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Optimizing Strategic Airlift

by

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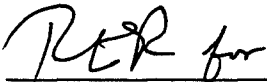
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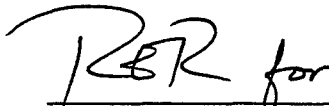
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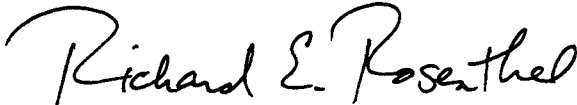
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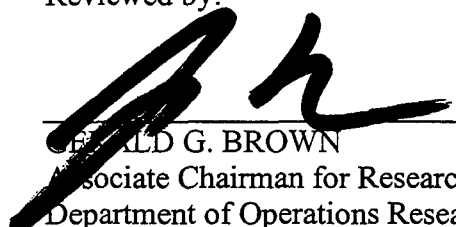

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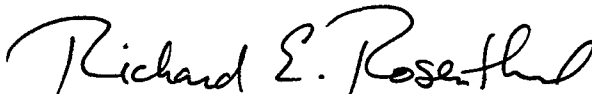

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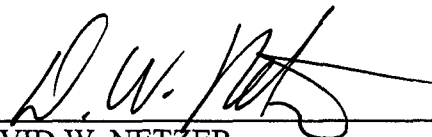

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Optimizing Strategic Airlift

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Abstract

We describe a large-scale linear programming model for optimizing strategic airlift capability. The model routes cargo and passengers through a specified transportation network with a given fleet of aircraft subject to many physical and policy constraints. The time-dynamic model captures a significant number of the important aspects of an airlift system in a large-scale military deployment, including aerial refueling, in-theater aircraft shuttles, and constraints based on crew availability. Several applications of the model are given.

Keywords: military operations research, large-scale linear programming, air transportation, airlift mobility

1 Introduction

In a large-scale military deployment, massive amounts of equipment and large numbers of personnel must be transported over long distances in a short amount of time. Airlift, sealift, and ground transportation assets are all used to execute such a deployment. In the Persian Gulf War, sealift moved 85 percent of the dry cargo, but the first ships did not arrive for weeks. Airlift played the dominant role in rapidly moving troops and cargo in the important weeks leading up to the war. (See Lund (1993) for more details of strategic airlift in the Persian Gulf War.) In this paper we describe a linear programming model that is primarily focused on the airlift system and we indicate some of the insights it has provided US Air Force planners.

Application of optimization modeling to logistics problems in transportation has a rich history. Dantzig and Fulkerson (1954) and Ferguson and Dantzig (1955) describe linear programming models for routing tankers and aircraft, respectively. See, for example, the books of Bramel and Simchi-Levi (1997) and Potts and Oliver (1972) for more on logistics and transportation. A number of specific military mobility models are reviewed in Schank et al. (1991). The optimization model we describe in this paper routes cargo and

troops through a transportation network with a given aircraft fleet, subject to numerous physical and policy constraints. It is not the purpose of the model to provide operational flight schedule recommendations. Instead the purpose is to provide insight into tactical and strategic issues concerning the airlift system. Some of the issues that our model has been used to examine include: allocating resources that govern the processing capacity of airfields; assessing the relative performance of different mixes of aircraft types; evaluating investment (or divestment) decisions in airfields; recommending fleet modernization strategies; and, studying roles for aerial refueling aircraft.

Our model is the result of a joint effort between research teams (then) at the Naval Postgraduate School (NPS) and RAND; it is called NRMO (NPS/RAND Mobility Optimizer). NRMO has directly benefited from four previous projects, drawing on their best features and learning from their shortcomings. The Mobility Optimization Model (MOM) was developed by NPS and the Joint Chiefs of Staff's Force Structure Resource and Assessment Directorate (J8); see Wing et al. (1991). MOM is a time-dynamic model that includes both airlift and sealift assets, but has a single-channel topology and hence is not designed to capture the airlift system's transportation network. THRUPUT is a time-static strategic airlift model on a general routing network that was developed by Yost (1994) at the US Air Force Studies and Analyses Agency (AFSAA). AFSAA desired a time-dynamic model with the ability to route aircraft through a general network and asked NPS to combine the features of MOM and THRUPUT in one model. This request led to THRUPUT II, first described in an NPS Master's thesis (Lim, 1994), extended in Morton, Rosenthal, and Lim (1996), and used in a recent aircraft acquisition study reviewed in Rosenthal et al. (1997). An ongoing relationship between AFSAA and NPS led to several M.S. theses that examined stochastic airlift models (Goggins, 1995), route generation techniques (Turker, 1995), route prioritization (Toy, 1996), and aggregation schemes (Fuller, 1996). THRUPUT II also served as a real-world test problem for the development of a solution methodology for large-scale staircase linear programs, described in Baker (1997) and Baker and Rosenthal (1998).

In parallel with the THRUPUT II efforts at NPS, a group at RAND developed a similar model called CONOP (Concepts of Operations) that was initially used to recommend policies for best utilizing dual-role KC-10 and KC-135 aircraft that can serve as both aerial refuelers and as haulers of cargo and passengers (Killingsworth et al., 1994). In addition to aerial refueling, the CONOP model captures: flow balance and utilization constraints for air crews; options for direct delivery versus delivering cargo that is subsequently transshipped by in-theater aircraft; and, optional in-theater recovery bases where aircraft may receive services and crew changes. With the encouragement and support of AFSAA, a new model (NRMO) was developed that captures the best features of both THRUPUT II and CONOP.

In this paper, we give an overview of NRMO in Section 2 and then give a detailed mathematical description of the linear programming model in Section 3. THRUPUT II, CONOP, and now, NRMO, have been designed to provide insight on a number of types of mobility questions concerning investment (or divestment) in airfield infrastructure, selection of airlift aircraft for acquisition, and the best use of dual-role aircraft. A number of

studies have been performed and some of these are discussed in Section 4.

2 Problem Statement and Model Overview

Our goal is to move equipment and personnel, in a timely fashion, from a number of origin bases through a transportation network to destination bases using a fleet of aircraft with differing characteristics. Such a deployment is driven by the movement requirements specified in the Time-Phased Force Deployment Data (TPFDD). The TPFDD contains a highly detailed list of cargo and troops that are required by contingency plans for a given theater of operation (Armed Forces Staff College, 1993). For our purposes, the movement requirements may be viewed as a list of requirement line identifications, or *line ids*, each of which specifies: the associated cargo's onload and offload bases; the day it is first available to move; the day by which it must be delivered; the number of short tons (stons) in each of three cargo classes called bulk, oversized, and outsized; and, the number of passengers. Bulk cargo is palletized on 88 × 108 inch platforms. Oversized cargo is non-palletized rolling stock and is larger than bulk. Outsized cargo is also non-palletized and represents the largest cargo class. The TPFDD also specifies the cargo's type (helicopter squadron, tank company, etc.) from which we derive an approximate loading efficiency for each aircraft type. Finally, after arriving at the offload base some line ids require subsequent delivery to a forward operating location, and in such cases, the TPFDD also lists the associated forward operating base. (Some aircraft can bypass the offload base and deliver cargo and troops directly to a forward location). Table 1 contains a small portion of a representative TPFDD that has been modified for use in NRMO.

The fleet of aircraft consists of several types of planes, and the fleet mix varies depending on the type of analysis being done. A brief summary of some of the fleet's aircraft is provided in Table 2. Aircraft differ in what they can carry, where they can go, and what sort of functions they can perform. The C-5 and C-17 can carry all cargo types as well as troops, while the C-141 can carry troops, bulk and oversized cargo. Tanker aircraft such as the KC-10 and KC-135 serve as aerial refuelers but can also function as strategic lifters, carrying bulk cargo and troops. Variants of the Boeing 747 can carry bulk and oversized cargo, or passengers. The C-17 can fly into austere environments that are inaccessible by other strategic airlifters. Each aircraft is also defined by a number of characteristics including: airspeed; average (maximum) flying hours per day; cargo- and passenger- carrying capacity; a range-payload curve; service times and airfield capacity consumed at onload, enroute, and offload bases; and, aerial refueling capability. A range-payload curve specifies the maximum payload that an aircraft can carry given the desired range. Range-payload curves for four representative airlift aircraft are shown in Figure 1.

Figure 2 depicts many of the key features of the underlying transportation network in NRMO. Cargo and troops are carried from aerial ports of embarkation (APOEs) to the theater on strategic airlift aircraft. The theater contains aerial ports of debarkation (APODs), forward operating bases (FOBs), and beddown bases for in-theater aircraft shuttles. A line id's cargo and troops depart from a specified APOE and may

Line ID	Onload	Offload	Forward	Load	Required	Bulk	Oversized	Outsized	Passengers	Owner	Type
UNIT1486	KBLV	RKPS		10	24	292	1009	59	0	9	
UNIT1487	KWRI	RKPS		10	24	116	349	35	0	23	
UNIT1488	KTIK	RKPS		10	24	6	9	2	0	2	
UNIT1489	KTCM	RKPK	RKTD	10	24	0	0	15	0	5	
UNIT1490	KTIK	RKPS		10	24	0	41	85	0	5	
UNIT1491	PAEI	RKPS		11	24	0	110	5	19	2	
UNIT1492	KSUU	RKPK	RKPP	11	24	133	32	7	59	18	
UNIT1493	KTIK	RKPS		11	24	29	764	9	0	18	
UNIT1494	PHIK	RKPS		11	25	63	182	7	0	18	
UNIT1495	KSUU	RKTY		11	25	634	562	880	0	4	
UNIT1496	KDOV	RKJK		11	25	220	208	212	0	1	
UNIT1497	KTIK	RKSO	RKSG	11	25	0	190	83	402	1	
UNIT1498	KHOP	RODN		11	25	47	44	12	44	1	
UNIT1499	KLFI	PHIK		11	25	0	0	0	1876	2	
UNIT1500	KOFF	PHIK		11	25	0	0	0	814	2	

Table 1: A small portion of a Time-Phased Force Deployment Data (TPFDD) document, when modified for NRMO use, lists the key movement requirements for each unit in the contingency: 1) unit name, 2) onload location (a K prefix denotes a US base), 3) offload location (an RK prefix denotes a Korean base), 4) forward operating location (when appropriate), 5) available-to-load date, 6) required delivery date, 7) the number of short tons of bulk, oversized and outsized cargo, 8) the number of passengers, and 9) the categorized type of unit owner.

require delivery to either an APOD or a FOB. Strategic airlifters make deliveries to APODs and certain aircraft, such as the C-17, can also make deliveries directly to FOBs. Cargo destined for a FOB can also be dropped at an APOD by a strategic lifter and then transshipped to the FOB, either by an in-theater shuttle or via ground transportation. Multiple routing options are typically available to the theater. For example, a mission departing from the lower APOE in Figure 2 can either go through the depicted enroute base, or for appropriate aircraft, can fly nonstop to the APOD by in-flight refueling from a tanker aircraft. Routes from an APOE to the theater are called *delivery routes* and routes from the theater to an APOE are called *backchannel routes*. We further distinguish between *direct delivery routes* (to an APOD or FOB) and *transshipment routes* (to an APOD) which then require subsequent ground or shuttle delivery to a FOB. Because recent US military strategy mandates the capability to fight in two nearly-simultaneous major regional contingencies (alternatively known as major theater wars), some studies have two theaters.

One important aspect of the airlift system not captured in Figure 2 concerns the notion of a *recovery base*. NRMO contains two types of delivery routes: *quickturn routes* and *standard routes*. In a standard route, maintenance operations, crew changes, refueling, and other routine service procedures are performed at the destination base, in addition to offloading the aircraft. On a quickturn route, the aircraft is offloaded and only minimal servicing is provided at the destination. The aircraft then departs for a (presumably less busy) recovery base in the theater where it receives a much fuller range of services, and usually a crew change, before continuing on its backchannel route to an APOE. We distinguish between quickturn and standard

Name	Manufacturer	First Flown	Capacity (stons)	Range (nm)	Comments	Reference Year
C-5A	Lockheed	1968	110	3256	Outsized Cargo	1975-76
C-5B	Lockheed	1985	131	2982	Upgraded C-5A	1985-86
C-17A	Boeing and McDonnell-Douglas	1991	75	2800	Outsized Cargo	1998-99
C-141B	Lockheed	1977	35	2550	Oversized Cargo	1982-83
747F	Boeing	1993	125	4400	Oversized Cargo Not bought by USAF	1998-99
KC-10	McDonnell-Douglas	1980	85	3797	Military DC-10 Air Refueler	1981-82
KC-135	Boeing	1956	45	3735	Various 707 modifications	1972-73

Table 2: Aircraft used or considered by the US Air Force for strategic airlift have widely differing capabilities. Some are variants of civilian aircraft; others are of pure military design. Note that aircraft ranges are stated for the given capacity, but the model actually uses a more detailed range-payload curve. The last column specifies the publication year of the reference (Jackson).

routes because they consume airfield capacity differently.

An aircraft, such as a KC-10, may begin the deployment as an aerial refueler based at a tanker beddown airfield. After the initial days of the deployment, the KC-10 may then fly to an APOE, change roles, and begin delivering cargo and troops to the theater. Role changes of this type may occur throughout the deployment both between the strategic airlifter fleet and the tanker fleet and between the strategic airlifter fleet and the tactical in-theater shuttle fleet. This type of flexibility is attractive because the goal of some studies is to investigate the value of dual-role aircraft, i.e., aircraft that can serve as aerial refuelers and strategic lifters or aircraft that can serve as both tactical in-theater shuttles and strategic lifters.

Each type of aircraft has its own set of crews, and crews are not interchangeable between different aircraft fleets. Flow balance constraints are maintained for crews at a subset of the airfields called crew stage bases. Stage bases are placed along routes so as not to violate crew duty days; typically, crews are assured 12 hours rest after at most 16 hours on duty. When performing tanker or shuttle missions the crews stay with their planes. Crews within the strategic fleet are allowed to "deadhead," i.e., they can move from one crew-stage base to another with an appropriate time delay before they become available to fly. Crews need rest and so there are more crews than aircraft; a typical ratio is 3 to 1.

The primary decision variables in NRMO specify the number of aircraft missions for each line id, for each aircraft type, via each eligible route, in each time period. These include direct delivery and transshipment missions on standard and quickturn routes. Separate decision variables track the time-dynamic delivery of the number of short tons of each line id's equipment in each cargo class. Additional variables account for backchannel missions, in-theater shuttle flights, and the use of tankers to perform aerial refueling. A set of inventory variables specify the number of aircraft of each type at each base acting in the strategic role as well as the shuttle and tanker roles, and another group of variables allow appropriate aircraft to move between these roles. Finally, decision variables also account for the number of rested crews for each aircraft

type at each stage base and the number of crews deadheading between stage bases in each period. Based on information from the TPFDD, each line id has a time window in which delivery is permitted. The objective is to minimize a weighted sum of penalties for late and nondelivery plus secondary terms that measure system performance. The model’s constraints can be grouped into seven categories that govern: demand satisfaction; flow balance of aircraft, cargo and crews; aircraft delivery capacity for cargo and passengers; the number of shuttle and tanker missions per period; initial allocations of aircraft and crews; the usage of aircraft of each type; and, aircraft handling capacity at airfields.

To better facilitate understanding of the mathematical model presented in the next section, we give additional details on some modeling techniques we use. When tanker aircraft change roles they do so between an APOE and a tanker beddown base. We do not model each possible movement because there are a large number of such pairs. Instead all tanker reassignments are made through a fictitious central tanker control point that we refer to as the tanker “cloud.” Approximate time delays for changing roles (and geographical locale) are incorporated in travel times to the cloud. Reassignments as a tanker aircraft from one tanker beddown base to another are also modeled by traveling through the tanker cloud. Not all aerial refueling attempts are successful, and in NRMO a specified fraction of aerial refueling missions are penalized with a time delay and consume airfield capacity at a so-called *divert base*.

In order to reduce the number of flow balance constraints at airfields in the theaters we perform an aggregation. Each theater has one fictitious centrally-located “super node.” Flow balance of strategic airlifters arriving to a theater is maintained at its super node and not at each individual APOD and FOB. Surprisingly little resolution is lost by using this modeling construct. While routes terminate in the network at a super node, decision variables for delivering cargo are indexed by the line id the aircraft is delivering and each line id has a known destination. As a result, we can enforce airfield capacity constraints at each destination and transshipment airbase in the theater, even though aircraft balances are maintained only at the aggregate super nodes. In practice the airfields in a theater tend to be in close proximity so little is lost by not maintaining precise travel times. This aggregation is performed only for APODs and FOBs in the theater. Flow balance is maintained at each APOE and enroute base.

3 Mathematical Formulation

The following sections describe the sets, data, decision variables and finally the mathematical formulation for NRMO. The mathematical model is relatively complex, and as a result there is substantial detail in the presentation. However, a basic understanding is very accessible by first examining the decision variables and then the constraints, referring to the data definitions as needed. That being said, much of the effort in formulating such a model concerns the elimination of inadmissible combinations of indices. For example, we use i for line id, a for aircraft type, r for route, t for time and XD_{iart} denotes the number of aircraft of type a direct delivering line id i on route r , departing at time t . In order for the (i, a, r, t) -tuple to exist for

XD_{iart} :

route r must be a direct delivery route with the correct origin and destination for line id i ;

aircraft of type a must be able to fly the critical (longest) leg on route r with a certain minimal payload;

the start time t of the mission must be after line id i 's available-to-load date;

the delivery time, given that the mission starts at t , must be on or before the required delivery date;

aircraft a must be capable of carrying some cargo type (bulk, oversized, outsized or passengers) that line id i contains; and,

aircraft of type a must be available by time t at r 's origin.

This is just one example of the restrictions on allowable combinations of the indices. In the mathematical formulation, such restrictions are captured by defining appropriate subsets for indices. For example, we use $RD_{ia,dir}$ to denote the subset of direct delivery routes that can be flown by aircraft of type a carrying cargo and/or passengers for line id i . Because correctly restricting such combinations of indices is so essential for formulating a correct and computationally tractable model, we have decided to present such index restrictions via subsets in some detail. NRM0 is implemented with the algebraic modeling language GAMS (Brooke, Kendrick and Meeraus, 1992); the screening of index combinations in GAMS is accomplished with restriction operations that correspond closely with the sets defined below.

3.1 Sets

Sets of time periods

- T all time periods $\{1, 2, \dots, |T|\}$
- TW_i delivery time window for line id i
- T_u set of time periods associated with a utilization rate enforcement block, each block is typically 20 days, with a 10 day overlap between adjacent blocks
- U utilization rate enforcement blocks
- FT flow time periods $\{1, \dots, \text{maximum mission time}\}$

Sets of line ids

- I all line ids for delivery (from the TPFDD)
- I_{fob} subset of line ids whose destination is a FOB
- $I_{b,dst}$ subset of line ids that have base b (FOB or APOD) as a destination
- $I_{b,trn}$ subset of line ids that have APOD b as a transshipment node
- $I_{b,sup}$ subset of line ids that are to be delivered to theater (super node) b

Sets of cargo types

- C all cargo types {bulk, oversized, outsized, pax (troops)}
- CC cargo types excluding passengers {bulk, oversized, outsized}
- C_a subset of cargo types that can be carried by aircraft a

Sets of aircraft types

- A all aircraft types
- A_c subset of aircraft types that can carry cargo type c
- A_{pax} subset of aircraft types that can carry troops
- A_{mix} subset of aircraft types that can carry troops and at least one other cargo type (bulk, oversized, or outsized)
- A_{tkr} subset of tanker aircraft types
- A_{rfl} subset of aircraft types that can be refueled by a tanker
- A_{chp} subset of aircraft types that can serve as shuttles and hence be “chopped” to the theater

Sets of bases

- B all real and virtual bases (APOEs, APODs, FOBs, super nodes, enroute bases, beddown bases, and aerial refueling points)
- B_{sup} subset of bases that are super nodes
- B_e subset of bases that are embarkation nodes
- B_{arp} subset of bases that are aerial refueling points
- B_{tkr} subset of bases that are beddown bases for tankers
- B_{Srec} subset of super nodes that have at least one recovery base
- $B_{Sb,dwn}$ subset of super nodes that have b as the shuttle beddown node
- $BA_{b,tkr}$ subset of B_{arp} that are served by $b \in B_{tkr}$
- $BT_{b,arp}$ subset of B_{tkr} that serve $b \in B_{arp}$
- B_{crw} subset of bases that serve as crew stage bases

Sets of routes

R	routes
RD	delivery routes
RB	backchannel routes
RB_{rec}	subset of backchannel routes that include a recovery base
RD_b	delivery routes that use base b
$R_{b,ori}$	routes whose origin is base b
$R_{b,dst}$	routes whose destination is base b
$RD_{ia,dir}$	subset of routes that can be flown by a and carry i for direct delivery
$RD_{ia,trn}$	subset of routes that can be flown by a and carry i for transshipment
RB_{ab}	subset of backchannel routes that use b and can be flown by a
$RD_{b,div}$	set of delivery routes that have b as a divert base for a failed aerial refueling attempt
$RB_{b,div}$	set of backchannel routes that have b as a divert base for a failed aerial refueling attempt

While there are a large number of sets and subsets, we try to use revealing naming conventions. For example, $I_{b,dst}$ is the subset of line ids that have base b as their destination, and RB_{ab} is the set of backchannel routes that can be flown by aircraft of type a and use base b .

3.2 Data

Travel time data

$rtrv_{ar}$	real travel time (ground times included) for aircraft a to travel on route r (periods)
trv_{ar}	travel time (ground times included) for aircraft a to travel on route r (integer periods)
$etrv_{abr}$	travel time for aircraft a to reach base b when flying route r (integer periods)
$rttrv_{ab}$	tanker a 's real travel time from base b (either embarkation or tanker beddown) to the tanker cloud (periods)
$ttrv_{ab}$	rounded $rttrv_{abr}$ (integer periods)
$ctrv_{abr}$	trv_{ar} plus crew rest (integer periods)
$cttrv_{ab}$	$ttrv_{ab}$ plus crew rest (integer periods)
$dhtrv_{b'b}$	travel time for crew deadheading from b' to b (integer periods)
$gtrv_i$	in-theater ground travel time for i (periods)
$hrsper$	number of hours per period
$msntime_{arf}$	time flown f periods into a mission (hours)
	• $hrsper$ if $rtrv_{ar} > f$ (mission continues throughout its fth period) • 0 if $rtrv_{ar} < f - 1$ (mission terminates before its fth period) • $hrsper \cdot (rtrv_{ar} - (f - 1))$ if $f - 1 \leq rtrv_{ar} \leq f$ (mission terminates during its fth period)

Demand-related data

rdd_i	required delivery date (periods) for line id i
$demic$	stons of demand for line id i of type c
$latepen_i$	late delivery penalty for i per day per ston
$nogopen_i$	nondelivery penalty for i per ston

Data related to airfield capacity and its consumption

$gtime_{abr}$	ground time for aircraft a at base b when flying route r (hours)
$qtime_{abr}$	offload time only for aircraft of type a at base b when flying quickturn route r (hours)
$sgtime_{ab}$	ground time for shuttle aircraft a at base b (hours)
$acpkg_{ab}$	airfield capacity service slots consumed by aircraft a at base b
mog_b	airfield capacity: service slot hours per period at b
$mogeff_b$	mog efficiency at b

Data related to aircraft capacity

$purecap_{iac}$	number of stons of line id i 's cargo of type c that can be loaded on plane a for a flight of approximately 3200nm
$maxpax_a$	maximum number of troops that can be loaded on an aircraft of type a
$rangefac_{iar}$	proportion of a type a aircraft available for loading when flying route r for line id i
$paxfrac_a$	proportion of a type a aircraft's capacity that can be loaded with troops
$fuelgals_b$	gallons of fuel available per period at base b
$fuel_{abr}$	fuel required by aircraft a at base b when flying route r
$daysfuel_{ab}$	daily fuel required by shuttle or tanker aircraft at base b

Data associated with aerial refueling

$tkreqvs_{abr}$	proportion of a full tanker's fuel consumed by aircraft a refueling at aerial refueling point b on route r (KC10 equivalent)
$tkrprop_{abb'}$	proportion of a full tanker (KC10 equivalent) available when a is a refueler at aerial refueling point b' and is bedded at base b
$tkrrate_{abb'}$	maximum number of tanker shuttles to aerial refueling point b' per period for a tanker of type a when it is bedded at b
$dpct_a$	proportion of aerial refueling attempts by aircraft a (the one getting the fuel) that fail

Intra-theater shuttle data

$initchop_{ab}$	initial number of aircraft of type a assigned to shuttle duty in theater (super node) b
$shutrate_{ia}$	maximum number of shuttles per aircraft of type a per period when carrying line id i 's cargo

Aircraft utilization data

$urate_a$	number of hours per day that aircraft a can fly
$fltime_{arf}$	in-flight time only for aircraft type a on route r , f periods into a mission (hours)
$tkrttime_{abb'}$	in-flight time for tanker a flying from b to b' and back (hours)
$shuttime_{ia}$	in-flight shuttle time for aircraft type a carrying line id i (hours)

Other data and notation

$restrew_a$	unit reward for resting aircraft a at base $b \in B_e$
$usepen_a$	usage penalty for theater aircraft and tanker reassignments
$newac_{at}$	number of new aircraft of type a available in period t
$cumac_{at}$	cumulative aircraft available of type a by period t ($= \sum_{t' \leq t} newac_{at'}$)
$dhpen_a$	penalty for deadheading crews
$crewrat_a$	ratio of available crews to aircraft a
$\mathcal{I}(\cdot)$	indicator function; 1 if argument is true and 0 otherwise
$(x)^+$	positive part operator; $= \max\{0, x\}$
$\bar{S}$	complement of set S
$R \setminus S$	set difference; $= R \cap \bar{S}$

3.3 Decision Variables

Aircraft mission variables

XD_{iart}	number of aircraft a direct delivering i on standard (non-quickturn) route r departing at time t
XT_{iart}	number of aircraft a delivering a transshipment load of i on standard (non-quickturn) route r departing at time t
XDR_{iart}	number of aircraft a direct delivering i on quickturn route r departing at time t
XTR_{iart}	number of aircraft a delivering a transshipment load of i on quickturn route r departing at time t
XS_{iat}	number of (roundtrip) shuttle missions of aircraft a delivering i in t
Y_{art}	number of aircraft a departing at t on backchannel route r
$TKRA_{abb't}$	number of (roundtrip) tanker missions of type a flown between $b \in B_{tkr}$ and $b' \in B_{arp}$ in t

Aircraft inventory variables

RON_{abt}	number of aircraft of type a remaining over night at $b \in B_e$ in t
$RONT_{abt}$	number of aircraft of type a remaining over night at $b \in B_{sup}$ without recovery in t
$RONR_{abt}$	number of aircraft of type a remaining over night at $b \in B_{S_{rec}}$ with recovery in t
$IRON_{ab}$	number of aircraft of type a initially assigned to b (nonrecovery)
$IRONR_{ab}$	number of aircraft of type a initially assigned to b (recovery)
$THCHOP_{abt}$	number of aircraft assigned to super node b 's shuttle fleet from nonrecovery routes in t
$THCHOPR_{abt}$	number of aircraft assigned to super node b 's shuttle fleet from recovery routes in t
$TKRB_{abt}$	number of tankers a whose beddown base is $b \in B_{tkr}$ in t

Aircraft changing roles

$ALLOC_{abt}$	number of new aircraft a allocated to $b \in B_e$ in t
$TKREC_{abt}$	number of tankers a leaving $b \in B_e$ in t for service as a refueler (to cloud)
$TKRCE_{abt}$	number of tankers a leaving tanker fleet (from cloud) in t for $b \in B_e$ for cargo hauling
$TKRBC_{abt}$	number of tankers a leaving $b \in B_{tkr}$ in t for reassignment or service as a cargo hauler (to cloud)
$TKRCB_{abt}$	number of tankers a being reassigned (from cloud) in t to $b \in B_{tkr}$ for refueling

Cargo

$DTONS_{iact}$	stons of i 's cargo of type c direct delivered by a that will arrive in t
$TTONS_{iact}$	stons of i 's cargo of type c for transshipment by a arriving (at the transshipment node) in t
$STONS_{iact}$	stons of i 's cargo of type c shuttled by a in t
$GTONS_{ict}$	stons of i 's cargo of type c ground that will arrive at the FOB in t
$NOGO_{ic}$	stons of i 's cargo of type c not delivered

Crews

$SCREWS_{abt}$	number of rested strategic airlift crews available for aircraft a at base $b \in B_{crew}$ at the beginning of time t
$DHCREWS_{ab't}$	number of deadheading crews for a leaving b' at time t for reassignment to b

Each of the above decision variables is constrained to be nonnegative.

3.4 Objective Function

minimize

$$\sum_{i \in I} \sum_{a \in A} \sum_{c \in C_a} \sum_{t \in TW_i} \text{latepen}_i \cdot (t - rdd_i)^+ \cdot DTONS_{iact} \quad (1a)$$

$$+ \sum_{i \in I_{job}} \sum_{a \in A} \sum_{c \in C_a} \sum_{t \in TW_i} \text{latepen}_i \cdot (t - rdd_i)^+ \cdot STONS_{iact} \quad (1b)$$

$$+ \sum_{i \in I_{job}} \sum_{c \in C} \sum_{t \in TW_i} \text{latepen}_i \cdot (t - rdd_i)^+ \cdot GTONS_{ict} \quad (1c)$$

$$+ \sum_{i \in I} \sum_{c \in C} \text{nogopen}_i \cdot NOGO_{ic} \quad (1d)$$

$$+ \sum_{a \in A_{chp}} \sum_{b \in B_{sup}} \sum_{t \in T} \text{usepen}_a \cdot [THCHOP_{abt} + THCHOPR_{abt}] \quad (1e)$$

$$+ \sum_{a \in A_{tkr}} \sum_{b \in B_e} \sum_{t \in T} \text{usepen}_a \cdot TKREC_{abt} + \sum_{a \in A_{tkr}} \sum_{b \in B_{tkr}} \sum_{t \in T} \text{usepen}_a \cdot TKRBC_{abt} \quad (1f)$$

$$+ \sum_{a \in A} \sum_{b, b' \in B_{crew}} \sum_{t \in T} \text{dhpen}_a \cdot DHCREW_{abb't} \quad (1g)$$

$$- \sum_{a \in A} \sum_{b \in B_e} \sum_{t \in T} \text{restrew}_a \cdot RON_{abt} \quad (1h)$$

The first three terms of the objective penalize deliveries that arrive after the required delivery date for cargo arriving directly (1a), by shuttle (1b), and by ground (1c). The unit penalty increases in proportion to the number of days late, provided the arrival date is within the delivery window. Term (1d) penalizes nondelivered cargo. The objective also includes secondary terms that discourage: planes being left in the theater in shuttle fleets (1e), reassigning planes between delivery and tanker fleets (1f), and deadheading crews (1g). A small reward (1h) encourages planes to remain overnight at an APOE as this is often in the

continental US and nearby their home station. The penalty (and reward) structure is such that late delivery is preferred to nondelivery but neither will occur if there are sufficient resources to achieve ontime delivery. In practice, delivery “requirements” are typically aggressive and difficult to fully achieve. An elastic formulation with opportunities for late and nondelivery allows analysts to discover when, and which, resources are being fully utilized. While NRMO does not explicitly model uncertainty, the idea behind providing a small reward for planes remaining overnight at an APOE is that they are then well-positioned to respond to unforeseen contingencies, as well as undergo unforeseen repairs.

3.5 Demand Satisfaction Constraints

$$\begin{aligned} & \sum_{a \in A_c} \sum_{t \in TW_i} DTONS_{iact} + NOGO_{ic} \\ & + \mathcal{I}(i \in I_{job}) \cdot \left[\sum_{a \in A_c} \sum_{t \in TW_i} STONS_{iact} + \sum_{t \in TW_i} GTONS_{ict} \right] = dem_{ic} \quad \forall i \in I, c \in C \end{aligned} \quad (2)$$

For each line id and cargo class (bulk, oversized, outsized, and troops) deliveries that arrive directly and, if the destination is a forward operating base, by shuttle and ground must equal the demand or be counted as nondelivered cargo.

3.6 Flow Balance Constraints

3.6.1 Aircraft balance constraints at embarkation nodes

$$\begin{aligned} & \sum_{i \in I_{job}} \sum_{r \in RD_b \cap RD_{ia, trn}} XT_{iart} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia, dir}} XD_{iart} \\ & \sum_{i \in I_{job}} \sum_{r \in RD_b \cap RD_{ia, trn}} XTR_{iart} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia, dir}} XDR_{iart} \\ & + \mathcal{I}(a \in A_{tkr}) \cdot [TKREC_{abt}] + RON_{abt} = RON_{ab, t-1} + \sum_{r \in RB_{ab}} Y_{ar, t-trv_{ar}} \\ & + ALLOC_{abt} + \mathcal{I}(a \in A_{tkr}) \cdot [TKRCE_{abt}] \quad \forall a \in A, b \in B_e, t \in T \end{aligned} \quad (3)$$

The terms on the left-hand side of the equation represent all the ways that an aircraft of type a can depart an embarkation base b in period t : Planes leave the base for transshipment and direct deliveries on both standard and quickturn routes; dual-role tanker aircraft can depart the base in order to join the aerial refueling fleet; and, aircraft can remain on the ground until the next period. The right-hand side of the equation represents available aircraft including inventoried aircraft from the previous period, planes that have arrived along a backchannel route or from the tanker fleet, and newly allocated aircraft. Note that $Y_{ar, t-trv_{ar}}$ denotes the number of aircraft of type a flying backchannel route r that depart from theater at time $t - trv_{ar}$ and hence arrive at base b at time t .

3.6.2 Aircraft balance constraints at super debarkation nodes

$$\begin{aligned}
& \sum_{r \in RB_{ab} \cap \overline{RB}_{rec}} Y_{art} + RONT_{abt} + THCHOP_{abt} = \\
& \sum_{i \in I_{job}} \sum_{r \in RD_b \cap RD_{ia, trn}} XT_{iar, t-trv_{ar}} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia, dir}} XD_{iar, t-trv_{ar}} \\
& + RONT_{ab, t-1} + THCHOP_{ab, t-1} + I(t=1) \cdot IRONT_{ab} \quad \forall a \in A, b \in B_{sup}, t \in T
\end{aligned} \tag{4}$$

$$\begin{aligned}
& \sum_{r \in RB_{ab} \cap RB_{rec}} Y_{art} + RONR_{abt} + THCHOPR_{abt} = \\
& \sum_{i \in I_{job}} \sum_{r \in RD_b \cap RD_{ia, trn}} XTR_{iar, t-trv_{ar}} + \sum_{i \in I} \sum_{r \in RD_b \cap RD_{ia, dir}} XDR_{iar, t-trv_{ar}} \\
& + RONR_{ab, t-1} + THCHOPR_{ab, t-1} + I(t=1) \cdot IRONR_{ab} \quad \forall a \in A, b \in BS_{rec}, t \in T
\end{aligned} \tag{5}$$

A super node is a surrogate for all of the bases in a theater. Aircraft flow balance constraints are enforced at super nodes, but other resources, such as airfield capacity, are modeled at individual bases. In constraints (4) and (5) aircraft depart the theater along backchannel routes, are inventoried, or are reassigned to serve as shuttles in the theater. Aircraft arrive at the super node on transshipment or direct delivery routes, because they rested there from last period, are part of the theater's shuttle fleet, or because at the beginning of the deployment they were assigned to the theater. Constraints (4) and (5) are identical in form, but the former accounts for aircraft on quickturn routes while the latter tracks aircraft that recover at an APOD in the theater. We distinguish between these two types of missions because of the differing ways that the aircraft consume airfield capacity; see the subsequent airfield capacity constraints in Section 3.12.

3.6.3 Tanker fleet balance constraints

$$\begin{aligned}
& \sum_{b \in B_e} TKREC_{ab, t-ttrv_{ab}} + \sum_{b \in B_{tkr}} TKRBC_{ab, t-ttrv_{ab}} = \\
& \sum_{b \in B_e} TKRCE_{abt} + \sum_{b \in B_{tkr}} TKRCB_{abt} \quad \forall a \in A_{tkr}, t \in T
\end{aligned} \tag{6}$$

$$TKRBC_{abt} + TKRB_{abt} = TKRCB_{abt} + TKRB_{ab, t-1} \quad \forall a \in A_{tkr}, b \in B_{tkr}, t \in T \tag{7}$$

Constraint (6) models tanker aircraft reassignments. The constraint may be viewed as an aircraft flow balance constraint at a central control point, called the "tanker cloud." An aircraft must travel through the cloud in order to change roles between serving as an aerial refueler and a cargo lifter or when changing its beddown location as a refueler. The left-hand side of (6) models aircraft flying to the cloud and the right-hand side models aircraft departing the cloud. We use this modeling construct because it significantly reduces the number of decision variables over allowing all possible point-to-point flights. The number of tankers in the fleet at each tanker beddown base is tracked in constraint (7).

3.6.4 Transshipped cargo flow balance constraints

$$\sum_{a \in A_c} TTONS_{iact} = \sum_{a \in A_c} STONS_{iact} + \mathcal{I}(t + gtrv_i \in TW_i) \cdot GTONS_{ic,t+gtrv_i} \quad (8)$$

$$\forall i \in I_{job}, c \in C, t \in TW_i$$

In each period, flow balance is maintained for transshipped cargo in each class for every line id by constraint (8). The left-hand side represents the amount flown into the transshipment point by strategic lifters while the right-hand side captures flow to the final destination by shuttle aircraft or by ground transportation. Note that no explicit geography is needed in this constraint because it is implicit within the line id index i .

3.6.5 Strategic crew flow balance

$$\begin{aligned} SCREWS_{ab,t+1} &= SCREWS_{abt} \\ &+ \sum_{i \in I} \sum_{r \in RD_{ia,dir} \cap RD_b \cap \bar{R}_{b,ori}} [XD_{iar,t-ctrv_{abr}} + XDR_{iar,t-ctrv_{abr}}] \\ &+ \sum_{i \in I_{job}} \sum_{r \in RD_{ia,trn} \cap RD_b \cap \bar{R}_{b,ori}} [XD_{iar,t-ctrv_{abr}} + XDR_{iar,t-ctrv_{abr}}] \\ &+ \sum_{r \in RB_{ab} \cap \bar{R}_{b,ori}} Y_{ar,t-ctrv_{abr}} \\ &- \sum_{i \in I} \sum_{r \in RD_{ia,dir} \cap RD_b \cap \bar{R}_{b,dst}} [XD_{iar,t-etrv_{abr}} + XDR_{iar,t-etrv_{abr}}] \\ &- \sum_{i \in I_{job}} \sum_{r \in RD_{ia,trn} \cap RD_b \cap \bar{R}_{b,dst}} [XT_{iar,t-etrv_{abr}} + XTR_{iar,t-etrv_{abr}}] \\ &- \sum_{r \in RB_{ab} \cap \bar{R}_{b,dst}} Y_{ar,t-etrv_{abr}} \\ &+ \mathcal{I}(b \in B_e) \cdot crewrat_a \cdot [TKRCE_{ab,t-cttrv_{ab}} - TKREC_{abt}] \\ &+ \mathcal{I}(b \in B_{sup}) \cdot crewrat_a \cdot [THCHOP_{ab,t-1} - THCHOP_{abt} + \mathcal{I}(t=1) \cdot IRONT_{a,b}] \\ &+ \mathcal{I}(b \in B_{S_{rec}}) \cdot crewrat_a \cdot [THCHOPR_{ab,t-1} - THCHOPR_{abt} + \mathcal{I}(t=1) \cdot IRONR_{a,b}] \\ &+ \mathcal{I}(b \in B_e, t \neq 1, newac_{at} > 0) \cdot crewrat_a \cdot ALLOC_{abt} \\ &+ \sum_{b' \in B_{crw}} DHCREW_{ab'b,t-dhtrv_{b'b}} - \sum_{b' \in B_{crw}} DHCREW_{abb't} \quad \forall a \in A, b \in B_{crw}, t \in T \setminus \{|T|\} \end{aligned} \quad (9)$$

Each aircraft fleet of type a has its own set of crews and flow balance of crews is maintained at each crew stage base in constraint (9). The number of available crews in period $t+1$ at b is: the number available in t ; plus crews made available because they have rested sufficiently from previous direct, transshipment and backchannel missions; less crews that depart in t on direct, transshipment and backchannel missions; plus the net number of crews made available from tanker deployments and returns; plus the net number of crews made available from shuttle deployments and returns; plus additional crews that enter an APOE with newly available aircraft; plus the net change in crews arriving and departing on deadhead missions.

3.7 Aircraft Delivery Capacity

Constraints (10), (11), and (12) are of identical form and differ only in that they account for delivery capacity for direct, transshipment, and shuttle flights, respectively. $purecap_{iac}$ represents aircraft capacities if solely loaded with cargo of type c from line id i ; these figures are for a 3200nm flight. The effective capacity of the aircraft is scaled by $rangefac_{iar}$ depending on the length of the longest (critical) flight leg on route r . These three sets of constraints are supplemented by (13), (14), and (15) which restrict the number of troops based on the aircraft's seating configurations. $paxfrac$ in (10)–(12) denotes the fraction of the plane filled when its seats are filled with troops. Note that $DTONS_{ia,pax,t}$ represents numbers of troops while $DTONS_{iact}$ for $c \in \{\text{bulk, oversized, outsized}\}$ has units of short tons.

3.7.1 Direct delivery capacity

$$\begin{aligned} & \sum_{c \in C_a \cap CC} \frac{DTONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot DTONS_{ia,pax,t}}{maxpax_a} \cdot \mathcal{I}(a \in A_{pax}) \\ & \leq \sum_{r \in RD_{ia,dir}} rangefac_{iar} \cdot [XD_{iar,t-trv_{ar}} + XDR_{iar,t-trv_{ar}}] \quad \forall i \in I, a \in A, t \in TW_i \end{aligned} \quad (10)$$

3.7.2 Transshipment delivery capacity

$$\begin{aligned} & \sum_{c \in C_a \cap CC} \frac{TTONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot TTONS_{ia,pax,t}}{maxpax_a} \cdot \mathcal{I}(a \in A_{pax}) \\ & \leq \sum_{r \in RD_{ia,trn}} rangefac_{iar} \cdot [XT_{iar,t-trv_{ar}} + XTR_{iar,t-trv_{ar}}] \quad \forall i \in I_{job}, a \in A, t \in TW_i \end{aligned} \quad (11)$$

3.7.3 Shuttle delivery capacity

$$\begin{aligned} & \sum_{c \in C_a \cap CC} \frac{STONS_{iact}}{purecap_{iac}} + \frac{paxfrac_a \cdot STONS_{ia,pax,t}}{maxpax_a} \cdot \mathcal{I}(a \in A_{pax}) \\ & \leq srange_{ia} \cdot XS_{iat} \quad \forall i \in I_{job}, a \in A, t \in TW_i \end{aligned} \quad (12)$$

3.7.4 Direct delivery troop capacity

$$\begin{aligned} & DTONS_{ia,pax,t} \leq \\ & \sum_{r \in RD_{ia,dir}} maxpax_a \cdot [XD_{iar,t-trv_{ar}} + XDR_{iar,t-trv_{ar}}] \quad \forall i \in I, a \in A_{mix}, t \in TW_i \end{aligned} \quad (13)$$

3.7.5 Transshipment delivery troop capacity

$$\begin{aligned} & TTONS_{ia,pax,t} \leq \\ & \sum_{r \in RD_{ia,trn}} maxpax_a \cdot [XT_{iar,t-trv_{ar}} + XTR_{iar,t-trv_{ar}}] \quad \forall i \in I_{job}, a \in A_{mix}, t \in TW_i \end{aligned} \quad (14)$$

3.7.6 Shuttle delivery troop capacity

$$STONS_{ia,pax,t} \leq maxpax_a \cdot XS_{iat} \quad \forall i \in I_{job}, a \in A_{mix}, t \in TW_i \quad (15)$$

3.8 Shuttle and Tanker Capacity Constraints

$$\sum_{i \in I_{b, sup} \cap I_{job}} \frac{XS_{iat}}{shutrate_{ia}} \leq THCHOP_{abt} + THCHOPR_{abt} \quad \forall a \in A, b \in B_{sup}, t \in T \quad (16)$$

$$\sum_{b' \in BA_{b, tkr}} \frac{TKRA_{abb't}}{tkrrate_{abb'}} \leq TKRB_{abt} \quad \forall a \in A_{tkr}, b \in B_{tkr}, t \in T \quad (17)$$

$$\begin{aligned} & \sum_{i \in I} \sum_{a \in A_{rf}} \sum_{r \in RD_b \cap RD_{ia, dir}} tkreqs_{abr} \cdot XD_{iar, t-etr_{abr}} \\ & + \sum_{i \in I} \sum_{a \in A_{rf}} \sum_{r \in RD_b \cap RD_{ia, trn}} tkreqs_{abr} \cdot XT_{iar, t-etr_{abr}} \\ & + \sum_{i \in I} \sum_{a \in A_{rf}} \sum_{r \in RD_b \cap RD_{ia, dir}} tkreqs_{abr} \cdot XDR_{iar, t-etr_{abr}} \\ & + \sum_{i \in I} \sum_{a \in A_{rf}} \sum_{r \in RD_b \cap RD_{ia, trn}} tkreqs_{abr} \cdot XTR_{iar, t-etr_{abr}} \\ & + \sum_{a \in A_{rf}} \sum_{r \in RB_{ab}} tkreqs_{abr} \cdot Y_{ar, t-etr_{abr}} \\ & \leq \sum_{b' \in BT_{b, arp}} \sum_{a \in A_{tkr}} tkrprop_{ab'b} \cdot TKRA_{ab'bt} \quad \forall b \in B_{arp}, t \in T \end{aligned} \quad (18)$$

Constraint (16) restricts the number of shuttle missions based on the size of the shuttle fleet of type a aircraft at time t in the theater associated with super node b . $shutrate_{ia}$ is the maximum number of roundtrip missions per period that can be performed by aircraft a carrying line id i . The number of tanker missions per period in each theater is similarly constrained by (17). The number of aircraft flying on routes that use aerial refueling point b is constrained by (18), based on the tankers serving b .

3.9 Initial Allocation of Aircraft and Crews

$$\sum_{b \in B_e} ALLOC_{abt} = newac_{at} \quad \forall a \in A, t \in T \quad (19)$$

$$\sum_{b \in B_{crew}} SCREWS_{abt} + crewrat_a \cdot \sum_{b \in B_{tkr}} TKRB_{abt} = crewrat_a \cdot newac_{at} \quad \forall a \in A, t = 1 \quad (20)$$

$$IRONT_{ab} + IRONR_{ab} = initchop_{ab} \quad \forall a \in A_{chp}, b \in B_{sup} \quad (21)$$

Constraint (19) governs the allocation of newly available aircraft to embarkation bases. A similar function is performed by (20) for allocating the crews to stage bases for $t = 1$. In future time periods, new crews are allocated with their aircraft; see constraint (9). For each super base, constraint (21) divides the initial shuttle fleet among recovery and nonrecovery bases in the theater.

3.10 Aircraft Utilization Constraints

$$\begin{aligned}
& \sum_{t \in T_u} \sum_{i \in I} \sum_{r \in RD_{ia, dir}} \sum_{f \in FT} flttime_{arf} \cdot XD_{iar, t-(f-1)} \\
& + \sum_{t \in T_u} \sum_{i \in I_{job}} \sum_{r \in RD_{ia, trn}} \sum_{f \in FT} flttime_{arf} \cdot XT_{iar, t-(f-1)} \\
& + \sum_{t \in T_u} \sum_{i \in I} \sum_{r \in RD_{ia, dir}} \sum_{f \in FT} flttime_{arf} \cdot XDR_{iar, t-(f-1)} \\
& + \sum_{t \in T_u} \sum_{i \in I_{job}} \sum_{r \in RD_{ia, trn}} \sum_{f \in FT} flttime_{arf} \cdot XTR_{iar, t-(f-1)} \\
& + \sum_{i \in I_{job}} \sum_{t \in T_u} shuttime_{ia} \cdot XS_{iat} + \sum_{t \in T_u} \sum_{r \in RB_b} \sum_{f \in FT} flttime_{arf} \cdot Y_{ar, t-(f-1)} \\
& + \mathcal{I}(a \in A_{tkr}) \cdot \left[\sum_{b \in B_{tkr}} \sum_{b' \in B_{arp}} \sum_{t \in T_u} tkrttime_{abb'} \cdot TKRA_{abb't} \right. \\
& + \sum_{b \in B_c} \sum_{t \in T_u} hrsper \cdot rttrv_{ab} \cdot TKREC_{abt} \\
& + \left. \sum_{b \in B_{tkr}} \sum_{t \in T_u} hrsper \cdot rttrv_{ab} \cdot TKRBC_{abt} \right] \\
& \leq \sum_{t \in T_u} cumac_{at} \cdot urate_a \quad \forall a \in A, u \in U
\end{aligned} \tag{22}$$

Based on historical data, an aircraft of type a can average only a certain number of flight hours per day. These averages capture a number of factors, such as aircraft reliability, that are not directly modeled. See Wilson (1985) and Gearing et al. (1988) for more detailed discussions of utilization rates. We do not enforce the utilization limit on a daily basis because that would be overconstraining. Rather, we enforce it over blocks of time, denoted T_u for $u \in U$. We use blocks with twenty days, and adjacent blocks have ten days of overlap. $flttime_{arf}$ specifies the number of hours that aircraft a is airborne in the f th period of its mission when flying route r . The left-hand side of (22) sums the flight times for all of the aircraft of type a within the block of time periods specified by T_u . The sum over $f \in FT$ captures all missions initiated in periods prior to t but not yet complete by t .

3.11 Aircraft Consumption Constraints

$$\begin{aligned}
& \sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} msntime_{arf} \cdot XD_{iar,t-(f-1)} \\
& + \sum_{i \in I_{job}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} msntime_{arf} \cdot XT_{iar,t-(f-1)} \\
& \sum_{i \in I} \sum_{r \in RD_{ia,dir}} \sum_{f \in FT} msntime_{arf} \cdot XDR_{iar,t-(f-1)} \\
& + \sum_{i \in I_{job}} \sum_{r \in RD_{ia,trn}} \sum_{f \in FT} msntime_{arf} \cdot XTR_{iar,t-(f-1)} \\
& + \sum_{i \in I_{job}} \frac{hrsper}{shutrate_{ia}} \cdot XS_{iat} + \sum_{r \in RB} \sum_{f \in FT} msntime_{arf} \cdot Y_{ar,t-(f-1)} \\
& + I(a \in A_{tkr}) \cdot \left[\sum_{b \in B_{tkr}} \sum_{b' \in B_{arp}} \frac{hrsper}{tkrrate_{abb'}} \cdot TKRA_{abb't} \right. \\
& + \sum_{b \in B_c} rttrv_{ab} \cdot hrsper \cdot TKREC_{abt} \\
& + \left. \sum_{b \in B_{tkr}} rttrv_{ab} \cdot hrsper \cdot TKRBC_{abt} \right] \\
& + \sum_{b \in B_c} hrsper \cdot RON_{abt} + \sum_{b \in B_{sup}} hrsper \cdot [RONT_{abt} + RONR_{abt}] \\
& \leq hrsper \cdot cumac_{at} \qquad \forall a \in A, t \in T
\end{aligned} \tag{23}$$

Constraint (23) has a similar mathematical structure to the aircraft utilization constraint (22) but the multiplying coefficients in (23) are designed to capture all the time consumed in period t by each aircraft activity, not just the flying time. The right-hand side of (23) is the total number of hours available for aircraft of type a through period t , and the left-hand side accounts for all possible aircraft activities through t (delivery flights, shuttle flights, backchannel flights, tanker missions and aircraft remaining overnight). Formulating the aircraft balance constraints with travel times rounded down to an integer number of periods can lead to overly optimistic results, and (23) helps remedy this. See Morton, Rosenthal, and Lim (1996) for supporting experimental results. We note that if all of the travel times are integer-valued, then (23) is redundant.

3.12 Airfield Capacity Constraints

3.12.1 Airfield parking and servicing capacity constraints

$$\sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia, dir}} gtime_{abr} \cdot acpkg_{ab} \cdot [XD_{iar, t-etr_{v_{abr}}} + XDR_{iar, t-etr_{v_{abr}}}] \quad (24a)$$

$$+ \sum_{i \in I_{b, dst}} \sum_{a \in A} \sum_{r \in RD_{ia, dir}} gtime_{abr} \cdot acpkg_{ab} \cdot XD_{iar, t-trv_{ar}} \quad (24b)$$

$$+ \sum_{i \in I_{b, dst}} \sum_{a \in A} \sum_{r \in RD_{ia, dir}} gtime_{abr} \cdot acpkg_{ab} \cdot XDR_{iar, t-trv_{ar}} \quad (24c)$$

$$+ \sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia, trn}} gtime_{abr} \cdot acpkg_{ab} \cdot [XT_{iar, t-etr_{v_{abr}}} + XTR_{iar, t-etr_{v_{abr}}}] \quad (24d)$$

$$+ \sum_{i \in I_{b, trn}} \sum_{a \in A} \sum_{r \in RD_{ia, trn}} gtime_{abr} \cdot acpkg_{ab} \cdot XT_{iar, t-trv_{ar}} \quad (24e)$$

$$+ \sum_{i \in I_{b, trn}} \sum_{a \in A} \sum_{r \in RD_{ia, trn}} gtime_{abr} \cdot acpkg_{ab} \cdot XTR_{iar, t-trv_{ar}} \quad (24f)$$

$$+ \sum_{i \in (I_{b, dst} \cap I_{job}) \cup I_{b, trn}} \sum_{a \in A} sgtime_{ab} \cdot acpkg_{ab} \cdot XS_{iat} \quad (24g)$$

$$+ \sum_{b' \in BS_{b, down}} \sum_{a \in A} hrsper \cdot acpkg_{ab} \cdot [THCHOP_{ab't} + THCHOPR_{ab't}] \quad (24h)$$

$$+ \sum_{a \in A} \sum_{r \in RB_{ab}} gtime_{abr} \cdot acpkg_{ab} \cdot Y_{ar, t-etr_{v_{abr}}} \quad (24i)$$

$$+ \mathcal{I}(b \in B_{tkr}) \cdot \left[\sum_{a \in A_{tkr}} hrsper \cdot acpkg_{ab} \cdot TKRB_{abt} \right] \quad (24j)$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b, div} \cap RD_{ia, dir}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XD_{iar, t-etr_{v_{abr}}} \quad (24k)$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b, div} \cap RD_{ia, dir}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XDR_{iar, t-etr_{v_{abr}}} \quad (24l)$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b, div} \cap RD_{ia, trn}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XT_{iar, t-etr_{v_{abr}}} \quad (24m)$$

$$+ \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_{b, div} \cap RD_{ia, trn}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot XTR_{iar, t-etr_{v_{abr}}} \quad (24n)$$

$$+ \sum_{a \in A_{rfl}} \sum_{r \in RB_{b, div}} dpct_a \cdot gtime_{abr} \cdot acpkg_{ab} \cdot Y_{ar, t-etr_{v_{abr}}} \quad (24o)$$

$$\leq mog_b \cdot mogeff_b \quad \forall b \in B \setminus B_{sup} \setminus B_{arp}, t \in T$$

The ability of airfields to handle aircraft is captured in two sets of constraints: (24) and (25). The first set captures parking ramp space and non-fuel related services while the second constrains throughput based on fuel limitations. Even though flow balance is only maintained at the theater's super node, these capacity constraints are enforced at all "real" bases in the model, i.e., all modeled bases except aerial refueling points, whose capacity is captured in (18) and super nodes, which need no capacity constraints. The amount of ground time, and hence airfield capacity, that an aircraft consumes depends on whether the base serves as an onload, enroute or offload base for a strategic lifter.

Term (24a) captures ramp and service consumption at enroute bases for standard and quickturn direct delivery routes. Quickturn routes (24c) require minimal servicing at the offload base and hence spend less time there than standard routes (24b). Terms (24d), (24e), and (24f) serve the same purpose as (24a), (24b), and (24c) except that they are for transshipment routes. Capacity is consumed by in-theater shuttles at their FOBs and transshipment APODs in (24g) and at their beddown base in (24h). Consumption of ramp and service capacity for backchannel routes is captured in (24i), and tanker aircraft consume capacity at their beddown bases in (24j). Finally, in the model a certain fraction of aerial refueling attempts fail and, as a result, associated cargo lifters are diverted to their tanker's beddown base and consume airfield capacity there, (24k)–(24o).

3.12.2 Airfield fuel capacity constraints

$$\begin{aligned}
& \sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia, dir}} fuel_{abr} \cdot [XD_{iar, t-etr_{vabr}} + XDR_{iar, t-etr_{vabr}}] \\
& + \sum_{i \in I_b, dst} \sum_{a \in A} \sum_{r \in RD_{ia, dir}} fuel_{abr} \cdot XD_{iar, t-trv_{ar}} \\
& + \sum_{i \in I_b, dst} \sum_{a \in A} \sum_{r \in RD_{ia, dir}} fuel_{abr} \cdot XDR_{iar, t-trv_{ar}} \\
& + \sum_{i \in I} \sum_{a \in A} \sum_{r \in RD_b \cap RD_{ia, trn}} fuel_{abr} \cdot [XT_{iar, t-etr_{vabr}} + XTR_{iar, t-etr_{vabr}}] \\
& + \sum_{i \in I_b, trn} \sum_{a \in A} \sum_{r \in RD_{ia, trn}} fuel_{abr} \cdot XT_{iar, t-trv_{ar}} \\
& + \sum_{i \in I_b, trn} \sum_{a \in A} \sum_{r \in RD_{ia, trn}} fuel_{abr} \cdot XTR_{iar, t-trv_{ar}} \\
& + \sum_{b' \in BS_b, down} \sum_{a \in A} daysfuel_{ab} \cdot [THCHOP_{ab't} + THCHOPR_{ab't}] \\
& + \sum_{a \in A} \sum_{r \in RB_{ab}} fuel_{abr} \cdot Y_{ar, t-etr_{vabr}} \\
& + I(b \in B_{tkr}) \cdot \left[\sum_{a \in A_{tkr}} daysfuel_{ab} \cdot TKRB_{abt} \right] \\
& + \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b, div \cap RD_{ia, dir}} dpct_a \cdot fuel_{abr} \cdot XD_{iar, t-etr_{vabr}} \\
& + \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b, div \cap RD_{ia, dir}} dpct_a \cdot fuel_{abr} \cdot XDR_{iar, t-etr_{vabr}} \\
& + \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b, div \cap RD_{ia, trn}} dpct_a \cdot fuel_{abr} \cdot XT_{iar, t-etr_{vabr}} \\
& + \sum_{i \in I} \sum_{a \in A_{rfl}} \sum_{r \in RD_b, div \cap RD_{ia, trn}} dpct_a \cdot fuel_{abr} \cdot XTR_{iar, t-etr_{vabr}} \\
& + \sum_{a \in A_{rfl}} \sum_{r \in RB_b, div} dpct_a \cdot fuel_{abr} \cdot Y_{ar, t-etr_{vabr}} \\
& \leq fuelgals_b \quad \forall b \in B \setminus B_{sup} \setminus B_{arp}, t \in T
\end{aligned} \tag{25}$$

Constraint (25) is of very similar form to the ramp and service consumption constraint (24) except that aircraft consume gallons of fuel instead of parking-space hours. Also, note that shuttle aircraft are fueled for an entire day at their beddown base and so there is no analog of (24g) in (25).

3.13 Initial conditions

$$RON_{abt} \equiv 0 \quad \forall t \leq 0$$

$$XD_{iart} \equiv 0 \quad \forall t \leq 0$$

$$XT_{iart} \equiv 0 \quad \forall t \leq 0$$

$$Y_{art} \equiv 0 \quad \forall t \leq 0$$

$$THCHOP_{abt} \equiv 0 \quad \forall t \leq 0$$

$$TKRB_{abt} \equiv 0 \quad \forall t \leq 0$$

$$TKRBC_{abt} \equiv 0 \quad \forall t \leq 0$$

$$TKREC_{abt} \equiv 0 \quad \forall t \leq 0$$

4 Analyses

In this section we discuss five examples of the ways in which NRMO and related airlift optimization models have provided analyses to inform air mobility decisions.

4.1 Analyzing the Effects of Airfield Resources on Airlift Capacity

The ability of an airlift system to deliver cargo and passengers depends on a number of factors including the ground resources available at airfields. Stucker and Williams (1998) performed a study of the impact of airfield resources on airlift capacity and we review some of the results of the analysis here. This RAND study utilized NRMO in conjunction with another model called ACE, the Airfield Capacity Estimator. ACE models parking and servicing, loading and unloading, and fueling operations in detail and is described in Stucker and Berg et al. (1998). For our purposes, we may view ACE as taking inputs that describe an airfield and its resources and providing for NRMO estimates of aircraft ground times ($ptime_{abr}$ and $ptime_{abr}$) and airfield capacities (mog_b). We note that ACE allows for several ground-servicing roles for an airfield including the notion of quickturn and recovery stops versus a full-service offload stop.

The primary purpose of Stucker and Williams' study was to investigate how the level of airfield resources affects the quantity of strategic airlift deliveries. The study's sponsor, the Force Projection Directorate in the Office of the Secretary of Defense (OSD), asked that a previously constructed major regional contingency (MRC)-East deployment scenario be used. In this scenario, cargo and passengers depart the US from Dover, Delaware and are delivered to Dhahran, Saudi Arabia via enroute bases in England, Germany, and Spain. The relevant distances are shown in Table 3. Each of these enroute bases actually has the combined resources of two bases from their country. The English base has the capability of Mildenhall and Fairford, the German

base, Ramstein and Rhein Main, and the Spanish base, Moron and Rota. Table 3 shows that the critical leg in each route is the US-Europe leg. The route via England has the shortest critical leg and the shortest overall distance. Politics clearly plays an important role in such deployments, and while NRMO contains little political modeling, the legs between the English and German bases and the destination base in Dhahran contain detours around Central and Eastern Europe. The study uses the 1996 Air Mobility Command fleet of 95 C-5s, 18 C-17s, 174 C-141s, and 37 KC-10s plus the Civil Reserve Air Fleet (CRAF) of 64 WBCs (wide-body cargo planes), 109 WBPs (wide-body passenger planes), and 51 NBCs (narrow-body cargo planes). Under the CRAF agreement, the Department of Defense leases civilian passenger and cargo aircraft in times of national emergency. The CRAF share resources with the military aircraft at onload and offload bases but use separate nonmilitary enroute European bases. The focus of the study concerns the role of enroute airfield capacity at the military European bases.

	Dover (nm)	Dhahran (nm)	Total (nm)
Mildenhall	3,123	2,953	6,076
Ramstein	3,437	2,765	6,202
Moron	3,213	2,879	6,092

Table 3: Distances in nautical miles between the three enroute bases in Western Europe and the origin base in Dover, Delaware and the destination base in Dhahran, Saudi Arabia. (Stucker and Williams, 1998)

Under the baseline scenario, all of the *passenger* movements are completed within their allotted time windows, with an average of 6,600 passengers delivered per day over the 30 days of the model's time horizon. All of the passengers are carried by CRAF aircraft. Over 30 days, 135,000 stons of cargo are delivered, an average of 4,500 stons per day.

4.1.1 The impact of existing enroute airfield capacity

Three main types of airfield resources are considered: aircraft-specific maintenance, ramp space, and fuel pumping rates. The supply of specialized aircraft servicing personnel is limited and each type of aircraft may not be able to be fully serviced at each enroute airfield. To capture this limitation the C-5, C-17, and C-141 service personnel are each assigned to a different enroute base and all of the associated flights by, say, C-5 aircraft must be routed through a unique enroute service center. The KC-10's service personnel are also assigned to one of the three enroute bases, so that particular base will handle two types of aircraft. These aircraft-specific service personnel restrictions are called "birds of a feather flock together" constraints. Ramp constraints impose a maximum number of parking-space hours per day at each airfield (mog_b), and fuel constraints limit the number of gallons of fuel that can be pumped at an airfield each day ($fuelgals_b$). Table 4 contains these values for the three enroute bases.

In order to assess the impact of each type of airfield capacity constraint, the model was run four times: (i) with no airfield capacity constraints, (ii) with just service center (birds of a feather flock together) restrictions,

Airfield	Ramp Space (mog_b) (narrow-body-equivalent hours per day)	Fuel ($fuelgals_b$) (million gallons per day)
England	240	1.61
Germany	336	1.57
Spain	168	0.82

Table 4: Existing airfield ramp and fuel resources at the three enroute bases. Ramp space is measured in terms of narrow-body-equivalent parking space hours per day. A narrow-body space corresponds to that required by a C-141. The C-17 and C-5 are wide-body aircraft that require multiple narrow-body spaces. Fuel pumping rates are in millions of gallons per day. (Stucker and Williams, 1998)

(iii) with service center and ramp constraints, and (iv) with service center, ramp, and fuel constraints. The service center constraints are implemented using an integer programming variant of NRMO in which binary decision variables partition the C-5, C-17 and C-141 among the bases in England, Germany and Spain and also assign the KC-10 to one of these three enroute bases.

Table 5 summarizes the results of these runs. When no airfield constraints are present, all aircraft are routed through England since it has the shortest critical leg and shortest overall length. When service center constraints are enforced and the centers are allocated to the three enroute bases, C-5s fly through Spain, C-17s through Germany and C-141s through England. Daily cargo deliveries decrease by 100 stons, less than two percent, to about 5,600 stons per day. This decrease is primarily due to the fact that increased flying times on the longer routes result in fewer round trips due to binding aircraft utilization constraints (Section 3.10). Additional runs showed that these choices of the service centers are not critical and similar results can be achieved with other assignments. Imposing restrictions for ramp space has a larger impact and average daily deliveries decrease by 600 stons to 5,000 stons per day. The service center constraints remain in place and C-5s still go through Spain, saturating its ramp space from day 2 to day 30. The C-17 and C-141 service centers swap locations. The C-17s, along with the small KC-10 fleet, utilize all of the ramp space at the English base on half of the days and utilize it at over a 90 percent level every day. The C-141s use over 90 percent of the German base's ramp space every day. Imposing fuel pumping constraints also has a significant impact, decreasing average daily deliveries by another 500 stons to the baseline result of 4,500 stons per day. In this case, the location of the service centers have all changed. This is primarily driven by the relatively small fuel capacity of the Spanish base. The smaller C-17 fleet is now routed through Spain and consumes its fuel supply each day. Ramp space constrains C-5s in Germany and C-141s in England.

The results of systematically mislocating the specialized aircraft service centers are shown in Table 6. Strategy A, the optimal solution with all airfield capacity constraints enforced (the right-most column of Table 5) serves as the baseline. Strategy B, with the C-5 center in Spain, the C-17 center in England, and the C-141 center in Germany leads to a two percent reduction in daily deliveries. Strategy C leads to nearly a seven percent reduction, primarily because the large C-141 route is forced through the fuel-limited base in

	Airfield capacity constraints present at enroute bases:			
	None	Service	Service/Ramp	Service/Ramp/Fuel
C-5 center	England	Spain	Spain	Germany
C-17 center	England	Germany	England	Spain
C-141 center	England	England	Germany	England
Daily Cargo (stons)	5,700	5,600	5,000	4,500

Table 5: This table shows the results of four runs with differing types of airfield capacity constraints enforced. Service center (birds of a feather flock together) constraints require that each type of aircraft be routed through its unique enroute maintenance airbase. The location of the service center is shown for each aircraft. Note that the average daily cargo delivered decreases as additional airfield resource constraints are incorporated. (Stucker and Williams, 1998)

Spain.

Strategy	C-5 Center	C-17 Center	C-141 Center	Daily Delivery (stons)
A	Germany	Spain	England	4,500
B	Spain	England	Germany	4,400
C	England	Germany	Spain	4,200

Table 6: Daily deliveries are shown under three strategies for locating the specialized aircraft service centers at the enroute bases. (Stucker and Williams, 1998)

In contrast to conclusions from some previous studies (see the discussion in Stucker and Williams, 1998), these results indicate that airfield capacity constraints at enroute bases can play a critical role in an airlift system's ability to deliver cargo.

4.1.2 Redistributing ramp space and fuel pumping rates

At each of the three enroute bases, the fraction of the airfield, as well as the fuel resources, accessible by the US airlift aircraft may be negotiable. For this reason it can be valuable to study optimal allocations of ramp space and fuel pumping equipment. Stucker and Williams do so in the following manner. They assume the ramp space and fuel totals over all three bases remain constant but they allow redistribution among the three bases. The original and the optimally redistributed values are shown in Table 7. The redistribution yields a 12 percent increase in daily cargo deliveries from 4,500 stons per day to 5,100 stons per day. Recall that the case with no enroute airfield capacity constraints delivers 5,700 stons per day so that this redistribution results in a significant increase.

The C-5 is the largest aircraft, hauls the most cargo, and consumes the most fuel. Its service center is relocated in Spain where the redistribution increased both the ramp space and fuel pumping rate. England now has more ramp space to accommodate the wide-body C-17. Finally, the ramp space and pumping rate in Germany are significantly reduced, but the base still has enough capacity to handle 82 narrow-body C-141s per day.

	Ramp Space (narrow-body-equivalent hours per day)		Fuel Pumping Rate (million gallons per day)		Service Center
	Existing	Preferred	Existing	Preferred	
Airfield					
England	240	281	1.61	0.99	C-17
Germany	336	178	1.57	1.01	C-141
Spain	168	285	0.82	2.00	C-5

Table 7: This table shows the original and redistributed ramp and fuel resources among the three enroute bases. The resulting locations of the service centers for each aircraft type are also shown. The NRMO model estimates that this redistribution and relocation leads to a 12 percent increase in deliveries over the first 30 days of the deployment. Such insight is valuable because the US may be able to negotiate the amount of airfield capacity made available by our NATO allies. (Stucker and Williams, 1998)

These results estimate that under this MRC-East scenario if the the US were to negotiate with its European allies in order to redistribute existing ramp space and fuel pumping rates in the recommended fashion, deliveries could be increased by 12 percent over the first 30 days of the deployment.

4.2 Fleet Modernization: Comparison of NRMO with an Airlift Simulation

Concurrent with the RAND/OSD infrastructure analysis described above, the Air Mobility Command's Studies and Analyses Flight (AMCSAF) at Scott AFB, Illinois, was exploring alternatives for airlift fleet modernization in the next decade. AMCSAF conducted this study, as well as all of its most detailed analyses, with a large simulation model known as the Airfield Flow Module (AFM) of the Mobility Analysis Support System (Air Mobility Command, 1996). Because AFM is an established and respected model, its results provided an opportunity to help validate NRMO, as well as to compare and contrast the two modeling approaches, optimization and simulation. Thus, the purpose of using NRMO in the fleet modernization study was twofold: (i) to instill confidence in, and familiarity with, an optimization model for airlift mobility, and (ii) to highlight additional insight that can be gleaned from an alternative modeling approach to airlift mobility.

Any plan to modernize the airlift fleet must consider several wartime scenarios. Foremost among these scenarios are a war near the Arabian peninsula (MRC-East), and a war on the Korean peninsula (MRC-West). Although they are only a small subset of the possible missions, these two contingencies are among the most stressful from an airlift standpoint; both have huge delivery requirements, and both are thousands of miles from the continental United States. In this study, the onload, enroute, and offload airbase capacities were varied to reflect current infrastructure, as well as the forecast infrastructure of the next decade. Although AMCSAF modeled many fleet alternatives using AFM, we chose two of the leading contenders for the comparison with NRMO. Specifically, we assumed an unmodified C-5 fleet of 95 aircraft, as well as an upgraded C-5 fleet of the same size. The upgraded fleet offered enhanced reliability due to replaced engines, avionics, landing gear, and some structural components. Increased reliability is reflected in NRMO via larger

$urate_a$ values and smaller groundtime ($gtime_{abr}$ and $qtime_{abr}$) values. Both fleets also included 95 C-17 aircraft, as well as 174 contracted CRAF aircraft.

Commonality of input between the optimization and simulation models is very important, not only because this allows direct comparison of the outputs, but because providing input data for large models is labor intensive. We have developed a number of utilities that convert the established AFM input files into NRMO input format. These include the movement requirements, the aircraft capacities for cargo types and classes, the airfield locations and capacities, and the route structure. As is frequently the case with optimization, NRMO provides a prescriptive solution at the expense of additional detail that a descriptive simulation (AFM) offers. To accommodate this reduced detail, the conversion utilities allow the aggregation of similar movement requirements and airfields. For example, several small movement requirements that have the same origins, destinations, time windows, and cargo densities can be combined into one larger requirement with minimal loss of model fidelity. Nearby airfields may be similarly aggregated.

4.2.1 Korean Peninsula

Airlift operations from the United States to Korea are characterized by long overwater flights, stopovers in congested Japanese bases, and offloads at small Korean airfields with limited parking and servicing capability. Most missions fly a northern Pacific route through Alaska, or a mid-Pacific route through Hawaii, and sometimes Guam or Okinawa. Missions that originate on the East coast or in the Midwest will also stop at an Air Force base near Seattle or San Francisco. Because most aircraft return to the US empty, many of the eastbound enroute stops are unnecessary, provided the aircraft is fully fueled in Japan.

The results of the AFM simulation model and the NRMO optimization model were similar with respect to average daily cargo throughput. Figure 3 shows that both models indicate a cargo throughput of just over 4000 stons per day using the current airfield infrastructure, regardless of whether the C-5 is modified or not. However, the simulation was more sensitive to the modified C-5 than the optimization. With modified C-5s and the proposed infrastructure, AFM averaged 5000 stons per day, while NRMO averaged 4550 stons per day (500 stons per day is roughly equivalent to 5 or 6 fully loaded C-5s, or 7 or 8 fully loaded C-17s). It is likely that both models underestimate the contribution of modified C-5s, since neither directly incorporates stochastic ground times due to aircraft reliability.

One of the most significant insights gleaned from the NRMO runs had nothing to do with comparing optimization and simulation. Previous large-scale airlift analyses did not account for the effects of wind, principally because AFM did not use wind direction and velocity as an input. In contrast, most human airlift planners routinely use a west wind at 50 knots as a rough approximation of summertime winds at flight level. In the jet stream, wintertime winds in Northeast Asia are often 100 knots at cruising altitude. When NRMO was run with 100 knot westerly winds, daily cargo throughput dropped by an average of 15.6%. Thus, wind can have more effect on throughput than either the proposed infrastructure or aircraft improvements! Air

Mobility Command is now incorporating wind into the next AFM release. We note that Middleton (1998) develops a stochastic variant of a deterministic optimization model developed by Whisman and Borsi of AMCSAF. While this model is simpler than NRMO in many respects, it uses multiple scenarios to capture uncertainties in weather as well as maintenance, and damage to airbases or planes by enemy activities.

4.2.2 Arabian Peninsula

As described in the infrastructure study of Section 4.1, airlift deployments to the Arabian peninsula involve at least one intermediate stop, usually in England, Germany, or Spain. Fueling and servicing capability at the offload locations, while generally less restrictive than in Korea, is still constrained. Additionally, the political assumptions are trickier; permission to fly over any of the patchwork of countries in Europe is not assured, and may change depending on who is fighting whom. For instance, the US had very few overflight and enroute refueling options during the resupply of Israel in the Yom Kippur War of 1973, yet had numerous alternatives during the Gulf War of 1990-91.

Our focus for NRMO in this study did not involve a direct comparison with AFM. Rather, we wanted to show how an optimization solution could complement a simulation solution. We looked at route prioritization and offload airfield congestion.

Route priorities for each aircraft in AFM must be specified by the user, whereas NRMO selects an optimal route for a given time, aircraft, and unit delivered. As noted in the infrastructure study, making the best match between routes and aircraft types is a function of the critical leg as well as the airfield capacities. Making inappropriate matches can be rather punitive. Similar to that seen in the infrastructure study, the optimization preferred and flew C-17s on the route with the shortest critical leg 72% of the time, and the route with the longest critical leg only 1% of the time. In order to reserve capacity at the enroute airbases for C-17s, C-5 route preferences were reversed; 29% of those missions flew the shortest-critical-leg route, while 40% flew the longest-critical-leg route. Thus, NRMO output may be used to specify AFM input in instances where both models are used in an analysis.

Determining where to spend additional infrastructure dollars is essentially a by-product of any NRMO run. Although not a goal of the fleet modernization analysis, examination of the Arabian peninsula dual solutions showed a large range of airbase congestion, as indicated by the offload bases' airfield parking capacity constraints. The optimal dual variable levels ranged from an average of only 26.1 stons delivered per parking space per day, up to 104.4 stons delivered per parking space per day. Marginal analysis from NRMO dual solutions provided additional insight that was unavailable from AFM.

4.3 A Fleet-Mix Tradeoff Analysis

One of the immediate predecessors of NRMO was THRUPUT II, a model built by an NPS Master's student (Lim, 1994). In 1995 a team of students and faculty at NPS, guided by military analysts at AFSAA in

the Pentagon, used THRUPUT II to help decide whether to buy the (then) McDonnell-Douglas C-17, or a modified Boeing 747 (NDAA) as the next-generation USAF airlifter (Rosenthal et al., 1997). Ultimately, the C-17 was chosen, and Boeing acquired McDonnell-Douglas.

The C-17/NDAA study presented two significant challenges. Foremost was the size of the problem. The scenario called for simultaneous airlift to both the Arabian and Korean peninsulas, which roughly doubled the number of airfields, routes, and delivery requirements used in a typical scenario. Second, the input data were classified, yet the model runs were conducted on unclassified computers, in part by non-US military officers. Consequently, huge amounts of data had to pass through input and output "classification filters."

Our analysis showed that while the modified 747 fleets performed slightly better than the C-17 fleets (because of its longer range and ability to carry all cargos) this improvement was deemed insufficient to overcome the C-17's advantage with respect to combat flexibility. Furthermore, the analysis demonstrated a need for modeling in-theater and air-refueling operations, as well a need for a more parsimonious formulation that could do similar analyses with fewer variables and constraints. As a result, NRMO was developed.

4.4 Utilizing Aerial Refueling Aircraft

Killingsworth et al. (1994) conducted an investigation of the utility of tanker aircraft within the air mobility system. The CONOP (CONcept of OPERations) model was developed specifically for this study, which had three major objectives: (1) Evaluate the utility of aerial refueling in support of strategic airlift operations, (2) Perform tradeoff analyses on the use of enroute bases to support airlifter and tanker operations, and (3) Examine how the employment and availability of tankers could influence airlift force structure decisions. The study found that the KC-135 is the preferred aircraft for performing the aerial refueling mission because it can provide more fuel at aerial refueling points per unit of base capacity it consumes. The KC-10 was preferred as a cargo hauler under most conditions and levels of availability. However, if the enroute base system is limiting, and substantial numbers of KC-10s are available, they can be useful as aerial refuelers based out of coastal continental US airfields. Aerial refueling of airlifters increases cargo throughput most during the earliest stages of the deployment, before the enroute system has been expanded. As for the use of aerial refueling to reduce logistics risk associated with unreliable airlift aircraft, the study found that there is no substitute for highly reliable aircraft. Broken aircraft impede the cargo flow substantially, and aerial refueling has only a limited ability to improve the situation. Although aerial refueling was used to a greater degree when aircraft were unreliable, the approach did not prevent a substantial adverse impact on cargo throughput capability at APODs. Finally, the study found that the difference in marginal costs between aerial-refueling and cargo-hauling concepts of operation is greatest for smaller cargo movements. However, these types of movements are often characterized by urgency and the desire for early closure, and also have lower costs that may make them affordable under the circumstances. Using aerial refueling to the maximum extent to support large deployments results in relatively small additional costs, but, at least in the case of

MRC-West, it can substantially shorten the overall time to close the requirement.

4.5 Analyzing the Benefits of Tactical Delivery Aircraft

Killingsworth and Melody (1995) supported the C-17 Tactical Utility Analysis (TUA) study, conducted by the Office of the Secretary of Defense, Program Analysis and Evaluation. Past analyses of the roles and missions of the C-17 had centered chiefly on its effectiveness in moving military equipment over intercontinental distances. In contrast, the C-17 TUA provided an in-theater perspective on C-17 operations. The CONOP model was used to help understand how and why C-17s might be used as theater airlifters. The original CONOP model was modified for this study to include the representation of tactical, or in-theater, cargo movements as well as the strategic flow, allowing analysis of the tradeoff of pulling the C-17s from the strategic fleet to support the tactical movement. The model was allowed to select the mixes of C-130s and C-17s to most efficiently deliver the in-theater cargo, while also requiring that the strategic cargo be efficiently delivered. In NRMO, this corresponds to allowing C-17s to perform direct deliveries to FOBs and allowing C-17s and C-130s to be reassigned (“chopped”) to the theater to perform shuttle missions that deliver cargo and troops from APODs to FOBs. The scenario used for the analysis was again based on two nearly simultaneous major regional contingencies (MRCs).

The study consisted of a parametric analysis of the following: (1) amount of outsized cargo, (2) allowable lateness, (3) capacity of shuttle beddown bases, and (4) total number of C-17s available. At baseline values for these parameters, approximately one squadron of C-17s was recommended for theater operations. Although these numbers varied according to the parameter values, some level of C-17 presence in-theater was usually indicated. The optimization model also usually preferred to utilize C-17s for direct deliveries from a continental US APOE to a theater FOB whenever this option was available. In general, the analysis supported a robust role for C-17s operating in-theater during major regional contingencies, with as much as a squadron of about 12 aircraft in each theater. It was found that number of deployed aircraft could probably be reduced substantially using concepts of operation such as the “stratshuttle”, where a C-17 flying strategic cargo into APODs would perform one day of in-theater shuttles before returning to the strategic fleet.

5 Summary

In recent years, the US military has re-postured from a forward-deployed force countering a relatively few areas of likely conflict, to a largely US-based force reacting to many disparate smaller conflicts. The resulting burdens on the strategic airlift force have become acute, and have been the subject of numerous analyses for updated aircraft, infrastructure, and concepts of operation.

NRMO has played a significant role in the conduct of these analyses as it was designed to model the delivery of troops and cargo in the early stages of a conflict. NRMO grew out of the combined advantages of several optimization models (MOM, THRUPUT, THRUPUT II and CONOP). NRMO and its progenitors

have been used to assist USAF planners in analyzing important issues concerning fleet modernization and aircraft acquisition, investment and divestment in airfield resources, and how to best use aircraft that may be utilized in multiple roles. Because NRMO has been developed over several years and utilized in multiple analyses, we have simultaneously streamlined the model for computational efficiency and expanded it to include many of the key features of the airlift system. We believe it has been instrumental in identifying key areas for improvement of this critical national resource.

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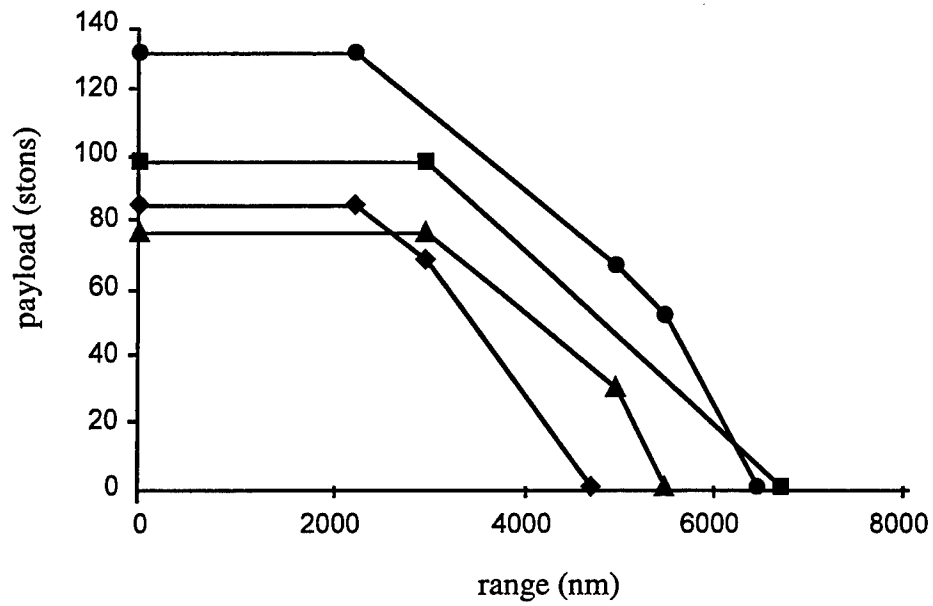


Figure 1: These range-payload curves for four typical airlift aircraft indicate the maximum payload (stons) that an aircraft can carry when flying a given number of nautical miles. The piecewise linear curves are constructed by using linear interpolation between specified points.

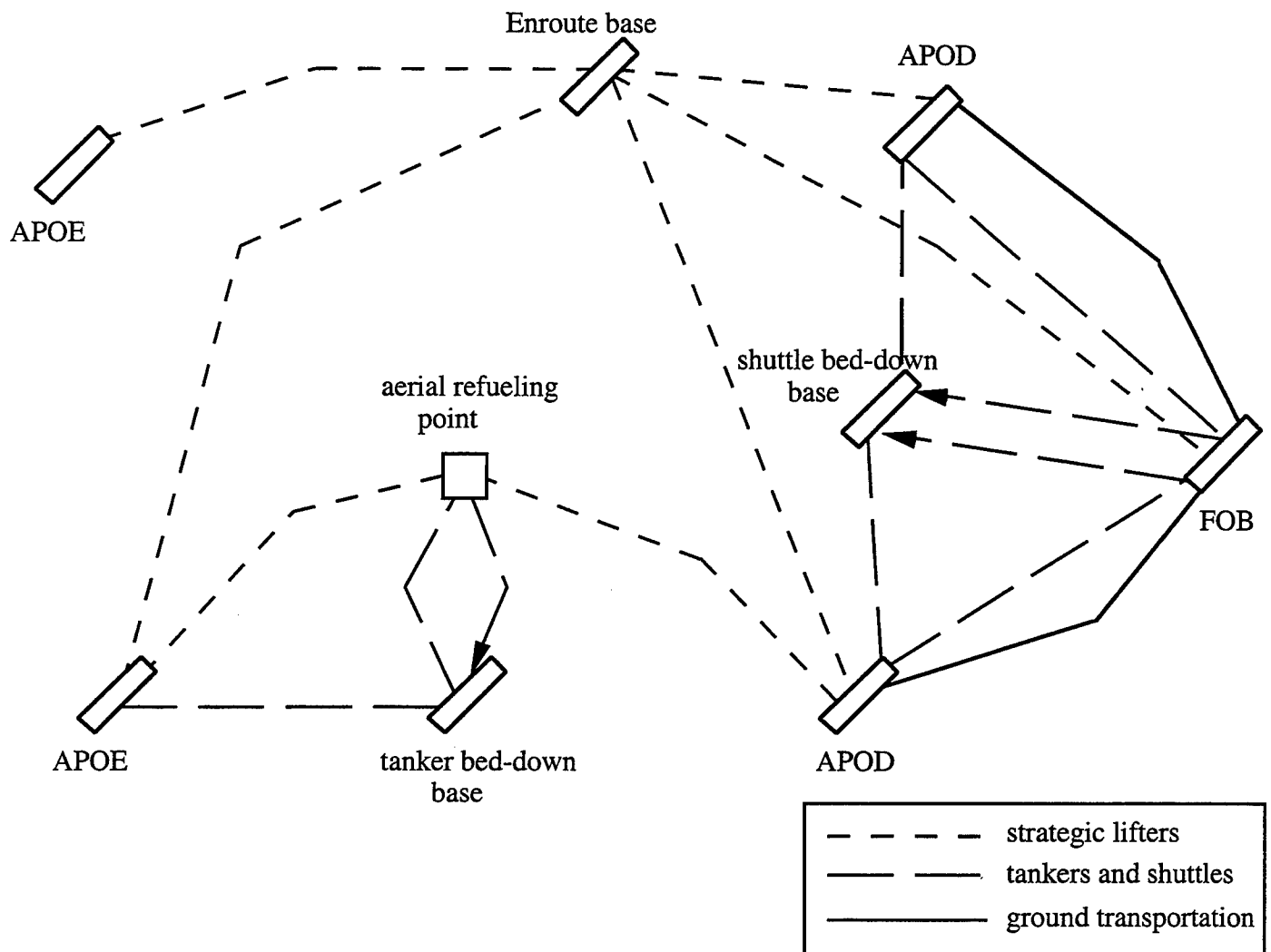


Figure 2: This figure depicts a number of the key components of the airlift transportation network including aerial ports of embarkation (APOEs), enroute bases, aerial ports of debarkation (APODs), forward operating bases (FOBs), in-theater shuttle beddown operations, and aerial refueling operations.

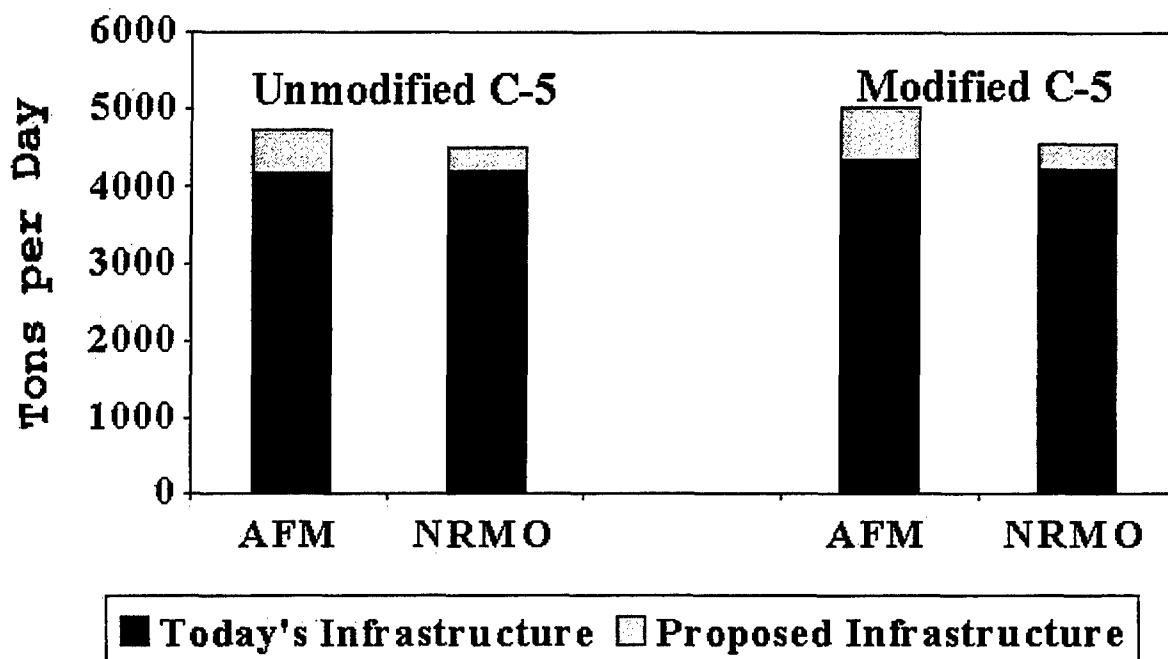


Figure 3: Both the AFM airlift simulation model and the NRMO airlift optimization model predict that similar amounts of cargo can be delivered to the Korean peninsula during a wartime contingency. Each bar shows the delivered stons per day assuming the current airbase infrastructure, as well as assuming proposed infrastructure improvements for the next decade. The two models differ somewhat regarding the effect of aircraft improvements; AFM suggests that an additional 500 stons per day can be delivered using a fleet of improved C-5 cargo aircraft, while NRMO suggests a much smaller improvement.

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