), before any ALCE deployment, and zero distance between the APOD and the deployment area should give all possible advantage to the C-5.

The C-5 response is

$$\frac{\partial R}{\partial (c5)} = -.0649 + .006\,(c5)$$

which again gives an inflection point of ≈ 10, which is below the problem bounds.

The C-17 response is

$$\frac{\partial R}{\partial (c17)} = 1.626 - .0182\,(c17)$$

which again gives an inflection point beyond (above) the problem limit. The model response is basically that there are presently sufficient C-5s in the active fleet, given the constrained airfield and constrained processing facilities.

Graphs were prepared which illustrate the need for C-17 aircraft to accomplish a set of fixed goals, given an APOD size, MHE level, and distance between the APOD and the deployment area. They are presented in Tables 12, 13, and 14, and Figures 11, 12, and 13.

It is readily apparent that for a fixed goal, the need for C-17 aircraft decreases as the parameters become less stringent. Assuming a large APOD and sufficient processing and handling equipment at the APOD, the graphs show that no C-17 aircraft are needed for both the lower goals. The trend, even with the highest goal, is to minimize the requirement for C-17 as the size of the APOD increases. However, these curves were drawn with C-17s added to the current force. Curves drawn with 50 C-5s added to the current force show virtually no improvement over the current force, as was demonstrated in the tabulated responses of Figure 10. The additional C-5 curve with zero slope shows no need for any additional C-5 aircraft in this region of restricted APOD size and MHE available. Without C-17, not even the lowest goal is consistently achievable at all points in the searched region.

COMBAT POWER GOAL = 100

		2	3	4	5	6	7	8	9	10
APODSIZE in C5 spaces		2	3	4	5	6	7	8	9	10
APOD MHE in ,000 Pallets/5 Days										
	1	X	X	X	43	34	25	17	10	4
DAPDFT=0	3	39	24	9	0	0	0	0	0	0
	5	32	12	0	0	0	0	0	0	0
	1	X	X	X	X	X	44	36	29	23
DAPDFT=5 Days	3	X	41	27	13	0	0	0	0	0
	5	49	30	11	0	0	0	0	0	0
	1	X	X	X	X	X	44	36	30	23
DAPDFT=10 Days	3	X	41	27	13	0	0	0	0	0
	5	49	30	12	0	0	0	0	0	0

Table XII. Numbers of C17 Needed, Plus Present Force, to Achieve a Set Goal (=100)

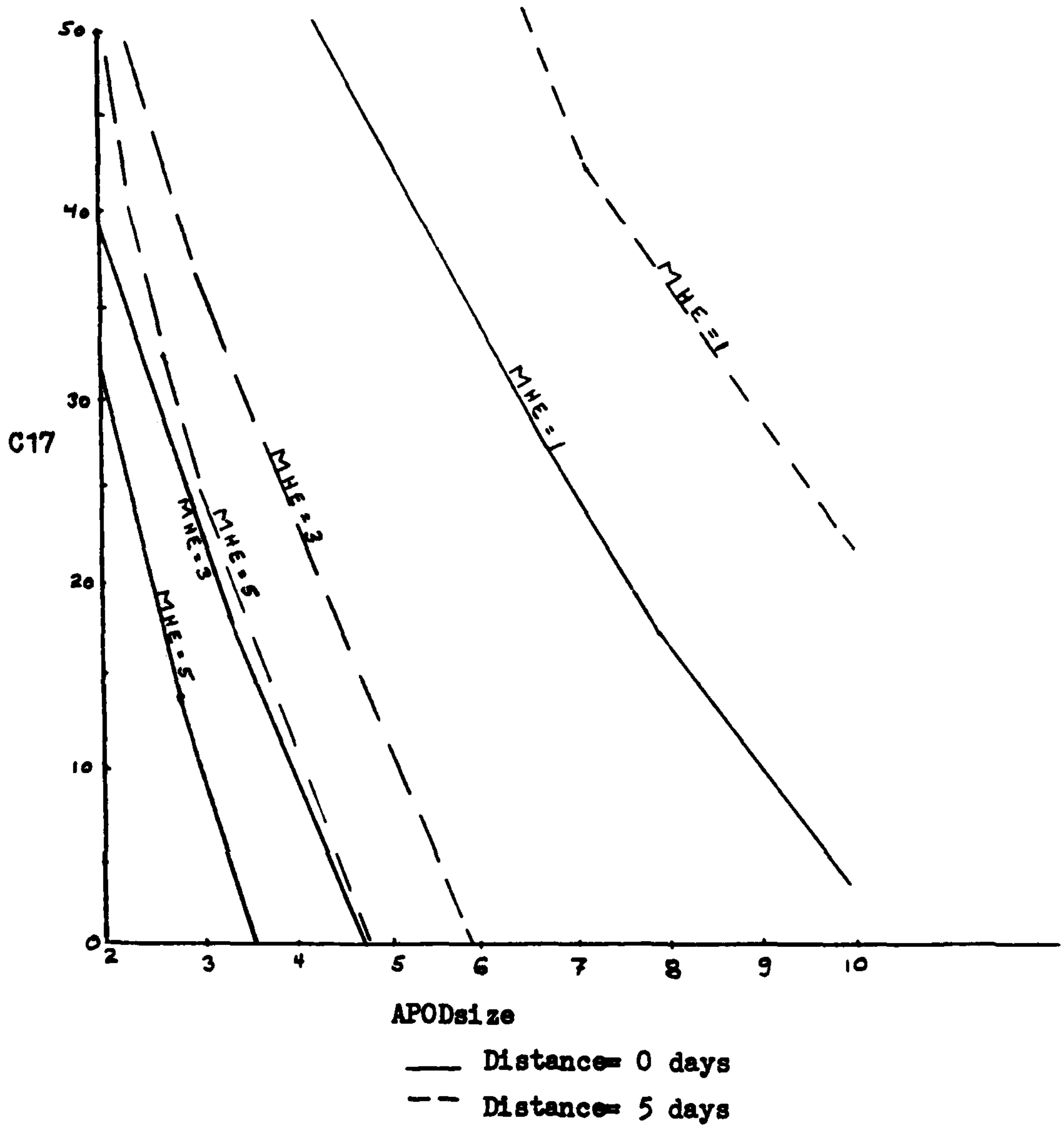


Figure 12. Need for C17, Constant Power (Goal=100).

COMBAT POWER GOAL = 125

APODSIZE in C5 spaces		2	3	4	5	6	7	8	9	10
APOD MHE in ,000 Pallets/5 Days										
	1	X	X	X	43	34	25	17	10	4
DAPDFT=0	3	X	X	49	35	22	9	0	0	0
	5	X	X	33	15	0	0	0	0	0
	1	X	X	X	X	X	X	X	X	X
DAPDFT=5 Days	3	X	X	X	X	40	27	15	4	0
	5	X	X	X	X	33	16	0	0	0
	1	X	X	X	X	X	X	X	X	X
DAPDFT=10 Days	3	X	X	X	X	40	28	16	4	0
	5	X	X	X	34	16	0	0	0	0

Table XIII. Numbers of C17 Needed, Plus Present Force, to Achieve a Set Goal (=125).

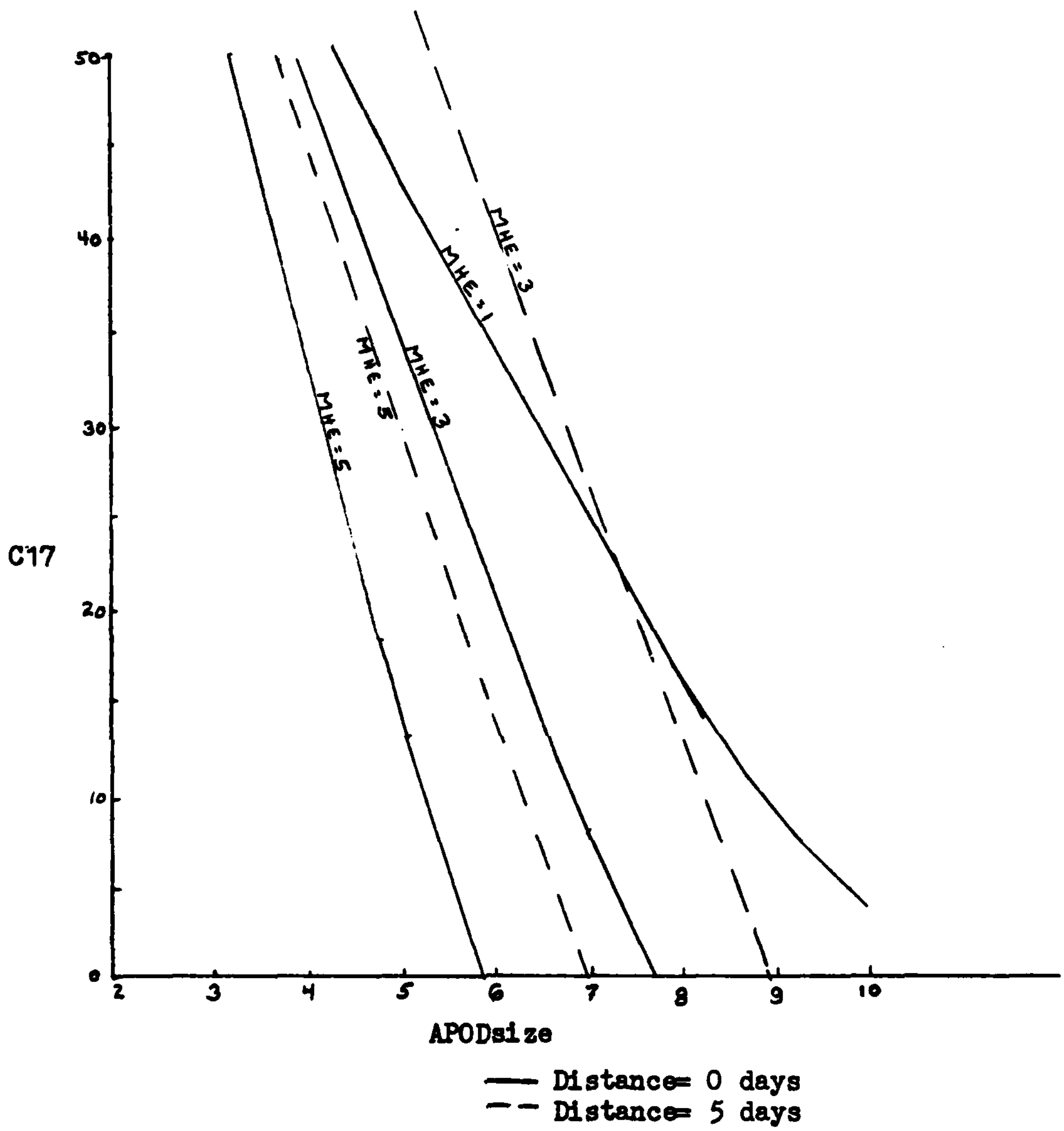


Figure 13. Need for C17, Constant Power (Goal=125).

COMBAT POWER FOAL = 150

APODSIZE in C5 spaces		2	3	4	5	6	7	8	9	10
APOD MHE in ,000 Pallets/5 Days										
	1	X	X	X	X	X	X	X	X	X
DAPDFT=0	3	X	X	X	X	X	50	39	27	17
	5	X	X	X	X	38	22	5	0	0
	1	X	X	X	X	X	X	X	X	X
DAPDFT=5 Days	3	X	X	X	X	X	X	X	47	36
	5	X	X	X	X	X	40	24	8	0
	1	X	X	X	X	X	X	X	X	X
DAPDFT=10Days	3	X	X	X	X	X	X	X	47	37
	5	X	X	X	X	X	41	24	9	0

Table XIV. Numbers of C17 Needed, Plus Present Force, to Achieve a Set Goal (=150).

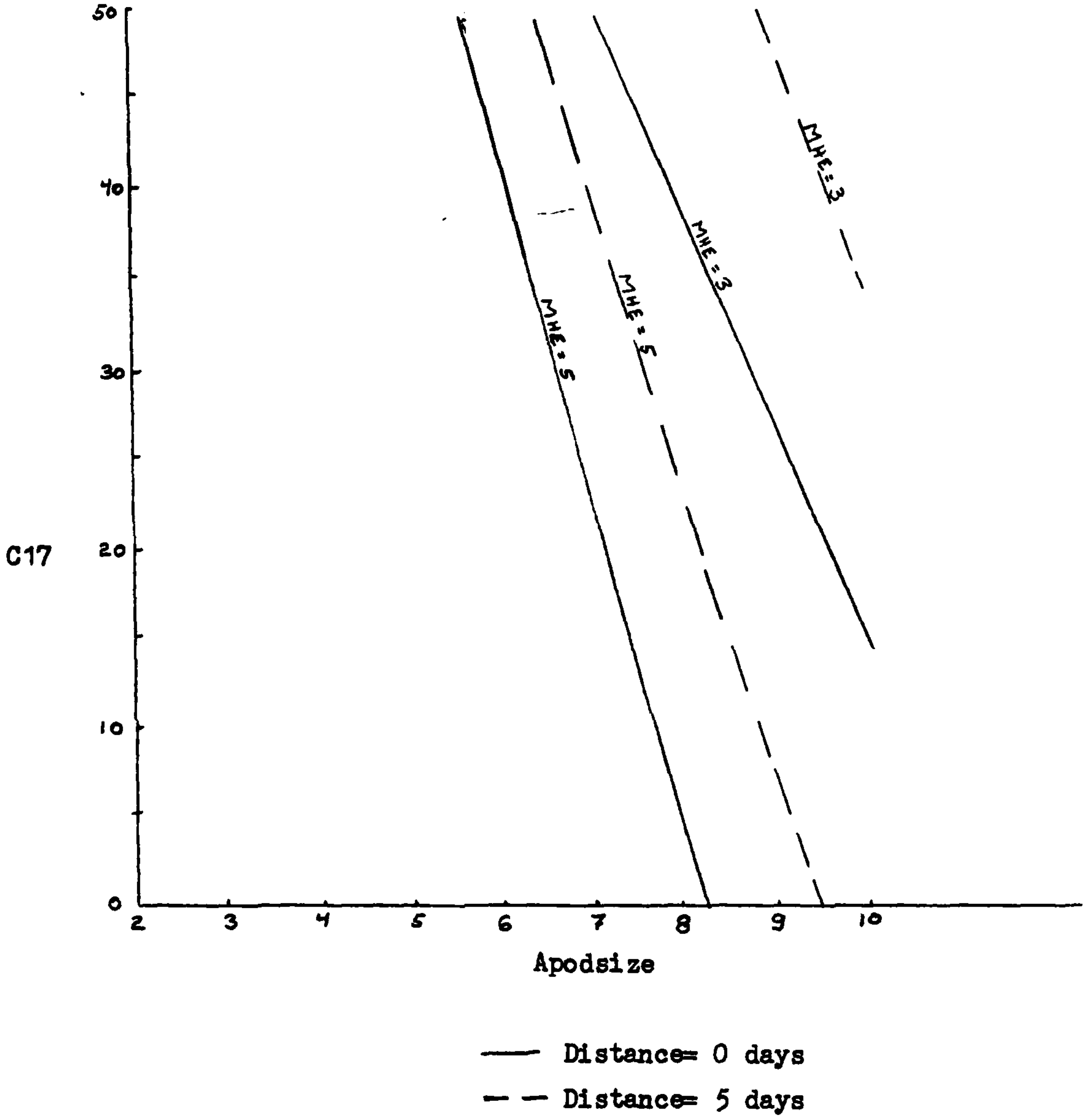


Figure 14. Need for C17, Constant Power (Goal=150).

The direct outputs of the response surface methodology as a means of determining sensitivity of the output variables to changes in several key parameters while maximizing combat power delivered to a theater have already been described. These outputs (combat power, C-130 usage, truck units deployed) were all generated using the basis variables and response variable for the single set of 41 runs of the model, shown in Appendiz A. Therefore, the single set of 41 runs gives the user the flexibility to search a very wide span of interrelated variables and how each is affected by any or all of the changing parameters, because the rotatable orthogonality of the used design insures independence of the regression output coefficients. This was substantiated not only by the design theory but also by the final covariance matrix output by the SPSS regression package. Because each point of the design is a result of a deterministic linear program, there is no stochasticity whatsoever in the output, and therefore, heterocedasticity is not a consideration. Multicollinarity could be a problem using a design such as this, but the design was searched using three way interactions beyond the full quadratic response, and their contribution found to be negligible.

Just as important as the variability in the basis vector of the 41 orthogonal runs were the commonalities. For all runs, the maximum allowable UTE rate of the C-141 fleet was an upper bound constraint for the first ten days. The highest C-5 UTE rate achieved for any scenario was 9.2. Also

for all runs, the capacity of the available quartermast
resupply airdrop companies to rig supplies for airdrop
upper bound constraint. Two runs of the model were mac
without any constraints on airdrop resupply, which resu
in all combat unit resupply being airdropped, a thirty
percent increase in combat power over the constrained c
and an extra brigade of the 101st Division being moved
end of twenty days. Since the UTE rate of the C-5 (at
was never an upper bound, several runs were made to det
what would cause it to become an upper bound. Even wit
most favorable airport conditions, only a decrease in C
ground time from 3.3 to 2.75 hours caused the C-5 UTE r
become a bounding constraint.

Limitations on the Response Surface

The response surface can only be utilized within t
bounds of its domain. Since it forces a mathematical m
to recreate an actual response, the bounds on that mode
integral parts of the generated coefficients. An
illustration of this point is shown below. If the actu
response is cubic in nature, and a quadratic surface ha
fit to one part of the variable range, the response at
1, 2, and 3 will be correct, but the surface response a
point 4 will be widely variant from the actual response
at point 5.

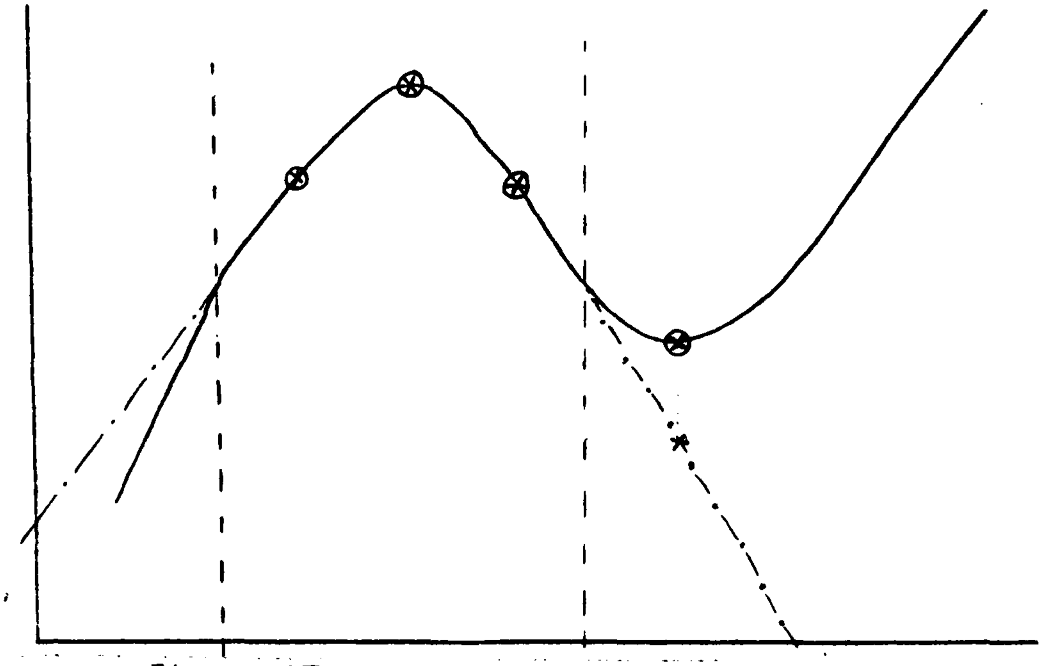


Figure 17. Response Surface Limitations.

In program add.f, which is the computerized version of the regression response surface output, points within the domain have a small error, but points outside the domain are unreliable. An illustration of this is to input APOD size as 25, MHE as 20, and the response for the current fleet capability is negative. This is due to the quadratic terms which "blow-up" past the domain boundaries. Therefore, to relook at the problem with expanded parameters, a new set of data points must be generated. Even to only expand one parameter, for example APOD from 10 to 12, the center points as well as the end-points would need to be redone in order to insure orthogonality of the matrix set and minimize covariance.

X Conclusions and Recommendations

This paper has described a multiobjective optimization based on force goals which interrelate intertheater movement, intratheater movement, and deployable unit capabilities. Decisive advantages are shown by the approach to the problem, which can be used to send at least the force needed, minimize the waste of resources, and accomplish these missions faster and more exactly than the current interservice operating system. In addition, it has been demonstrated that a flexible response surface methodology can result in a reduction of a fully computerized and intricate large scale model to an equation which can be programmed on a hand-held calculator, and with which major force design concepts may be rapidly searched, with minimal probable error.

Conclusions

Although the model explored in this particular response surface is a scaled version of the proposed full-scale model, several preliminary conclusions were drawn specific to the Mideast scenario studied. These are:

1. For the Air Force:

   a. For the given scenario, the UTE rate used in the model was consistently an upper bound on C-141 performance over the first ten days. Therefore, a UTE rate increase beyond the 12.5 assumed in the scenario for the C-141 stretch will increase productivity of the airlift fleet for rapid deployment.

b. The C-5 will benefit most, in the studied scenario, from decreasing the average ground time. A decrease in ground time of from 3.3 to 2.75 hours will make the C-5 much more productive at restricted airports. The highest UTE rate used in the model for the given scenario under goal programing methodology was 9.2, and therefore extreme efforts to increase the C-5 UTE rate beyond that figure in order to enhance the rapid deployment mission may be non-productive.

c. The key factors affecting the productivity of the current fleet was the availability of material handling equipment and the size of the APOD, as shown in the weight given to these factors in the response surface (Figure 8). A set of prepositioned ALCE and materiel handling equipment (MHE) at possible deployment airfields where the airfield is large in comparison to existing MHE capability would considerably increase the rapid throughput of any force.

2. For the Army:

a. The limitation on airdrop resupply due to the capabilities of existing rigger companies consistantly bound the problem. Unbounded by this, airdrop resupply greatly increased the rapid deployment of the force by lessening the congestion at the APOD. To enhance force deployment in the given scenario, either more rigger companies are required in the active Army, or prerigged pallets of supplies for a deployable force should be located at a C-141 base which doesn't deploy combat troops and equipment.

b. Medium truck companies were consistently deployed by the model to move cargo in the postulated scenario. Less truck companies were moved when C-17 aircraft were present, but the medium truck companies with their outsize cargo placed a significant burden on the C-5 fleet, in the developed scenario, for all but the largest airfields. Prepositioning of transportation assets at a critical APODs during peacetime might, similar to MHE equipment, be a less costly and more viable option than prepositioning of combat unit equipment, and would increase combat unit througnput at the APOD.

Recommendations

1. The model should be developed into a user-friendly computer package rather than its existing mathematical form.

2. A systems approach using goal programing should be used to generate unit movement and force structure requirements for the Rapid Deployment Force.

3. Based on the results of this research, a full scale model should be developed. A flexible response surface should then be created varying simultaneously the parametric factors of attrition, cost, UTE rate, load capability, ground time, plus the factors varied in this thesis. This would

provide a definitive conclusion as to which aircraft, the C-17 or the C-5, the Air Force should procure as an addition to the present airlift fleet for the force deployment mission, and where any tradeoff points exist.

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APPENDIX A

RESPONSE SURFACE ORTHOGONAL

ROTATABLE DESIGN

APPENDIX A.

	INPUT DESIGN					OUTPUT RESPONSES		
	C5	C17	APD	MHE	DIST	PWR	TRK	C130 sorties days 1-10
1	85	25	6	3	5	120.45	.912	0
2	110	50	6	3	5	129.76	.529	0
3	110	0	6	3	5	101.39	.400	157.9
4	60	0	6	3	5	101.39	.400	159.9
5	60	50	6	3	5	129.76	.529	0
6	60	25	10	3	5	146.24	1.55	0
7	60	25	2	3	5	81.832	.739	0
8	60	25	2	3	5	81.832	.739	0
9	110	25	10	3	5	147.47	1.95	0
10	110	25	6	5	5	132.16	2.125	0
11	110	25	6	1	5	86.755	0	0
12	110	25	6	1	5	86.75	0	0
13	60	25	6	5	5	132.16	2.125	0
14	60	50	6	5	5	144.21	1.87	0
15	85	0	6	5	5	112.38	1.34	83.3
16	85	0	6	1	5	57.847	.512	47.24
17	85	50	6	1	5	95.621	0	0
18	85	25	10	1	5	103.81	1.3	0
19	85	25	2	1	5	60.55	0	0
20	85	25	2	5	5	82.076	.809	0
21	85	25	10	3	5	165.80	2.681	0
22	85	50	10	3	5	153.66	1.68	0
23	85	0	10	3	5	124.87	.728	166.6
24	85	0	2	3	5	61.032	.831	0
25	85	50	2	3	5	93.37	.669	0
26	85	50	6	3	0	138.86	0	0
27	85	0	6	3	0	108.84	0	0
28	85	25	6	5	0	148.66	0	0
29	85	25	6	1	0	90.474	0	0
30	85	25	10	3	0	156.17	0	0
31	85	25	2	3	0	88.781	0	0
32	110	25	6	3	0	128.13	0	0
33	60	25	6	3	0	128.13	0	0
34	85	50	6	3	10	126.44	.670	0
35	85	0	6	3	10	99.369	.679	166.6
36	85	25	6	5	10	127.6	0	0
37	85	25	6	1	10	86.755	0	0
38	85	25	10	3	10	141.08	.17	0
39	85	25	2	3	10	80.344	.356	0
40	110	25	6	3	10	117.90	.615	0
41	60	25	6	3	10	117.9	.615	0

APPENDIX B

RESPONSE SURFACE

OUTPUT PROGRAM

```
      program add
10    write(6,*)'input c5'
      read(5,*)w1
      write(6,*)'input C17'
      read(5,*)w2
      write(6,*)'input APOD SIZE'
      read(5,*)w3
      write(6,*)'input MHE'
      read(5,*)w4
      write(6,*)'input DISTANCE'
      read(5,*)w5
c           calculate mean value
      r1= 1.2645*w3*w4-.0089*w2*w3-.4593*w5+1.2396*w2+.1273*
      r2=9.4356*w3+23.7924*w4-2.7839*w4*w4-.4079*w3*w3-.0091
      r3=-.4535*w4*w5-.0832*w3*w5-.0297*w2*w4-.0059*w2*w5
      r4=.0031*w1*w3-.0680*w1+.0003*w1*w1-1.4603
      respm=r1+r2+r3+r4
c           calculate lower 95% limit
      r5=.9869*w3*w4-.0311*w2*w3-1.9267*w5+.0264*w5*w5+.9461
      r6=6.5146*w3+19.3339*w4-3.4149*w4*w4-.5657*w3*w3-.0132
      r7=-.6556*w4*w5-.1942*w3*w5-.0741*w2*w4-.0237*w2*w5
      r8=-.0191*w1*w3-.7687*w1-.0037*w1*w1-42.3157
      respb=r5+r6+r7+r8
c           calculate upper 95% limit
      r9=1.5420*w3*w4+.0133*w?*w3+1.0081*w5+.2283*w5*w5+1.53
      r10=12.3566*w3+28.2508*w4-2.1530*w4*w4-.2502*w3*w3
      r11=-.0051*w2*w2-.2115*w4*w5+.0279*w3*w5+.0147*w2*w4
      r12=.0119*w2*w5+.0253*w1*w3+.6326*w1+.0043*w11+39.3951
      respt=r9+r10+r11+r12
c           interact with user
      print*,'mean=',respm
      print*,'bottom limit=',respb
      print*,'top limit=',respt
      print*,'another run? y/n=1/0'
      read(5,*)nans
      if(nans.eq.1)go to 10
      end
```

APPENDIX C

C-17 VERSUS FIXED GOAL PROGRAM

```
      program c
      w1=60.0
      w4=3.0
      w5=5.0
 10   print*,'input goal'
      read(5,*)w6
      do 20 i=2,10,1
      w3=i
      a=-0.665+.009*w3
      b=1.264*w3*w4-3.345*w5+0.221*w5*w5+7.521*w3+17.362*w4
      b1=b-2.197*w4*w4-0.261*w3*w3+20.672-w6
      c17=b1/a
      print*,'C17= ',c17
 20   continue
      print*,'another? y/n= 1/0'
      read(5,*)nans
      if(nans.eq.1)then
       print*,'change data? y/n = 1/0'
       read(5,*)nans2
       if(nans2.eq.1)then
        print*,'MHE='
        read(5,*)w4
        print*,'DISTANCE ='
        read(5,*)w5
       endif
      endif
      if(nans.eq.1)go to 10
      end
```

Vita

James Christopher Cooke was [redacted] He graduated from college with an A.A. in Engineering in 1968, and graduated from the U.S. Military Academy at West Point in 1973 with a B.S. concentration in civil engineering. After attending airborne and ranger schools, he worked as a rifle platoon leader, mortar platoon leader, company executive officer, and Division Staff officer in the 82nd Airborne Division. He also completed Air Movement Operations School and worked on the J-3 Army (AIR) on the CINCLANT staff. After the Infantry Officer Advanced Course, he went to Germany and served as a mechanized infantry company commander, Brigade S-3 (AIR), and battalion executive officer in the Third Armored Division.

Permanent Address: [redacted]

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This paper describes a goal programming approach to modeling the rapid deployment of combat units which offers decisive advantages over any current methodology. It accounts for both intertheater and intratheater airlift, and can be used to optimally plan movement schedules for predetermined forces or optimally choose and move a force from a list of available units and airlift resources to meet specified goals. Both methods are demonstrated, showing that the goal programming model minimizes wasted resources and accomplishes desired goals both faster and more exactly than the current interservice operating system. The model developed for demonstration uses 212 variables and 136 separate equations. In addition, a flexible response surface methodology is used to generate a full parametric sensitivity analysis, resulting in the reduction of a fully computerized and intricate large scale programming model to an equation programmable on a hand-held calculator, with minimal error. A demonstration is presented comparing relative advantages of C-5 and C-17 aircraft procurement, in a proposed addition of 50 aircraft to the current airlift fleet, with simultaneously varying airport capacities and deployment distances.