Optimizing Intratheater Military Airlift in Iraq and Afghanistan

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ABSTRACT

The Air Tasking and Efficiency Model (ATEM) has been used since 2006. Its development was motivated by an urgent need to plan and evaluate intratheater airlift of passengers and palletized freight for Operation Iraqi Freedom in Iraq and Operation Enduring Freedom in Afghanistan. ATEM plans routes and aircraft configurations (capacity of passenger seats and pallet positions) for a heterogeneous fleet of aircraft flying between multiple airfields. ATEM respects limits on crew duty periods, times and abilities of each airfield to handle and fuel each aircraft type, and aircraft speed and carrying capacity. Initially, ATEM advised improving daily and weekly route ensembles, conveying more passengers and pallets and using fewer aircraft than prior manually generated solutions. This early use reduced the required number of ground convoys and thereby exposure to improvised explosive devices. Later, ATEM advised where to advantageously move aircraft to new home airfields, how to shift aircraft between theaters, and when to bring aircraft home from war.

> That I have hoisted sail to all the winds,
> which should transport me farthest from your sight.
>
> Shakespeare, Sonnet

INTRODUCTION

The logistics of transporting, arming, feeding, clothing, sheltering, and fueling hundreds of thousands of personnel involved with our military operations in Iraq and Afghanistan has been a daunting challenge for US Central Command (CENTCOM), the unified combatant command whose area of responsibility includes those countries. The CENTCOM Deployment and Distribution Operations Center (CDDOC) at Camp Arifjan, Kuwait, receives specific demand signals and manages what is essentially the last echelon in a world-wide supply chain. This echelon conducts intratheater movement of materiel, using convoys of trucks and, when possible, airlift, to move personnel and their equipment to where they are needed in support of military operations.

In 2005 the CENTCOM commander directed US military leaders to do everything within their powers to reduce the number of ground convoys and thus reduce exposure of personnel to the ever-increasing number of improvised explosive devices. The director of CDDOC pressed his staff, ''We cannot fly everything, but we need to fly everything we can.''

The United States Transportation Command divides intratheater air routes into two broad categories, frequency channel routes and requirements channel routes (United States Transportation Command, 2005). Frequency channel routes are published in a schedule, much like an airline, based on anticipated demands for a given time period. Requirements channel routes are decided each day, and move emergent demand as necessary. Author Brau was stationed at Camp Arifjan in October 2005, and at that time he found that air planners were manually scheduling CENTCOM intratheater airlift using basic tools such as whiteboards and simple Microsoft Excel spreadsheets to keep track of assets and materiel. He immediately started working on an optimization model to assist planners in creating the requirements channel routes and prescribing air and ground movement of passengers (PAX) and air freight pallets (PALS), hereafter referred to collectively as *cargo*. He contacted the other authors soon after he started this effort, and by December 2005 our team had begun development of a decision support tool called the Air Transportation and Efficiency Model (ATEM) for quickly creating requirements channel routes, to help clear backlogged cargo, and to design high-quality weekly frequency channel routes for future demands. The solutions provided by ATEM maximize the flow of PAX and PALS on intratheater airplanes: by analyzing daily operations data, we realized this presented the greatest opportunity to make a significant near-term improvement.

ATEM would be of little utility without an interface making it easy for nonanalyst planners to understand and use. So, we developed a portable, laptop-based graphical user interface using Microsoft Excel and Visual Basic (Microsoft, 2012a,b), and a mathematical modeling suite including the General Algebraic Modeling System (http://www.gams.com) and several commercial optimization packages. A trip to Kuwait by two of our co-authors confirmed that such a decision support tool would be a significant improvement in both frequency and requirements channel planning, and helped solidify the structure of the model based on our direct experience with air logistics in Iraq and on our discussions with planners in theatre.

MILITARY AIRLIFT PLANNING TOOLS

Our intratheater distribution problem is a variant of the vehicle routing problem (VRP) (Dantzig and Ramser, 1959). The objective of VRP is to design a set of routes for a given fleet of vehicles that satisfies customer demands at dispersed locations from one or more depots, at lowest cost. Side constraints added to the basic VRP create variants of the problem. Typical variants include the capacitated vehicle routing problem, where vehicles have limited capacity, the vehicle routing problem with pickups and deliveries, where customers can both receive material from and return material to a depot, the vehicle routing problem with time windows, where visits to customers must be made within a specified time epoch, and the shuttling problem, where each customer is both an origin and a destination for shipments from and to other customers, and the dial-a-ride problem, where customer pickups and drop-offs are merged into a set of vehicle routes. See Toth and Vigo (2002) for a survey of VRP problems and solution techniques.

We find intratheater airlift as required in Operation Iraqi Freedom (OIF) and Operation Enduring Freedom (OEF) to be a unique VRP. Feillet, Dejax, and Gendreau (2005) present the profitable arc tour problem that shares much in common, but in addition to the features they describe we also must plan for multiple depots, multiple (here, two) types of cargo capacity on each vehicle, and a limited heterogeneous vehicle fleet.

Joint Pub 3-0 (Joint Chiefs of Staff 2001) defines three levels of war: strategic, operational, and tactical. Military logistics must enable operations at all three levels. The Joint Staff and service staffs concentrate on strategic logistics matters. Combatant Commanders (COCOM) link strategic- and operational-level logistics. Finally, subordinate commanders blend operational and tactical logistics to accomplish missions assigned by the COCOM (Joint Chiefs of Staff 2000). Strategic distribution, the movement of forces from Continental US (CONUS) bases into a theater of operations, flows along intertheater distribution channels. Operational distribution, the movement of materiel within a COCOM theater, flows along intratheater logistics channels. VRPs are inherent in both intertheater and intratheater distribution, and the Department of Defense employs many tools to solve both these problems.

The major strategic distribution models in use when we started ATEM and still in use today are the Global Deployment Analysis System (GDAS), Joint Flow and Analysis System for Transportation (JFAST), Model for Intertheater Deployment by Air and Sea (MIDAS), the Mobility Simulation Model (MobSim), and the Consolidated Air Mobility Planning System (CAMPS). Barnes and McKinzie (2004) survey these systems. In addition to these, other simulation models in use today include the Air Mobility Operations Simulation (AMOS) and the Analysis of Mobility Platform (AMP).

GDAS uses alternating greedy cargo and greedy vehicle heuristics combined with route insertion to assign passengers to modes of transportation (air, ground, and sea) for transport between points of CONUS embarkation to points of debarkation in some area of operations. JFAST employs local search to plan strategic lift from CONUS to some deployment area of operations (see Koprowski [2005], and his references for a summary). MIDAS is a simulation that represents strategic deployment of unit personnel and equipment by air and sealift into theater ports of debarkation (Military Surface Deployment and Distribution Transportation Engineering Agency Command, 2005). MobSim is a network-based discrete event stochastic model. CAMPS, the replacement for both ADANS (Air Mobility Command Deployment Analysis System) and CMARPS (Combined Mating and Ranging Planning System), is a heuristic planning tool (Becker et al., 2004). AMOS is a rule-based, discrete-event simulation of worldwide airlift with the ability to model detailed air to air refueling and airfield congestion (see Mason [2009] and Wu and Powell [2009]). AMP is a simulation that includes MIDAS and other legacy simulation models (Raytheon, 2013). Noel and Stratton (2012) catalog the portfolio of more than 40 models (including those referenced above) that have had some use at Air Mobility Command.

Intratheater distribution tools are less common. Barnes et al. (2004) provide approximate solutions to an intratheater VRP with a tabu search metaheuristic, but we know of no installation of their product. They claim that, at the time of publication of their paper, all other theater distribution tools were simulation-based. These include ELIST (Enhanced Logistics Intratheater Support Tool), TRANS (Transportation Resource Assessment Network Simulator), and MASS (Mobility Analysis Support System). Transway (Pohl 2006) uses a tabu search metaheuristic to help plan intertheater (and intratheater) distribution. Burks et al. (2010) also tackle intratheater distribution with tabu search. We have no evidence that either of these products were ever used by the Department of Defense.

ATEM INTEGER LINEAR PROGRAM FORMULATION

We present an integer linear program (ILP) formulation of ATEM. ATEM takes as input a list of airport pairs and the number of PAX and PALS traveling between them; each of these pairs and associated demands is known as a *demand line*, because it is represented by a single line on a demand spreadsheet used by the planners.

ATEM also takes as input a (typically very large) list of *routes*, each of which is specific to an *airplane type* and to a particular *configuration* of that airplane. A route for one airplane on one day consists of a sequence of *flight legs*, where each leg is a single nonstop flight between an origin and a destination airfield. The first leg departs from the airplane's *home airfield*, and the last leg returns to this same home airfield. Each route consists of a *feasible* sequence of flight legs, in that the associated aircraft can, in one day, make all of the flights on the route in the sequence given without violating any operational restriction or resource requirement (such as fuel and total flight time).

This route and configuration data allows ATEM to determine which demand lines can be served by each route and what capacity, in terms of PAX and PALS, it can lift on each flight in that route: any cargo from a demand line whose origin precedes its destination on that route could conceivably be carried by an aircraft flying that route, although it might require several flight legs to get there. ATEM allows such loading of cargo and carrying it through one or more intermediate airfields before unloading it at its destination (planners call this *throughput*); the number of legs per load is controlled by a single parameter, *maxloadhops*, (where the number of *hops* a particular piece of cargo makes is just the number of consecutive flight legs between its origin and destination), and setting this parameter to one prevents any throughput (i.e., every passenger or pallet can travel on at most one leg in a route).

Finally, for each airport ATEM needs to know the maximum number of landings allowed each day, and the number of aircraft of each type that are based at that airport. Given an enumeration of every admissible route for each aircraft type, configuration, and home airport, ATEM seeks an optimal assignment of a single route to each aircraft and an allocation of cargo to those routes that maximizes (prioritized) PALS and PAX conveyed. It may not always be possible to fill each flight on a route with cargo. For instance, an empty flight (a *deadhead*) may be necessary to reposition an airplane, or to bring it back home at the end of its route.

Indices [$\sim$cardinality]

$a \in A$	set of airfields (alias a_i,a_j) [$\sim$20]
$c \in C$	set of cargo types (passengers and cargo pallets) [$\sim$2]
$p \in P$	set of airplane types [$\sim$5]
$p \in P_{a_i}$	set of airplanes of type p based at airfield a_i
$g \in G_p$	set of configurations for airplane type p [$\sim$5]
$(a_i, a_j) \in L$	set of possible flight legs or segments (airport of embarkation (APOE), airport of debarkation (APOD) pairs) [$\sim$100]
$r \in R_{pa_i}$	set of routes for airplane type p starting at airfield a [$\leq 100,000$]
$s \in \{1, 2, \ldots, S\}$	ordinal of stop on a route (alias s',s^o) [$\sim$7]

Data

len_r	number of stops on route r
$a(r, s)$	airfield at stop number s on route r, where $1 \le s \le len_r$
$carry_{a_i a_j cr}$	amount of cargo c on leg (a_i, a_j) that can be airlifted by route r
$cp_{a_i a_j c}$	priority of cargo c on leg (a_i, a_j)
$dem_{a_i a_j c}$	demand units on leg (a_i, a_j) for cargo c
cap_{rc}	capacity on route r of cargo type c
$\overline{landing}_a$	maximum number of landings in airfield a
$planes_{pa}$	number of airplane type p starting from airfield a
$maxloadhops$	the maximum number of consecutive legs the cargo from a single demand line can travel on one route

Calculated Sets

$(s, s') \in H_r$	stop s' comes after, and within $maxloadhops$ of, stop s on route r: $1 \le s < s' \le len_r, s' - s \le maxloadhops$

Variables

$SELECT_r$	integer number of times airplane type $p(r)$ is flown on route r
$LOAD_{rss'c}$	integer cargo units airlifted by airplane type $p(r)$ flying route r from APOE airfield s to APOD airfield s' of cargo type c

ATEM-ILP Formulation

$$\text{Maximize} \sum_{r,(s,s')\in H_r,c} cp_{a(r,s)a(r,s')c} LOAD_{rss'c} \qquad (1)$$

Subject to:

$$\sum_{r \in R_{pa_i}} SELECT_r \le planes_{pa_i} \quad \forall a_i \in A, p \in P_{a_i} \qquad (2)$$

$$\sum_{\substack{r,s,s': \\ (s,s')\in H_r, \\ a(r,s)=a_i, \\ a(r,s')=a_j}} LOAD_{rss'c} \le dem_{a_i a_j c} \quad \forall (a_i, a_j) \in L, c \qquad (3)$$

$$\sum_{\substack{(s,s')\in H_r : \\ s \le s^o < s'}} LOAD_{rss'c} \le cap_{rc} SELECT_r$$

$$\forall r, 1 \le s^o < len_r, c \qquad (4)$$

$$\sum_{\substack{r,s': \\ 1 < s' \le len_r, \\ a(r,s')=a_j}} SELECT_r \le \overline{landing_{a_j}} \quad \forall a_j \in A \qquad (5)$$

The objective function (1) calculates the priority-weighted value of all cargo conveyed on all routes. For each airfield and each airplane type based there, constraint (2) limits the number of routes selected to the number of airplanes available. For each demand line and cargo type, constraint (3) prevents airplanes from lifting more that the demand available and accounts for any extra lift capacity available. For each route, and each stop on that route that is not the last stop, and each cargo type, constraint (4) limits loading on the flight departing that stop by the airplane capacity for each cargo type, for the configuration used on that route. For each airfield, constraint (5) limits total daily landings by all routes selected; note that each route may land at an airfield more than once, and may carry portions of some demand line on two or more legs.

In the special case where $maxloadhops = 1$, the capacity available on each flight leg on a route is just the capacity of the aircraft assigned to the route, because the aircraft is completely emptied at each stop on the route. We can simplify the model and eliminate many constraints and all of the LOAD variables by defining a new set of variables, called EXTRA, that measure the unused capacity on each leg of each route selected. The ''Solving ATEM'' section of this paper more fully discusses the benefits of this simplification.

New Variables

$EXTRA_{a_i a_j c}$ unused capacity of selected routes for cargo c, on leg (a_i, a_j)
With these variables accounting for the overall loading of each leg on the route we can remove the LOAD variables and replace constraints (3) and (4) with:

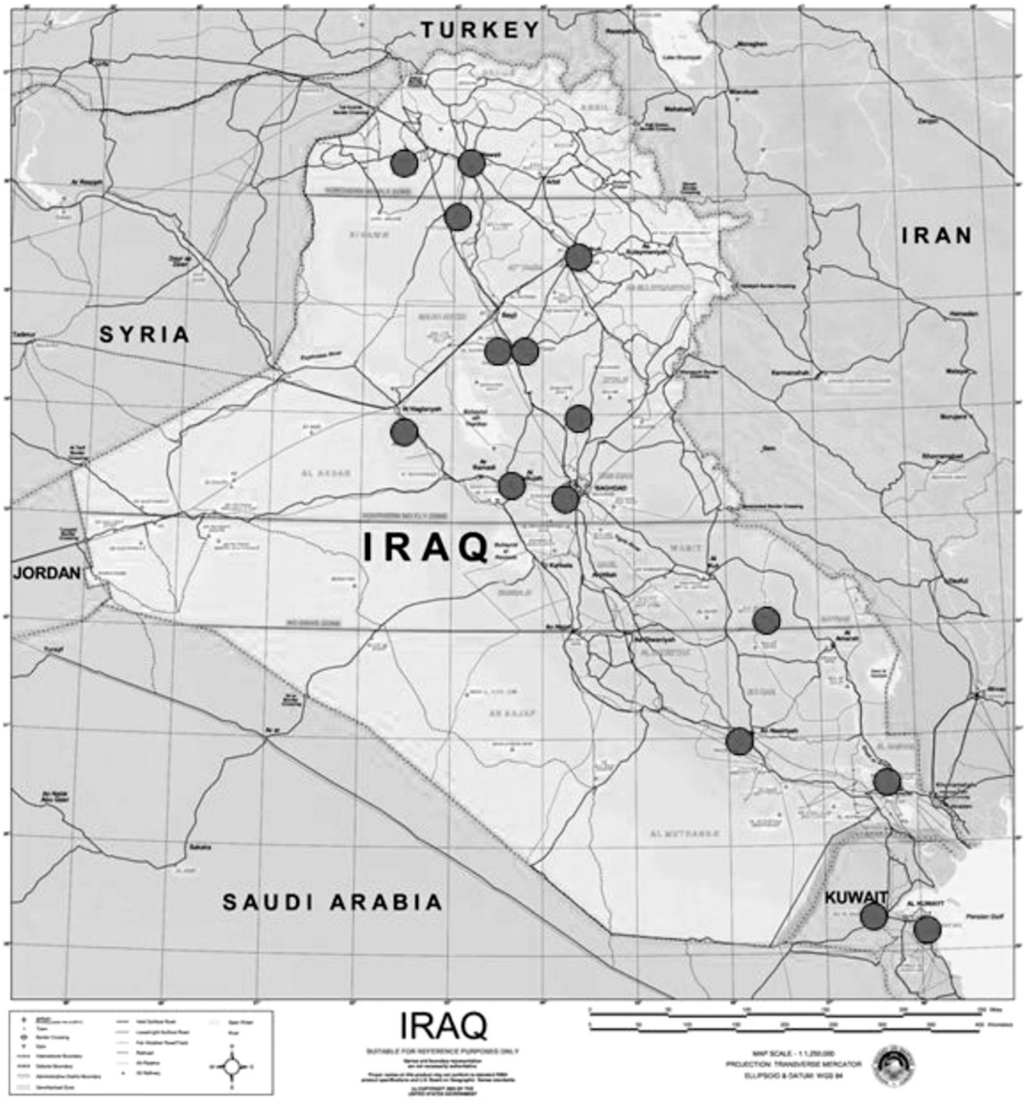


Figure 1. Map of Iraq indicating a sample of airfield locations by dots. Al Udeid (located 350 nautical miles to the southeast) in Qatar, and Incirlik (located 325 nautical miles to the northwest) in Turkey, are not shown. (After National Imaging and Mapping Agency, 2003; http://www.lib.utexas.edu/maps/middle_east_and_asia/iraq_planning_2003.jpg)

$$\sum_r carry_{a_i a_j c r} SELECT_r \le dem_{a_i a_j c} + EXTRA_{a_i a_j c} \quad \forall (a_i, a_j) \in L, c, \tag{6}$$

which explicitly accounts for unused space on each flight in a route, and replace the objective function with:

$$\text{Maximize} \sum_{(a_i,a_j)\in L,c,r} cp_{a_i a_j c} carry_{a_i a_j c r}\, SELECT_r - \sum_{(a_i,a_j)\in L,c} cp_{a_i a_j c}\, EXTRA_{a_i a_j c}, \tag{7}$$

which calculates the total carrying capacity of each route, and then subtracts any unused capacity to arrive at the total amount of cargo lifted.

ATEM also allows, for each aircraft, the selection of a different route on each day of a multiday planning horizon (e.g., one week). For simplicity of exposition, we have not included a day index, although one exists in ATEM. However, because airplanes return to their home airbase after each day of flying, the days in a plan are only linked by the cargo remaining to be lifted.

CENTCOM INTRATHEATER AIRLIFT

We consider the frequency and requirement channel route selection problems faced by the CENTCOM Combined Air Operations Center (CAOC), located at Al Udeid Air Force Base, near Doha, Qatar in 2005 and 2006.

Airfield Locations and Demand Data

We used about 20 airfields to support intratheater air distribution in Iraq, including several outside the country; Figure 1 shows locations of some of these for distribution in Iraq. Table 1 provides an excerpt from a longer sheet of demand lines. Each demand line expresses the number of PALS and PAX that need to be transported between an APOE and an APOD. A standard ‘‘463L’’ pallet is 88 inches long by 108 inches wide, and each carries a maximum of 10,000 pounds (Department of the Army, 1993). A passenger represents a single person and personal gear.

Our overall objective is to maximize the prioritized number of PAX and PALS lifted, where some PAX and PALS have different priority than others (e.g., delayed, or *frustrated*, cargo might be given a higher priority to encourage clearing out the backlog). Each cargo type and each individual demand line is assigned a priority. ATEM multiplies each demand by its cargo type priority and by its line priority, and maximizes the total resulting prioritized demand that is moved. Table 1 is an example of such demand data, including demand line priorities. Data presented in this table and the remaining tables are a sample of possible ATEM input values provided by CENTCOM planners for unclassified use. Planners can change the values of these ATEM input parameters at will as the situation dictates. Figure 2 presents a summary of one week of demand for pallets and passengers in Iraq.

Table 1. Example of demand lines, each with an origin and destination airfield, a number of PAX and PALS to carry, and a priority. There are 126 passengers and one pallet to fly from Al Salem to Alasad, with priority one. By contrast, the 44 passengers and one pallet to fly from Al Salem to Tallil have priority 100, signifying each of these PAX and PALS is 100 times more important to carry than a priority 1 demand. Priority is a simple way to highlight frustrated cargo. This demand may be for a day, a week, or some longer planning epoch.

APOE	AOPD	PAX	PALS	PRIORITY
Al Salem	Alasad	126	1	1
Al Salem	Al Taq	159	1	1
Al Salem	Balad	108	5	1
Al Salem	Baghdad	273	3	1
Al Salem	Mosul	47	4	1
Al Salem	Kirkuk	33	2	1
Al Salem	Q West	5	3	1
Al Salem	Al Sahra	51	1	1
Al Salem	Tallafar	52	2	1
Al Salem	Tallil	44	1	100
Al Salem	Al Udeid	113	8	1
Alasad	Al Salem	117	1	1
Alasad	Al Taq	17	3	1
Alasad	Balad	7	2	1
Alasad	Al Udeid	5	2	1
Al Taq	Al Salem	135	6	1
Al Taq	Kuwait	1	7	1
Al Taq	Alasad	14	17	1
Al Taq	Balad	2	2	1
Al Taq	Baghdad	2	1	1
Al Taq	Al Udeid	3	1	1
Balad	Al Salem	288	3	1
Balad	Kuwait	4	8	1
Balad	Alasad	6	2	1
Balad	Al Taq	7	5	1
Balad	Baghdad	13	7	1
Balad	Mosul	10	6	1

Airplanes and Load Configurations

The number and types of airplanes available for distribution also varies, but usually consisted when ATEM was first used of about 35 airplanes of five different types for CENTCOM intratheater airlift, including C-130E (see Figure 3), C-130J1, C-130J2, C-17 (see Figure 4), and IL-76. Each airplane type, with the exception of the IL-76, can be flown in any of a number of alternate configurations, with each configuration providing the passenger seat and pallet position capacities. Table 2 lists configurations by airplane type (with the exception of C-130J2) along with associated passenger and pallet capacities.

Airplane and aircrew endurance limit the length of a route, as shown in Table 3, which also shows a sample of possible fuel and crew constraints that limit routes. ‘‘Max #landings in

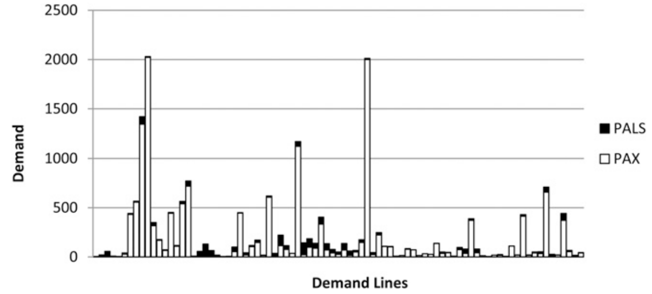


Figure 2. PALS and PAX demand for a seven-day Iraq scenario. Pallet demands are depicted in the upper, darker bar segments. There are about 20x20=400 airfield pairs, but only 85 of these have demand lines here. Demand lines vary widely in magnitude, and include some pure-passenger and some pure-pallet demands. Airfield pairs are suppressed for brevity.

box before recrew'' represents the number of landings into a combat area, where approach and departure involve evasive tactical maneuvers, and may be conducted at night without lighting. In addition to these constraints, planners also limit the maximum number of stops an airplane can make during a route. For example, a C-17, which is nominally based outside Iraq, can make no more than three landings in Iraq before it needs to return to its home base. However, it can recrew, and return to land in Iraq at most three more times before returning to its home airfield.

Airfield Capabilities

Table 4 is a sample of ground times at airfields by airplane type. Similarly, Table 5 samples airfield refuel times by airplane type. Table 6 lists airplane home airfields and the numbers of airplanes based at each. Flying times between airfields are given for each airplane type. Other input includes the number of landings permitted at each airfield per day, as well as the ability of each airfield to accommodate each airplane type.

ROUTE GENERATION

Given demand data, a fleet of airplanes with their home airfields, and a time horizon, ATEM prescribes a configuration and a route for each airplane on each day in the planning horizon that moves as much cargo as possible.

A complete flight ensemble specifies a route for each airplane on each day in the planning horizon. We have discovered, by hand, that

Figure 3. C-130E at Al Udeid. The tail ramp is positioned to transfer cargo pallets by fork lift or roll-on, roll-off k-loader vehicle. The C-130 has a single roller-rail track for manually pushing cargo pallets forward, or aft, or off. For scale, author Dell is standing under the inboard starboard engine. In the image on the right, an aircrew member folds up hammock seats in a configuration change to make room for another cargo pallet.

Figure 4. C-17 at Al Udeid. The aft k-loader vehicles are receiving rows of passenger seats pushed off (and abandoned until a later evolution here) in a configuration change to accommodate more cargo pallets. The C-17 has two, parallel roller-rail tracks for manually pushing cargo pallets forward, or aft. For scale, on the right, authors Brau and Dell appear standing on the tail ramp, working through the details of load configuration changes with the airplane's loadmaster.

conjuring these routes while synchronously determining their joint feasibility and effectiveness is the crux of solving this problem. Manual planning experience suggests thumb rules that can be a good guide here, but no manual planner can be expected to solve this complex problem every day with anything approaching optimality. There are a number of well-known ways to automate route construction. In this case, there are few enough airfields, and few enough demand lines, and each route can include at most few enough hops, that we can enumerate every feasible route, and thus not worry about missing any good one. For each airplane and its origin airfield, ATEM successively constructs every possible permutation of airfield-hops that can be visited in one duty period, ending with a return to the origin airfield. Simple rules, such as never flying two deadhead legs in a row, help limit the number of routes. Additional rules eliminate routes lacking a required refuel or crew replacement event.

We define a directed graph G = (N, A) with node set N defined by a start node s, an end node t (here, $s = t$), and an intermediate echelon of nodes for every stop on a route up to *maxroutehops*-1. For specificity, each of these intermediate nodes is named (airfield, hop number). We specify a directed arc in A connecting each node with "hop number" with every other node with "hop number+1" to which we might fly directly.

Given a flight time $t_{ij} > 0$ for each arc (i, j) in A, and a threshold value $T \equiv$MAX ROUTE HRS, the pseudocode in Figure 5 enumerates the finite number of s-t paths of length bounded by T.

For simplicity of exposition, we do not clutter this algorithm with the admissibility tests for refueling requirements along the route, the minimum and maximum route lengths, or the maximum number of flights (hops) per route (see Table 3 for examples of these data). However, these tests are easily included at the same point in the algorithm as the test for total route time. Although in general the number of paths in a single graph can be exponential in the number of nodes in the graph, for the OIF and OEF cases we have examined we can accommodate exhaustive enumeration. With data similar to that presented here, we generate on the order of a few hundred thousand feasible routes.

Filtering routes to limit the minimum number of hops, the maximum number of landings "in the box," and so forth, is a simple matter of keeping track of these numbers, suppressing the complete routes that do not meet the lower thresholds and fathoming enumeration of partial paths as soon as they exceed the upper thresholds.

Routes are generated separately for each airplane type and each origin home airfield for that airplane type. Any route longer than the given maximum time before refueling for that airplane type requires a (single) stop at a refueling

Table 2. Load configurations by airplane type with passenger and pallet capacities. A C-130E has passenger hammock seats that can be folded up or moved out of the way to make room for cargo pallets to be pushed aboard on a roller rail and can carry between zero and five cargo pallets with each additional pallet configuration reducing passenger capacity in discrete steps from 72 down to nine. Configuration changes don't take long, and some can be completed in-flight in anticipation of the next load. By contrast, the C-17 has two parallel cargo pallet roller rails, and some configuration changes require rows of passenger seats mounted on these rails to be rolled off and left on airfield, to be recovered later. These configuration changes are better assisted by special ground vehicles called k-loaders. The IL-76 is chartered to carry pallets only. (Not listed: C-130J2.)

Configuration	Airplane type	Passenger capacity	Pallet capacity
Acp2	C-130E	9	5
Acp3	C-130E	25	4
Acp4	C-130E	42	3
Acp5	C-130E	56	2
ap1	C-130E	72	0
jac2	C-130J1	0	8
Jacp2	C-130J1	18	7
Jacp3	C-130J1	34	6
Jacp4	C-130J1	50	5
Jacp5	C-130J1	60	4
Jacp6	C-130J1	74	3
Jacp7	C-130J1	94	2
jap1	C-130J1	115	1
C17c	C-17	0	18
C17cp	C-17	54	11
C17p	C-17	189	4
Ilc	IL-76	0	9

airfield between minimum time before refuel and maximum time before refuel. Similarly, for an airplane type with a crew replacement restriction (i.e., maximum number of landings in the box before crew replacement is a small integer, such as three) any route must return to its origin airfield before the number of landings at airfields "in the box" following the last landing at the origin airfield exceeds this limit. Routes violating either requirement are suppressed.

We find that selecting a feasible ensemble of routes that moves a large amount of cargo is relatively straightforward once we have enumerated all the feasible routes. This feasible ensemble could be used as an initial incumbent for a local search heuristic. However, we seek a certificate of optimality for our solutions, so we use the integer linear program in the "ATEM integer linear program formulation" section to choose an optimal set of routes (out of all feasible routes) and to establish an upper bound on how much additional cargo could have been moved.

SOLVING ATEM

The ATEM integer linear programming model has hundreds of thousands of variables and constraints for the optimization model with throughput, and tens of thousands of constraints for the reformulation without. If throughput is not allowed we can solve all of our problem instances using, e.g., GAMS/CPLEX [2012]. If we allow throughput (i.e., $maxloadhops > 1$), then the integer programs become significantly larger due to the quadratic dependence on *maxloadhops* of the number of LOAD variables. Some cases can still be solved with CPLEX, but we find that the execution times are much longer than in the case of no throughput. Schedulers do not have immediate access to commercial solvers, so we developed a companion heuristic algorithm to provide good solutions to ATEM in a very short runtime. Our basic heuristic consists of data preprocessing followed by greedy selection of routes. The preprocessing reduces demand lines that appear on routes that may have been fixed by the planner. After generating all of the routes a greedy heuristic makes a single pass through the list of aircraft (and their home cities) and for each of those and for each day in the planning horizon it chooses the route that maximizes lift of remaining cargo (without throughput) on that route, assigns that route to that aircraft on that day, and then removes that lifted cargo from those demand lines. In contrast with the ILP, the heuristic does not consider throughput. Bridges [2006] describes two additional iterative improvement steps to improve a greedy solution. He also considers generalizing relaxations including airplane configuration changes during a route, and throughput.

The results worksheet (Figure 6) serves as both an output display and an important input.

Table 3. Route limitations by airplane type. Limitations include the maximum time an airplane can operate, time between refueling, number of landings in the box, and number of times an airplane can replace aircrews. Each route for each airplane type is also limited by some Max Route Hops number of landings.

Airplane type	C-17	C-130E	C-130J1	C-130J2	IL-76
Max route time (hrs)	12.00	9.50	9.50	9.50	12.00
Max time before refuel (hrs)	12.00	5.00	5.00	5.00	12.00
Min time before refuel (hrs)	12.00	3.00	3.00	3.00	12.00
Max #landings in box before recrew	3	20	20	20	20
Max number recrews	1	0	0	0	0

The planner can use ATEM repeatedly to refine a plan. The planner can designate the first column of a favored route with ''fix'' and the number of days the route will be repeated by a specific airplane. Subsequent ATEM route revisions will honor this guidance. These distinguished routes have either been automatically generated by ATEM, or manually entered by the planner. Because ATEM considers all admissible routes, the only reason for a planner to key in a route is to violate some business rule ATEM would honor.

The routes selected worksheet in Figure 7 will indicate a planned refueling by a prefix, for example, ''F_Al_Salem.'' A planned crew-replacement event would appear ''C_Al_Salem.'' If any passenger or cargo is carried for more than one hop, this exception would appear as an intermediate line tracing the throughput in addition to the customary one-hop results shown.

Table 4. Sample of airfield ground times. Ground time varies by airfield and airplane type. In this example, a C-17 requires 45 minutes on the ground at Balad, while all other airplane types require 30 minutes there.

	Ground time (mins)				
Airfield	C-17	C-130E	C-130J1	C-130J2	IL-76
Alasad	45	60	60	60	60
Al Taq	45	30	30	30	30
Balad	45	30	30	30	30
Baghdad	45	60	60	60	60
Mosul	45	30	30	30	30
Kirkuk	45	45	45	45	45
Basrah	45	45	45	45	45
Q West	45	45	45	45	45
Al Sahra	45	30	30	30	30

EXAMPLES

We present four representative scenarios of intratheater airlift for Iraq and Afghanistan in 2005 and 2006. The first and smallest of these is a single-day requirement for logistics distribution to and within Afghanistan. Our second scenario is for a seven-day planning horizon that suggests frequency channels in Iraq. Next, we test a large, single-day distribution requirement within Iraq. Finally, we show how to parametrically remove airplanes from a channel design. The ATEM-ILP integer linear program is generated by GAMS (2012) and solved with GAMS/CPLEX 12.3 (2012) on a 3-GHz laptop, using a value of 0.01 for the relative optimality criterion (CPLEX terminates after finding a solution that is guaranteed to be within 1% of optimal).

Table 5. Sample of airfield refueling times. Refueling is concurrent with ground time. For example, if a C-17 requires refueling in Balad, its total ground time is 90 minutes. All other airplanes require 75 minutes on the ground to refuel at Balad. An ''n'' indicates that the airplane type cannot refuel at that airfield.

	Refuel time (mins)				
Airfield	C-17	C-130E	C-130J1	C-130J2	IL-76
Alasad	90	60	60	60	60
Al Taq	90	60	60	60	60
Balad	90	75	75	75	75
Baghdad	90	90	90	90	90
Mosul	n	n	n	n	n
Kirkuk	90	75	76	77	77
Basrah	n	n	n	n	n
Q West	n	n	n	n	n
Al Sahra	n	n	n	n	n

Table 6. Home airfields with associated airplanes. In this example, there are two C-130Es and four C-17s at Al Udeid, six C-130Es at Balad, 14 C-130Es at Al Salem, two IL-76s at Kuwait International, and one C-17 at Incirlik. Each airplane starts and ends each daily duty cycle at its home airfield.

Homebase	C-17	C-130E	C-130J1	C-130J2	IL-76
Al Udeid	4	2	0	0	0
Balad	0	6	0	0	0
Al Salem	0	14	0	0	0
Kuwait International	0	0	0	0	2
Incirlik	1	0	0	0	0

Afghanistan Scenario

Our Afghanistan scenario has a total demand of 404 PAX and 844 PALS on 40 demand lines that require transport among 14 airfields. Figure 8 provides an overview of the initial demand distribution among these 40 demand lines. The maximum demand line represents 152 PAX and PALS, and the minimum has just one PAX or one PAL. There are 14 airplanes available; six C-130Es at Bagram and eight C-17s at Al Udeid. Route limitations by airplane type are as shown in Table 3. For example, the maximum route time for a C-130E is 9.5 hours and the maximum route time for a C-17 is 12 hours. Enumeration yields 1,916 possible routes.

ATEM ILP solves in about three seconds, and uses all 14 airplanes. This solution transports 155 of 404 PAX and 398 of 844 PALS, airlifting 44.3% of unit demand. Our greedy heuristic takes slightly less time to solve, and does just as well in this case. Even though we do not move all the demand, ATEM-ILP certifies that this is an optimal solution: we know this is the best that can be done with this airplane fleet. Having such a certificate was important in early testing and acceptance of ATEM, especially given that some air planners evaluate a route ensemble by the fraction of available PAX seats and PAL spots filled.

Seven-Day Iraq Scenario

Our seven-day Iraq scenario has 17,704 cargo units on 85 demand lines that require movement among 17 airfields. Of this demand, 15,677 are PAX, and 2,027 are PALS. Figure 2 provides an overview of this demand. For this scenario, we have 30 airplanes available, and Table 7 lists the number of airplanes available by airplane type and home airfield. We assume that each airplane can fly each of the seven planning days. Table 3 provides route restrictions for each type of airplane. There are 272,024 possible routes to fly satisfying these restrictions.

Generating all routes takes less than a minute. The ATEM-ILP solves in about two minutes and the heuristic takes about the same amount of time. Both the ILP and HEURISTIC move almost all the demand.

Single-Day Iraq Scenario

Our single-day Iraq scenario has 505 passengers and 645 pallets on 82 demand lines connecting 17 airfields. Figure 9 provides an overview of this demand. Table 8 lists the types and home airfields of the 29 airplanes available. Airplane restrictions are the same as those in the Iraq seven-day scenario. ATEM generates 207,121 feasible routes.

Generating all routes takes less than a minute. ATEM-ILP solves in about 16 minutes and the ATEM-HEURISTIC takes about a minute. The ILP plan moves 1,059 of the required 1,150 demand units (92.1%); 445 PAX (88%) and 614 PALS (95%). The ATEM-HEURISTIC plan moves 1,044 demand units (90.8%); 456 PAX (90%) and 588 PALS (91%).

Removing Airplanes from the Seven-Day Iraq Frequency Channel Design

Table 9 shows a sequence of planning runs that successively restricts the available aircraft fleet for the frequency channels. Depending on exigent priorities, and how accurate you think the general future demand forecast is, such

Algorithm: constrained-path-enumeration

```
top = 0;
for i = 1 to n
     onPath(i) = 0;
top = top + 1;
PATH[top] = s;
T[top]=0;
onPath[s] = top;
next_arc[s] = point[s]
while top > 0
     i = PATH[top];
     while next_arc[i]<point[i+1]
          j = head[next_arc[i]];
          tij = t[next_arc[i]];
          next_arc [i] = next_arc[i]+1;
          if (onPath[j] == 0 AND T[top]+tij <= T)
               top = top + 1;
               PATH[top] = j;
               T[top]=T[top-1]+tij;
               onPath[j] = top;
               next_arc[j] = point[j];
               if j == t
                    print(PATH[]);
                    onPath[t] = 0;
                    top = top - 1;
               end
               i = PATH[top];
          end
     end
     onPath[PATH[top]] = 0;
     top = top - 1;
end
```

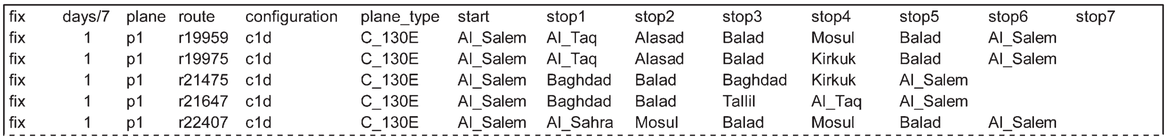
Figure 5. Algorithm enumerating all the (finite number of) *s*-*t* paths of length bounded by *T*. (See Byers and Waterman [1984] and Carlyle and Wood [2005].)

a study can help commanders decide where and when to draw down (i.e., reduce the number of) airplanes.

Table 9 also shows how quickly ATEM can provide decision support by either solving the full integer linear program or by using the greedy heuristic. We use ATEM to check on the performance of our heuristic, and to get a solution quality certificate on any feasible solution we have, whether generated automatically by ATEM or the heuristic, or manually by a planner.

WHAT ATEM DOESN'T DO, AND WHY

ATEM suggests a set of routes, and we use the term *ensemble*, rather than ''schedule,'' as a collective noun for these. We are not producing a complete, minute-by-minute enumeration of flight events. ATEM limits landings-per-day by airfield as a surrogate for details such as movement-on-ground constraints. In practice, airlift planners revised ATEM proposals as necessary to produce a detailed, timed schedule,



fix	days/7	plane	route	configuration	plane_type	start	stop1	stop2	stop3	stop4	stop5	stop6	stop7
fix	1	p1	r19959	c1d	C_130E	Al_Salem	Al_Taq	Alasad	Balad	Mosul	Balad	Al_Salem	
fix	1	p1	r19975	c1d	C_130E	Al_Salem	Al_Taq	Alasad	Balad	Kirkuk	Balad	Al_Salem	
fix	1	p1	r21475	c1d	C_130E	Al_Salem	Baghdad	Balad	Baghdad	Kirkuk	Al_Salem		
fix	1	p1	r21647	c1d	C_130E	Al_Salem	Baghdad	Balad	Tallil	Al_Taq	Al_Salem		
fix	1	p1	r22407	c1d	C_130E	Al_Salem	Al_Sahra	Mosul	Balad	Mosul	Balad	Al_Salem	

Figure 6. Portion of the Results worksheet. The prefix "fix" tells ATEM the planner wants to preserve the route in that line. This route may have been constructed by ATEM, or may have been manually designed by the planner (and thus may violate business rules ATEM would honor). The planner has fixed the first route here, which is used just one day for the airplane with tail number p1, indexed route catalog number r19959, configuration c1d, airplane type C_130E, taking off from Al_Salem and making hops as shown until returning there.

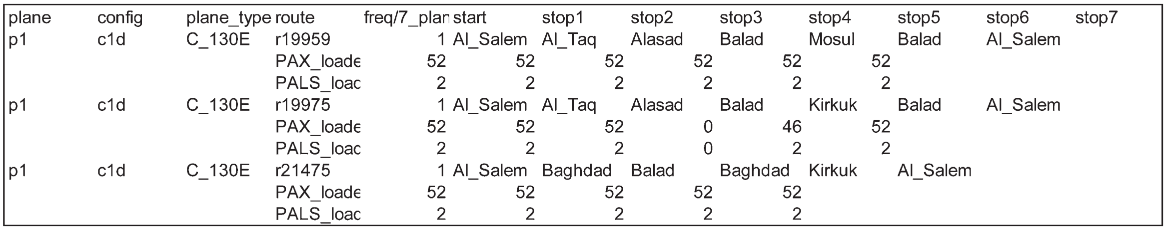
and did this better than we could, based on expert knowledge that we cannot access by computer.

ATEM does not discriminate below pallet-level detail. Although current, official planning doctrine dictates we consider the actual contents of each pallet (in US military vernacular, this is Time-Phased Force Deployment Data level IV detail), we could not do this, because such detail was simply not available. We assume safely loaded air pallets, have witnessed careful assembly of such pallets, but have also seen the final arbiter, an airplane's loadmaster, reject pallets. "In-transit visibility" is a noble goal we admire as much as anyone, but, lacking such detail, we prefer to suggest good cargo airlift plans for the demand we can see, rather than require detail that is not available.

ATEM does not change configurations during a route, even though our airplanes do this. We adopt this conservative assumption because configuration changes require time, aircrew effort, and sometimes also require support from ground crews and equipment, and storage of, for instance, passenger seats. Some configuration changes are influenced, or even precluded, by the current aircraft load. We know how to accommodate all this, but the result might be a little too clever, and the planner might be puzzled by the mysterious route time lost here.

Passengers board with bag pallets holding their personal gear. Depending on the type of passenger and the mission, the per-passenger volume of personal gear varies. ATEM cannot see this variation, and does not discriminate between bag pallets and cargo pallets. Planners adjusted configuration capacity as necessary to accommodate this complication.

We only plan direct deliveries. We do not suggest relay conveyance, where some cargo is picked up, left at some intermediate airfield, and thence conveyed by some other airplane to a subsequent destination. Planners can do this by adjusting demands to draw intermediate shipment. In practice, when an airplane is about to depart with an empty seat or cargo pallet position, airfield ground personnel will seize this opportunity to relay passengers or pallets. Many



plane	config	plane_type	route	freq/7_plan	start	stop1	stop2	stop3	stop4	stop5	stop6	stop7
p1	c1d	C_130E	r19959	1	Al_Salem	Al_Taq	Alasad	Balad	Mosul	Balad	Al_Salem	
			PAX_loade	52	52	52	52	52	52			
			PALS_loac	2	2	2	2	2	2			
p1	c1d	C_130E	r19975	1	Al_Salem	Al_Taq	Alasad	Balad	Kirkuk	Balad	Al_Salem	
			PAX_loade	52	52	52	0	46	52			
			PALS_loac	2	2	2	0	2	2			
p1	c1d	C_130E	r21475	1	Al_Salem	Baghdad	Balad	Baghdad	Kirkuk	Al_Salem		
			PAX_loade	52	52	52	52	52				
			PALS_loac	2	2	2	2	2				

Figure 7. Portion of the Routes_Selected worksheet. This shows more detail than the Results worksheet, including the planned numbers of PAX and PALS carried on each leg. Throughput (multihop deliveries) would be distinguished from single-hop deliveries, any fueling event would be indicated by an "F," and any crew-replacement event by a "C." There is no such event here. All planned legs shown here are completely full, except for a deadhead hop on route r19975 repositioning airplane p1 from Balad to Kirkuk, followed by another leg returning to Balad with 46 of 52 passenger seats occupied.

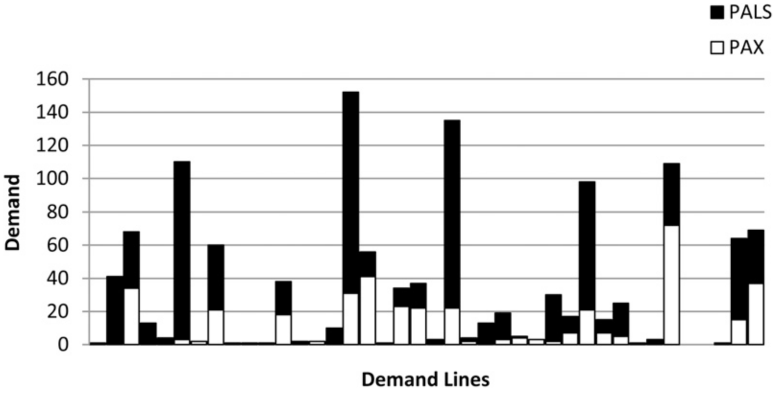


Figure 8. Demand for Afghanistan test case broken down by pallets (PALS) and passengers (PAX). For brevity, individual airfield pairs are not labeled on the horizontal axis.

routes resemble hub-and-spoke operations, and relaying to a hub is a good tactic.

CONCLUSION

In early February 2006, Brown and Dell traveled to Kuwait to deliver a prototype planner, and to iron out first-hand any details we might have overlooked concerning demands or signifying their importance. The trip to theater confirmed key features that planners needed, and isolated those of less importance. It also confirmed that no other tool was being used by the CAOC planners to help solve this difficult problem. CAOC planners were aware of a few software packages that advertised the ability to help with this planning, but the planners were not satisfied with the usability of these tools or their effectiveness.

During late February and early March, daily email exchanges provided ATEM updates and modeling support. ATEM was used extensively by CAOC planners to help answer a number of questions about fleet mix and size, and to verify the channel routes. ATEM was particularly helpful when used to justify stationing more airplanes in Afghanistan.

Table 7. Number of each type of airplane available at each home airfield for the seven-day Iraq scenario. We assume each airplane can fly every day.

Aircraft	Homebase	One day available	Seven days available
C-17	Al Udeid	4	28
C-17	Incirlik	1	7
C-130E	Balad	6	42
C-130E	Al Salem	16	112
C-130E	Al Udeid	1	7
IL-76	Kuwait	2	14

In late March and April, ATEM was used to develop the ‘‘star’’ routes of a hub-and-spoke distribution system and incorporated ATEM into daily scheduling. CAOC planners were able to fix the channel and star routes, optimize demand carried by these routes and then optimize assignment of the remaining demand to the remaining airplanes. Cargo was consistently moved within the 72-hour hold-time standard while leaving airplanes on the ground. This allowed much-needed crew rest and additional maintenance time. Prior to this, air planners rarely left operational airplanes on the ground.

Airlift operations became so efficient that CENTCOM reduced the C-130 fleet by 10 without increasing the number of other airplanes, while at once increasing the amount of cargo moved. As a telltale of this change, the US Army’s 3rd Corps Support Command at Camp Anaconda, 50 miles north of Baghdad, moved 6,500 pallets by air in October 2005. By the summer of 2006, this command moved nearly 16,000 pallets per month by air (Santana 2006).

By May 2006, we had developed a fast, purpose-built heuristic to solve ATEM models quickly (but approximately), permitting ATEM to be installed directly on machines connected with the Secret Internet Protocol Router network (SIPRnet). Comparisons such as those shown in

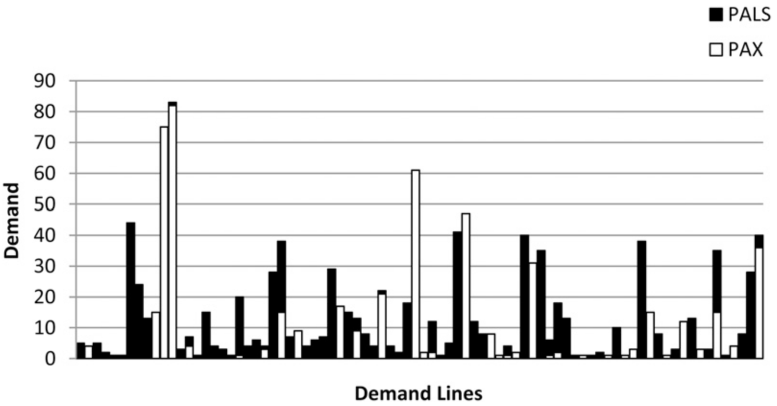


Figure 9. Demand broken down by PALS and PAX for the single-day Iraq test scenario. Demand line airfield pairs are intentionally omitted.

this paper between our heuristic and the exact mathematical solutions have reassured us that the heuristic quickly and reliably delivers high-quality route ensembles, but we maintained SIPRnet reach-back to true optimization at Naval Postgraduate School should any doubt arise.

In June, we issued a technical report (Brown et al. 2006) with planner guidance.

In November 2006, ATEM was conveyed to USTRANSCOM, Air Mobility Command. We have also distributed copies to other military agencies and civilian universities. In 2007, DeGrange (2007) used ATEM for CENTCOM CDDOC to justify withdrawing six more C-130s from theater with no reduction in service levels. As CAOC planners rotated every four months, we soon lost visibility of ATEM's use within the CAOC but ATEM has seen continued use in Air Mobility Command. One of the highlights includes its use in 2009 to help determine the proper mix of CH-47s and C-130s in both Iraq and Afghanistan with recommendations provided to the Chairman of the Joint Chief of Staff and fully implemented. Most recently, ATEM was used for the congressionally mandated Mobility Capabilities Assessment for the year 2018 (MCA-18). Air Mobility Command also plans to use ATEM to assist with the congressionally mandated Mobility Requirements and Capability Study that will commence in February 2013 (Anderson, 2013).

Wray (2009), working with the authors, created the Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT), an EXCEL-based, computer system with fast heuristic solver to schedule helicopter operations, especially those in Afghanistan. MASHPAT includes several helicopter-specific details ATEM lacks, such as: load templates by helicopter type to carry combinations of own fuel, passengers, bags, internally loaded tri-wall pallets, and external loads; restrictions to carry all passengers in a complete unit; ground and airborne fuel consumption rates; density altitude; requirements to conduct certain operations with multiple helicopters; day and night operational restrictions; and weather. Wray redeployed to Iraq and to Afghanistan and used MASHPAT in theater, and MASHPAT has been delivered to and used by Air Mobility Command.

Breitbach (2012) has recently developed custom demand data processing subroutines and used ATEM as part of his thesis to plan global air transport policies in Afghanistan with both intertheater and intratheater legs.

Table 8. Number of each type of airplane available at each home airfield for the single-day Iraq scenario.

Aircraft	Homebase	Aircraft available
C-17	Al Udeid	4
C-17	Incirlik	1
C-130E	Balad	6
C-130E	Al Salem	14
C-130E	Al Udeid	2
IL-76	Kuwait	2

Table 9. Removing airplanes from the seven-day Iraqi frequency channel design. Starting with the airplane fleet shown in Table 8, top-down, each row represents an increasingly restricted airplane fleet. The C-17 at Incirlik and the two IL-76s at Kuwait remain in service throughout all these restrictions. For instance, run 7 has no C-130E at Al Salem, only one remaining C-130E and one C-17 at Al Udeid, but all six C-130Es at Balad. From 212,816 routes by airplane-type and home base, ATEM-HEURISTIC finds a route ensemble that lifts 85.5% of demand, ATEM-ILP lifts 89.7%, contributes an upper bound of 90.9% for any airlift ensemble that may yet be found, but requires 90 minutes to do this. (An asterisk indicates the solver reached a preset 90 minute limit used for runs in this table.)

	Al Salem	Al Udeid		Balad					
Run	C-130E	C-130E	C-17	C-130E	Routes	Heu %	ILP %	ILP bnd	Solve mins
All	16	1	4	6	272,024	100.0%	99.4%	100.0%	2.6
1	3	1	4	6	272,024	100.0%	100.0%	100.0%	4.1
2	2	1	4	6	272,024	100.0%	99.7%	100.0%	5.1
3	1	1	4	6	272,024	100.0%	99.2%	100.0%	79.0
4	0	1	4	6	212,816	100.0%	99.4%	100.0%	40.0
5		1	3	6	212,816	99.5%	99.2%	100.0%	47.9
6		1	2	6	212,816	96.7%	98.1%	100.0%	90*
7		1	1	6	212,816	85.5%	89.7%	90.9%	90*
8		1	0	6	178,010	67.0%	71.3%	72.0%	15.5
9		0		6	176,846	63.1%	66.9%	67.6%	4.0
10				5	176,846	59.7%	63.4%	64.1%	3.3
11				4	176,846	56.3%	59.6%	60.2%	13.7
12				3	176,846	52.7%	55.4%	56.0%	10.5
13				2	176,846	48.3%	50.8%	51.3%	2.7
14				1	176,846	43.3%	44.8%	45.3%	0.7
15				0	18,344	35.7%	37.0%	37.2%	0.2

ATEM has saved taxpayers considerable money. One CDDOC study determined that the daily operating cost of a deployed C-130 is $250,000, so 10 airplanes amounts to $2.5 million per day.

However, the most important impact of ATEM has been its contribution to convoy mitigation and the reduction of personnel casualties. (See, e.g., recounting of these reports by Brigadier general M.J. Saunders 2006.)

ACKNOWLEDGEMENTS

A previous version of this paper was presented to the 2007 Military Operations Research Society annual meeting, and was awarded the Barchi Prize. The Navy awarded each of the civilian authors with the Superior Civilian Service Medal for this work. John Brau was awarded the Joint Service Commendation Medal for his tour of duty at CDDOC. We withheld this paper from general circulation until after withdrawal of our combat forces from Iraq in December 2011.

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