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THESIS

OPTIMIZING HELICOPTER ASSAULT SUPPORT IN A HIGH DEMAND ENVIRONMENT

by

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June 2009

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Helicopter assault support planning for a large Marine Corps operation is complex and time consuming. Hundreds of constraints and millions of potential solutions exist. The Marine Corps currently does this planning manually. The warfighters' logistical needs require a quick solution, and therefore speed is usually more important than a tight guarantee of optimality. The Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT) assists planners by leveraging automation speed and accuracy to consider millions of solutions and suggest a desirable plan. It demonstrates an ability to produce plans more quickly that are more efficient. MASHPAT runs on Navy Marine Corps (NMCI) computers in theater and is available now at no cost.

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OPTIMIZING HELICOPTER ASSAULT SUPPORT IN A HIGH DEMAND ENVIRONMENT

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ABSTRACT

Helicopter assault support planning for a large Marine Corps operation is complex and time consuming. Hundreds of constraints and millions of potential solutions exist. The Marine Corps currently does this planning manually. The warfighters' logistical needs require a quick solution, and therefore speed is usually more important than a tight guarantee of optimality. The Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT) assists planners by leveraging automation speed and accuracy to consider millions of solutions and suggest a desirable plan. It demonstrates an ability to produce plans more quickly that are more efficient. MASHPAT runs on Navy Marine Corps (NMCI) computers in theater and is available now at no cost.

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EXECUTIVE SUMMARY

The Marine Corps uses helicopters with diverse capabilities to provide assault support to sustained land-based combat operations over large regions. Maximizing the utility of these helicopters is a complex problem. Insufficient transportation infrastructure and enemy attacks along the roads in the current areas of operation place added burden on aviation logistical support. There are typically 50-125 requests for Marine air support servicing over 25 forward operating bases each day in support of operations in Iraq. Requests vary in priority, cargo type and weight. Pick-up and drop-off locations vary by request and are located throughout the area of operations.

Additional scheduling complexity derives from constraints that vary by helicopter. Each aircraft type has a unique fuel capacity and burn rate that determines feasible routes. Helicopters may only fly to bases where the air threat is manageable and the landing zone can accommodate the helicopter. Additionally, each helicopter type has a specific cubic capacity and weight limit. The weight limitation requires a tradeoff between fuel and cargo weight. Some helicopters must fly in formation of two or more in company. Flight through certain zones may be restricted by light level.

Each day, planners assigned to the headquarters of the Aviation Combat Element manually create a plan for approximately 15 helicopters to fly as many requests as possible (on the order of 75 per day) without violating operating constraints specified for each helicopter. Complexity and time limitations make it nearly impossible for planners to create an optimal solution, and they wouldn't know when they had one. New requests for logistical support continually arrive. When weather or maintenance issues delay flights, it is even more difficult to quickly reschedule requests.

To enable one person to manually plan a flight schedule each day, real-life constraints are simplified. Rather than considering fuel-cargo tradeoffs, a single cargo weight limit is listed for each helicopter type. Additionally, planners typically use a standard set of routes instead of exploring every permutation. Generic limitations are

placed on cargo combinations to prevent violation of cubic capacity. These necessary simplifications of operating constraints make manual scheduling possible but result in sub-optimal solutions.

The Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT) assists planners to fully explore planning options. The Excel-based program uses the speed and accuracy of a computer to consider millions of planning options and present the best solution found. The program creates all allowable routes for each helicopter type based on time and landing zone limitations. MASHPAT ranks each route by its ability to carry assault support requests in concert with all other candidate routes chosen for other helicopters, and displays the selection of routes and assigned requests found.

The program uses a modified greedy heuristic followed by a local search to identify desirable routes. This program allows planners to require certain routes with minimum requests specified for each leg. Thus, a planner can help MASHPAT find a better solution or add constraints that were not required in the original formulation, or perhaps are not written down. Planner experience and judgment are valuable and MASHPAT takes advantage of this.

Preliminary results show that with little or no planner interaction, MASHPAT generally identifies a plan that is better than a manually created plan, and it completes this plan in significantly less time than a manual planner can. During a ten-day test period on real-world operations, MASHPAT suggested significantly improved plans when compared to the manually-created ones based on the number of flight hours, number of helicopters used, and assault support requests (ASRs) left unscheduled.

MASHPAT allows planners to reduce the planning cycle from several hours to less than an hour. This speed-up is particularly helpful for rapid re-planning after flight cancellations. MASHPAT runs on Navy Marine Corps (NMCI) computers in theater, and is available now at no cost.

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I. MARINE CORPS LOGISTICS DEPENDS ON HELICOPTER ASSAULT SUPPORT

A. ASSAULT SUPPORT IS INTEGRAL TO THE MARINE CORPS MISSION

1. Marine Corps Capabilities Enable Varied Missions

The U. S. Marine Corps' mission is to conduct fast-paced operations that maintain the initiative in a dispersed area of operations (AO). Marines are placed into expeditionary units tailored in size and capability for specific missions throughout the world, ranging from humanitarian assistance to full-scale war. Deploying Marines and cargo to forward operating bases (FOBs) throughout an AO requires that each of these units be equipped with assault support helicopters, and requires the capability to rapidly and efficiently schedule its helicopters to perform resupply and troop movement.

2. Helicopter Assault Support Provides Movement of Cargo Over Any Terrain

The Marine Corps defines assault support as the actions required to airlift personnel, supplies and equipment. This function enables Marines to maintain a rapid pace of operations and focus their combat power. The Marine Corps currently uses the MV-22 Osprey, the CH-53E Super Stallion, the CH-53D Sea Stallion, and the CH-46E Sea Knight to fulfill helicopter assault support needs. Other military branches may also provide Marine forces with helicopter support. Each helicopter has unique limitations on its load capability that are generally classified by weight, dimensions and passenger seating.

Whether Marines are supporting humanitarian assistance, peacekeeping, or combat operations, typically several FOBs are established throughout the AO and must be logistically linked. Due to the dispersion of these FOBs and the potential for poor road conditions in the AO, helicopters are often used to maintain FOB supplies and

perform timely movement of personnel. In a large operation, the number of assault support requests (ASRs), i.e., shipments, can easily number over 100 per day.

B. SCHEDULING ASSAULT SUPPORT HELICOPTERS IS COMPLEX

1. ASRs Track Helicopter Movement Requests

To handle the information necessary to fulfill airlift requirements, the Marine Corps uses a standardized ASR form. The requesting unit fills in the form with requested pick-up zone, drop-off zone, date of move, number of passengers, weight of cargo, and dimensions of cargo. The ASR also has a block for additional comments that do not fit into one these categories.

a. *Helicopter Requests Adhere to a Strict Timeline*

An ASR should be submitted at least three days prior to the requested move date. This request is forwarded via the chain of command to the senior command unit (e.g. Marine Expeditionary Force or Marine Expeditionary Unit) for approval. After requests are compiled and prioritized, they are forwarded to the senior Marine aviation command (e.g. Marine Aviation Wing or Marine Aviation Group) for planning. The dimensions and weight for each request are checked for feasibility to ensure the ASR can be completed using the helicopters available.

b. ASR Changes Occur Throughout the Planning Cycle

The ASR list changes from the close of the 72-hour window until the time of execution. These changes can be due to ASRs being cancelled, unforeseen needs developing after the 72-hour window has closed, aircraft maintenance problems, and weather delays. Due to the length of time required to create a plan, it is not feasible to start over each time a new request arrives. Planners usually try to add new ASRs to the existing plan without changing aircraft routing. These additions are made by taking advantage of free space on aircraft that are already scheduled.

2. Numerous Planning Constraints Increase Complexity

Each helicopter has unique limitations based on its characteristics, the operating environment, and the theater regulations set for a particular operation. To track these distinctive and changing limitations imposed on the various helicopter types, a set of business rules is maintained for an operation. First, commanders throughout the chain of command for the operation develop regulations. These rules are unique for each theater and can include flight time limitations, crew rest requirements, and no-fly areas. Additionally, business rules may assign specific limitations for various threat level areas. These rules can include limits on number of passengers on board a single helicopter in various threat areas and aircraft survivability equipment required for a helicopter to operate in a threat area in different light conditions. Light conditions are broken down into day, high light level night, and low light level night. Finally, each squadron adds the operating limitations for its helicopter type in that specific AO. These limitations include maximum take-off and landing weights at each FOB, and maximum cargo and passenger combinations the helicopter can carry. The business rules can change throughout an operation due to changes in airlift needs, threat levels, and environmental conditions.

3. Manually Creating a Plan: Process and Timeline

A team of Marines from the aviation operations department is assigned to manually schedule the ASRs using the available helicopters as efficiently as possible. The planners ensure that the proposed plan complies with all business rules. To do this, they estimate how many passengers, and how much cargo, can fit on the aircraft for each leg and what fuel states are necessary to complete the plan. Fuel may not be available at every FOB. Because passengers and cargo often ride through several legs of a flight and fuel levels can be adjusted to meet weight limitations, tracking all of the limitations for each leg of a flight can be complicated. Upon completion of a proposed plan by the senior aviation unit, representatives from the tasked squadrons then check the proposed operations. They ensure the expected takeoff and land times are realistic and the dimensions and weight of the cargo are within limitations for their helicopter types.

C. CURRENT PROCEDURES CREATE INEFFICIENT PLANS

1. Simplifying Constraints Creates Unnecessary Restrictions

Planning complexity and time limitations require planners to restrict and simplify real-world constraints when manually scheduling aircraft. While planners do their best to make the plan as efficient as possible, the focus is on completing as many of the tasks as possible in the time requested to give the warfighter every achievable advantage in the operation. For instance, rather than considering fuel-cargo tradeoffs, a single cargo weight limit is listed for each helicopter type. Additionally, a standard set of routes, perhaps repeated day-by-day, is generally used instead of exploring every permutation. Generic limitations are placed on cargo combinations to prevent violation of cubic capacity. These restrictions on the constraints make manual scheduling possible but result in sub-optimal solutions.

2. Sub-optimal Plans May Have Tactical Consequences

The inefficiencies in scheduling may achieve a level of service that could have been achieved with fewer flight hours. These inefficiencies result in an unnecessary exposure to enemy threats as well as increasing the potential for an aviation mishap. Furthermore, if there are not enough helicopters to fulfill all of the ASRs, some requests may go unfilled. More efficient planning could schedule more of the ASRs with the same number of helicopters. This improvement could have significant effects on the operation.

3. Sub-optimal Plans Strain Aviation Resources

Planning inefficiencies also lead to additional costs and potential degradation to future mission capability. Additional flight hours result in increased maintenance costs and fuel consumption. The increased fuel consumption can strain the overland logistic network providing that fuel, potentially lowering the support available for other units in the AO. Moreover, the increased number of aircraft in the sky can strain the air traffic control system and require additional assets in the AO to support safe air operations. The

added flight hours may require deployment of more helicopters to the theater than needed to complete the mission. This additional deployment could have effects on other Marine Corps operations or training and readiness levels. Due to delays in the acquisition of the MV-22 and CH-53K, a higher-than-expected utilization of the current assault support helicopters could result in degraded capabilities in the near future.

4. Constant Changes in ASRs Increase Planning Complexity

When weather or maintenance problems delay flights, meeting planning deadlines is further complicated. ASRs that are incomplete due to flight cancellations are rolled (moved from one tasking day to a subsequent day). The impact of these delays is often unknown until a few hours before the next planning day begins. The difficulty in changing flight plans and notifying passengers of changes requires that a flight schedule, once published, remain as persistent as possible. At the same time, planners must quickly find room for as many rolled requests as possible to complete coordination.

D. AUTOMATING PLANNING IMPROVES EFFICIENCY

The Marine Assault Support Helicopter Planning Assistance Tool (MASHPAT) is a simple-to-use Excel-based application developed to help produce better plans more quickly. While fully automated planning is desirable, decision rules for numerous unique situations would be needed. The MASHPAT algorithm uses a heuristic that can quickly create a helicopter flight plan that assigns ASRs in an efficient way while complying with all constraints. By accommodating expression of business rules as data with amenable structure, the MASHPAT model can solve most planning scenarios efficiently.

E. MASHPAT AUTOMATES PLANNING

1. Planners Provide Input Data

The information input by the planner is broken down into four basic categories: aircraft characteristics (static, seldom needing revision), operation limitations (static, seldom needing revision), FOB information (dynamic, but not changing daily) and ASR

information (changing daily, if not hourly). Initial application in a particular operation requires a lot of data entry to capture the information in the business rules. Once scenario setup is complete for an operation, modifications for FOB information and aircraft characteristics require minimal or no attention for day-to-day operation.

a. Operation Data Contains Information Specific to a Campaign

The operation data expresses information unique to a specific campaign. This section may contain data on established flight windows, maximum flight times and the minimum number of aircraft that must fly together in a flight. This information may change due to evolving enemy or mission requirements.

b. FOB Data Contains Information Specific to Each Landing Zone

FOB information expresses the characteristics that limit operations at each particular landing zone. Because every helicopter in a theater may not be compatible with each FOB, a list of compatible aircraft is included in the FOB description. Additionally, fueling capability of the FOB must be annotated. Because the time to load and unload an aircraft varies by FOB due to differences in staffing and equipment at the landing zone, the loading times for various numbers of passengers and amounts of cargo is estimated here as well.

c. Aircraft Data Contains Information Specific to Each Helicopter Model

The aircraft information expresses each helicopter's unique capabilities and limitations. A matrix with travel times between each FOB is created for each aircraft type. A separate matrix shows maximum take-off and landing weights for day and night operations for each helicopter at each FOB. Additionally, fuel capacity, maximum fuel burn rate, minimum fuel burn rate and maximum cargo capability are tracked.

d. Cargo Data Contains Information About Categories of Cargo

In addition to passengers and external loads, Marine Corps cargo can be broken down into three basic internal load categories: seabags, triwalls, and pallets. A seabag is a cylinder with length three feet and radius one foot (see Figure 1). A triwall is a cardboard box with dimensions 48" X 40" X 26" commonly used by Marine Corps logisticians for gear transported by helicopter (see Figure 2). A pallet is 48" X 48" X 48" and is used for gear too large for a triwall (see Figure 3). Gear larger than a pallet requiring helicopter transport is slung below the helicopter by an external pendant.

Figure 1. The primary means of moving personal gear is the seabag such as those shown here.

Figure 2. A triwall (depicted above) allows helicopters to move medium size cargo without eliminating passenger seating.

Figure 3. Pallets are used for cargo too large or heavy for a triwall. Pallets require a forklift for loading and eliminate adjacent passenger seating on helicopters.

2. Planners Customize Rules

MASHPAT is designed to require very little planner input and interaction unless more control is desired. Upon completion of initial theater setup, most daily updates only require changes to the ASR information and helicopter availability. With this information entered, the planner simply hits one button. If the planner wishes to place additional constraints on the MASHPAT model, he may require certain routes be flown and specify ASRs that must fly on a particular helicopter.

3. MASHPAT Automatically Creates an Easy-to-Read Plan

MASHPAT provides three levels of detail to display each plan. An overview displays each helicopter assigned, the route assigned to it and the ASRs carried on each leg of that route. A detailed display adds information on the fuel plan as well as detailed information on the cargo load to prove feasibility. A summary page displays metrics such as helicopter usage and percentage of ASRs completed for the planner to evaluate.

4. MASHPAT Algorithm Does Not Guarantee an Optimal Solution

The MASHPAT algorithm does not guarantee an optimal plan but often outperforms a manually created plan by reducing flight hours, aircraft needed and/or number of rolled ASRs. MASHPAT offers a priority for each of these metrics, and the planner can adjust these to change emphasis.

a. Constraints Are Simplified to Improve Run Time

While MASHPAT is able to more fully explore the feasible region of this optimization problem than a manual planner, some additional restrictions are placed on the program to achieve better response time. Instead of considering every possible refueling plan, the number of fuel stops is minimized to reduce route time and then the fuel taken is minimized to maximize room for cargo. Rather than considering every feasible choice for assigning ASRs to selected routes, a greedy heuristic with local search is used to identify a desirable load plan.

To avoid a time-consuming cargo capacity problem, cargo sizes are classified in terms of the basic cargo categories and matched with helicopter limitations in the same categories. Instead of considering the dimensions of each helicopter and each requested piece of cargo, each squadron sets cubic capacities for the type of helicopter it operates in terms of the number of seabags, triwalls, and pallets. To compensate for these variables, the MASHPAT model invites specification of a set of standard cargo-loading templates for each helicopter type to describe alternative they can feasibly load. This is a generalization of the manual method using one capacity number, but a restriction of reality with more alternatives.

II. MATHEMATICAL FORMULATION ACCURATELY SUMMARIZES PLANNING CONSTRAINTS

A. INTEGER LINEAR PROGRAM FORMULATION OF THE PLANNING PROBLEM

The helicopter planning problem presented in chapter one can be formulated and solved as an Integer Linear Program (ILP). In this formulation, a flight consists of one or more helicopters flying from an origin to a destination landing zone. A duty period is a 12-hour daylight epoch for flight operations, or an equivalent night epoch. A flight route is a sequence of landing zones.

Indices [~cardinality]

$h \in H$	name for each available helicopter (tail number, or callsign)
$m \in M$	models of helicopters (e.g., CH53D)
$m(h)$	model of helicopter h
$h \in H_m$	model m helicopters
$b \in B$	fuel burn rate category (flying or ground turn)
$a \in A$	landing zones (LZs) $[\sim 20]$
$a \in A_f \subseteq A$	landing zones with fuel available
$m(r)$	helicopter model for route r
$r \in R_m$	set of reasonable routes for helicopter model m
$r \in R_h$	set of flyable routes for helicopter h
$\ell \in L$	light condition (e.g., day, night)
$\ell(h)$	light condition for helicopter h
$\ell(r)$	light condition for route r

$s, s'' \in S_r$	lift-offs on route *r* (i.e., *s* =1,2,…,*S*-1, an ordinal set)
$a(s \in S_r)$	landing zone (LZ) in position *s* of route *r*
$as(h), ae(h)$	starting, ending airfields of helicopter *h*
$h \in H_r$	helicopters capable of completing route *r* (i.e., those with sufficient hours available and with $\ell(h) = \ell(r)$ and with $as(h) = a(s = 1)$ and $ae(h) = a(s = \mid S_r \mid)$).
$s' \in S'_r$	landings on route *r* (i.e., *s* =2,…,*S*) (A flight, or hop, consists of an ordered pair $\{s, s'\}$ connecting LZs $\{a(s), a(s')\}$).
$d \in D$	demand request $[\sim 100]$
$o(d) \in A$	origin LZ for request *d*
$u(d) \in A$	destination LZ for request *d*
$d \in D_r$	demand request that can be satisfied by a leg of route *r*
$h \in H_d$	helicopters capable of (perhaps partially) lifting demand request *r*
$c \in C$	cargo categories (e.g., pax, seabags, pax-with-seabag, triwalls, pallets, and externals)
$c \in C_d$	cargo categories in request *d*
$t \in T_m$	cargo loading templates for helicopter model *m* $[\sim 50]$
$c \in C_t$	cargo categories appearing in load template *t*

Data

$demand_{d,c}$	units of cargo category *c* in demand line *d*
pri_dem_d	priority of demand line *d* (multiplicative weight)
can_split_d	binary: 1 if demand *d* can be split between flights

pri_cargo_c priority of cargo type *c* (multiplicative weight)

$unit\_weight_c$ weight per unit of cargo category *c*

$max\_units_{t,m,c}$ maximum units of cargo category *c* for cargo loading helicopter model *m* with template *t* (e.g. t34 consists of a maximum of 12 pax, 20 seabags, 2 triwalls, and 2 pallets)

$burn\_rate_{m,b}$ fuel burn rate in pounds/hour for helicopter model *m* at burn rate *b*

$fuel\_top_m$ maximum fuel load for helicopter model *m* in pounds

$fuel\_low_m$ minimum fuel load for helicopter model *m* in pounds

$leg\_hrs_{m,\ell,a,a'}$ time in hours for helicopter model *m* to fly in light condition ℓ from LZ *a* to LZ *a'*

$ground\_hrs_m$ ground time in hours for helicopter model *m* between legs

$fueling\_hrs_m$ hours to fuel helicopter model *m*

min_flight_m minimum number of helicopters in flight of model *m*

max_flight_m maximum number of helicopters in flight of model *m*

max_weight_m maximum weight of fuel and cargo load for helicopter model *m*

hrs_avail_h hours available for helicopter *h*

$route\_hrs_r$ hours required by route *r*

(i.e., $r \in R_h \subseteq R_{m(h)} \mid hrs\_avail_h \geq route\_hrs_r$.)

$start\_fuel_h$ start-up fuel for helicopter *h*

Decision Variables

$ROUTE_r$ binary: 1 if route *r* is selected

$SELECT_{r,h}$	binary: 1 if route *r* will be flown by helicopter *h*
$TEMPLATE_{h,s,t}$	binary: 1 if helicopter *h* loads cargo with template *t* at *s*
$ASSIGNED_{r,s,d}$	binary: 1 if demand *d* is assigned to route *r* lift-off *s*
$FUEL\_STATE_{h,s}$	fuel level in pounds of helicopter *h* in pounds at lift-off *s*
$FUEL\_STOP_{h,s}$	binary: 1 if helicopter *h* loads fuel at stop *s*
$FUELED_{h,s}$	fuel in pounds taken by helicopter *h* at stop *s*

Formulation

$$\text{MAX} \sum_{\substack{r\in R, s\in S_r \\ d\in D, c\in C_d}} pri\_dem_d \, pri\_cargo_c demand_{d,c} ASSIGNED_{r,s,d} \qquad (0)$$

Subject to:

$$SELECT_{r,h} \le ROUTE_r \qquad \forall r \in R, h \in H_r \qquad (1)$$

$$\sum_{h\in H_r} SELECT_{r,h} \ge min\_flight_{m(r)} ROUTE_r \qquad \forall r \in R$$

$$\sum_{h\in H_r} SELECT_{r,h} \le max\_flight_{m(r)} ROUTE_r \qquad \forall r \in R \qquad (2)$$

$$\sum_{r\in R_h} SELECT_{r,h} \le 1 \qquad \forall h \in H \qquad (3)$$

$$ASSIGNED_{r,s,d} \le ROUTE_r \qquad r \in R, s \in S_r, d \in D_r \qquad (4)$$

$$\sum_{r\in R, s\in S_r} ASSIGNED_{r,s,d} \le 1 \qquad \forall d \in D \qquad (5)$$

$$\sum_{t\in T_{m(h)}} TEMPLATE_{h,s,t} \le \sum_{r\in R_h} SELECT_{r,h} \qquad \forall h \in H, s \in S \qquad (6)$$

$$\sum_{r\in R, s\in S_r, d\in D} demand_{d,c} ASSIGNED_{r,s,d}$$

$$\leq \sum_{t \in T_{m(h)}} max\_units_{t,m(h),c} TEMPLATE_{h,s,t} \quad \forall h \in H, c \in C, s \in S \quad ` \qquad (7)$$

$$\sum_{r \in R, s \in S_r, c \in C} unit\_weight_c demand_{d,c} ASSIGNED_{r,s,d} + FUEL\_STATE_{h,s-1}$$

$$\leq max\_weight_{m(h)} \qquad \forall d \in D, h \in H, s \in S \backslash 1 \qquad (8)$$

$$FUEL\_STOP_{h,s} \leq \sum_{r \in R_h | s \in S_r \wedge a(s) \in A_f} SELECT_{r,h} \qquad \forall h \in H, s \in S \qquad (9)$$

$$FUELED_{h,s-1}$$

$$\leq (fuel\_top_m - fuel\_low_m) FUEL\_STOP_{h,s-1} \quad \forall h \in H, s \in S \backslash 1 \qquad (10)$$

$$FUEL\_STATE_{h,s} = FUEL\_STATE_{h,s-1}$$

$$- \sum_{r \in R_{m(h)}} leg\_hrs_{m(h),\ell(h),a(s-1),a(s)} burn\_rate_{m(h),flying} SELECT_{r,h}$$

$$- burn\_rate_{m(h),ground} ground\_hrs_{m(h)}$$

$$- [burn\_rate_{m(h),ground} fueling\_hrs_{m(h)} FUEL\_STOP_{h,s}$$

$$+ FUELED_{h,s}]_{a \in A_f} \qquad \forall h \in H, s \in S \backslash 1 \qquad (11)$$

$$FUEL\_STATE_{h,s-1}$$

$$- \sum_{r \in R_{m(h)}} leg\_hrs_{m(h),\ell(h),a(s-1),a(s)} burn\_rate_{m(h),flying} SELECT_{r,h}$$

$$\geq fuel\_low_{m(h)} \qquad \forall h \in H, s \in S \backslash 1 \qquad (12)$$

$$ROUTE_r \in \{0,1\} \qquad \forall r \in R$$

$$SELECT_{r,h} \in \{0,1\} \qquad \forall r \in R, h \in H_r$$

$$TEMPLATE_{h,s,t} \in \{0,1\} \qquad \forall h \in H, s \in S, t \in T_{m(h)}$$

$$ASSIGNED_{r,s,d} \in \{0,1\} \qquad \forall r \in R, s \in S_r, d \in D$$

$$fuel\_low_{m(h)} \le FUEL\_STATE_{h,s}$$

$$\le fuel\_top_{m(h)} \qquad \forall h \in H, s \in S$$

$$FUEL\_STATE_{h,1} \equiv start\_fuel_h$$

$$FUEL\_STOP_{h,s} \in \{0,1\} \qquad \forall h \in H, s \in S$$

$$0 \le FUELED_{h,s} \le fuel\_top_{m(h)} - fuel\_low_{m(h)} \quad \forall h \in H, s \in S \qquad (13)$$

1. MASHPAT Formulation Discussion

The ILP formulation filters out infeasible solutions and chooses the set of assignments to maximize the stated objective function. This formulation assumes that a feasible and reasonable set of flight routes is generated in advance for each helicopter model available for tasking. It also assumes that ASRs cannot be split among multiple flights. Given a large set of flight routes, this optimization model assigns available helicopters to the best set of routes. The objective function (0) evaluates the ASRs carried by a plan. The planner controls priorities associated with ASR cargo categories.

The model ensures that limited resources are not overscheduled. Each constraint (1) allows assignment of helicopters to a route only if that route has been selected. Each constraint (2) requires that if a route is selected, the number of helicopters assigned to the route stays within policy limits. Each constraint (3) allows at most one route selection per helicopter.

Demands may only be assigned to helicopters capable of performing the requested lift. Each constraint (4) allows demand requests to be assigned to a route only if that route has been selected. Each constraint (5) requires that a demand request be assigned to a single route. Each constraint (6) allows at most one load template to be selected for each assigned helicopter flight leg. Each constraint (7) limits units loaded to those allowed by the load template used.

The model finds a feasible and optimal fuel plan that honors the fuel constraints while maximizing load capacity. Each constraint (8) limits the maximum useful load

(fuel plus cargo) of each helicopter at each lift-off. Each constraint (9) permits a fuel stop only if the helicopter is flying a route with fuel available at that stop. Each constraint (10) allows fueling only if a fueling stop is signaled. Each constraint (11) accounts for the fuel state of each helicopter at each lift-off of a route, and each constraint (12) accounts for the fuel state of each helicopter at each landing of a route. Constraints (13) define decision variable domains.

This formulation does not permit "throughput" (i.e., an ASR flown over more than one leg). Generalizing to admit this is straightforward, but further clutters the exposition.

B. GAMS IMPLEMENTATION

The MASHPAT model has been implemented in the General Algebraic Modeling System (GAMS), as formulated above. Using the ILOG CPLEX solver and a desktop computer with a 3.16-gigahertz processor and 3.25 gigabytes of random access memory, the model was run on a typical size (75 ASRs and 16 helicopters) planning problem. At the completion of a 96-hour period, GAMS still showed an optimality gap over 70%. A typical size helicopter-planning problem is too complex for a commercial solver to solve optimally as an ILP.

C. HEURISTIC ALGORITHM OVERVIEW

MASHPAT employs the algorithm below to build feasible routes and assign a desirable set of routes with ASRs.

MASHPAT Algorithm

Input: Planner data on MASHPAT worksheets
Output: Route and ASR assignments

1. Generate All Feasible Routes for Each Helicopter Type, Light Condition and Starting LZ

1.1. Top = 1

1.2. If there is an LZ on the stack at position top, add it to the path at position top.

Else, badRoute = True. Goto 1.8

1.3. If the helicopter is not allowed to land at the LZ based on input from the "Can

Land?" column on the "LZs" worksheet, badRoute = True, goto step 1.8

1.4. If adding this LZ causes a maximum route time violation based on input from the "Helo Types" worksheet, badRoute = True, goto step 1.8

1.5. If adding this LZ causes a maximum hop violation based on input from the "Dashboard" worksheet, badRoute = True, goto step 1.8

1.6. If the last leg on the current path cannot carry any ASR and the last LZ on the path is not a fuel LZ (information attained from the "LZs" worksheet), badRoute = True, goto step 1.8

1.7. If the last LZ equals the first LZ, goto step 1.9, else, top = top + 1, goto step 1.2.

1.8. If badRoute = True then top = top – 1, badRoute = False. If top =1, goto step 2.1, else, goto step 1.2.

1.9. Set fuel state for each leg

1.9.1. currentLeg = 1

1.9.2. fuel(currentLeg) = startFuel (set by the planner on the "Helo Types" worksheet)

1.9.3. currentLeg = currentLeg + 1

1.9.4. if currentLeg > top, goto 1.10

1.9.5 fuel(currentLeg) = fuel(currentLeg – 1) – legFuelBurn(1)

1.9.6 if fuel(currentLeg) > minFuel (set by the planner on the "HeloTypes" worksheet), goto 1.9.3

1.9.7 if fuel(currentLeg) < minFuel, currentLeg = currentLeg – 1. If currentLeg < 1, badRoute = True. Goto 1.8

1.9.8 if canFuel (currentLeg), fuel(currentLeg) = maxFuel, goto 1.9.3. Else, goto 1.9.6

1.10. Record route. top = top + 1. Goto 1.2

2. Select Desirable Routes and ASR Loads

2.1. Identify available helicopter. If all available helicopters have been evaluated, goto 3

2.2. Pick a feasible route for selected helicopter. If all available routes have been evaluated, goto 2.1.

2.3. Load as many ASRs as possible on this route without constraint violations

2.3.1. leg = 0

2.3.2. leg = leg + 1. If leg > top, goto 2.4

2.3.3. Select the highest priority ASR (based on planner input and internal capacity scaling) remaining for consideration that can be carried by this leg. If no ASRs remain, goto 2.3.2

2.3.4. If ASR can be added without weight (limit set in the "LZs" worksheet) or cubic capacity (based on available templates in "Load Templates" worksheet) violations, temporarily assign the ASR to the candidate route. Update route score.

2.3.5. Goto 2.3.3

2.4. Load as many ASRs as possible on this route using throughput

2.4.1. throughput = 0, leg = 0

2.4.2. throughput = throughput + 1. If (leg + throughput) > top, goto 2.5

2.4.3. leg = leg + 1. If leg > (top – throughput), leg = 0, goto 2.4.2

2.4.4. Select the highest priority ASR remaining for consideration that has pick-up at path(leg) and drop-off at path(leg + throughput). If no ASRs remain, goto 2.4.3

2.4.5. If ASR can be added without weight or cubic capacity violations on any of the effected legs, temporarily assign the ASR to the candidate route. Update route score.

2.4.6. Goto 2.4.4

2.5. Add planner set bonuses to the route based on performance.

2.6. If candidate route score is greater than the best score, record the candidate route as best route.

2.7. Goto 2.2

3. Output Results

D. BUILDING FEASIBLE AND USABLE ROUTES FOR LOADING CONSIDERATION

The MASHPAT algorithm uses stack-based enumeration with strict filtering rules to create every feasible and usable route for each helicopter model (see, e.g., Kreher and Stinson, 1999). To improve run time, the enumeration only considers landing zones

listed as a pick-up or drop-off for at least one ASR and zones that offer fuel. After adding a stop on a proposed route, the MASHPAT algorithm looks for violations in the following constraints:

- Flight time,
- Overall number of stops,
- Fuel minimums, or
- Incompatibility between a helicopter model and landing zone.

To reduce the number of routes generated, leg repetition is eliminated based on available cargo. The route builder gives the solver a full range of options by creating every route that may be useful. Building only feasible and usable routes reduces the workload on the optimization portion of the problem.

A time matrix of every potential leg provides data for route time and fuel burn estimations. For the MASHPAT algorithm to create every feasible route, this matrix must have entries for each leg. Even with an assumption of symmetry for flight times, a scenario with 80 landing zones (LZs) requires 6,320 entries. To ease the data entry burden, MASHPAT is able to estimate all flight times based on LZ latitude and longitude along with planner input airspeed and landing transition time.

E. EXCEL-BASED HEURISTIC SOLVER CHANGES TO THE FORMULATION

1. Model Restrictions and Omissions in a Heuristic Solution

The heuristic is necessary to improve run time but requires changes to the problem formulation that likely introduce an optimality gap (i.e., the difference between the objective value of our heuristic solution and a truly optimal one). Considering every permutation of routing, helicopter and tasking is not possible in the allotted time for daily planning. A heuristic uses generic rules to consider only the solutions that are likely to produce desirable results. Reducing the number of solutions considered improves run time, but the optimal solution might not be considered. Bridges (2006) develops a greedy

algorithm, with some post-processing involving load modifications, to solve a simpler model for fixed-wing aircraft. The MASHPAT algorithm extends this concept to consider the added complexities of helicopter planning.

a. Fuel State as a Discrete Decision Variable

The huge number of feasible fuel plans for a route requires a technique to reduce the number of fuel plans. Because fuel onboard is continuous, the number of feasible fuel levels is unlimited. Even if fuel levels are broken into discrete 50-pound blocks, most routes would still have hundreds of feasible fuel plans.

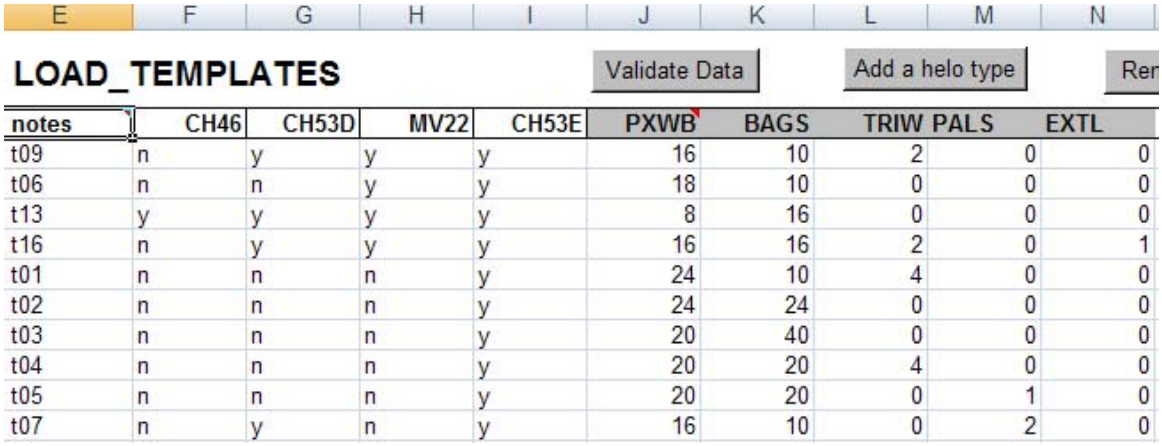
Instead of considering all possible (continuous) fueling levels at each stop of a route, the MASHPAT algorithm finds one fuel plan for each route that minimizes the number of fuel stops and allocates as much weight as possible for cargo loading. As each route is built for a helicopter model, fuel burn rates are tracked along the route. Fuel is added each time a route includes a landing zone capable of providing fuel. If a route is feasible with respect to fuel, the MASHPAT algorithm minimizes the number of fuel stops without introducing a fuel violation. If the fueling time plus the route time does not violate the maximum route time constraint, the route is accepted. If a route is accepted, fuel states for each takeoff along the route are calculated by setting the fuel level at the aircraft's minimum fuel allowed prior to each refueling and then calculating the estimated fuel at the remaining landing zones by using appropriate fuel burn rates.

b. Cubic Capacity Limitations as a Loading Template Selection

Solving exactly the cubic capacity portion of the problem would be complex and data intensive. To determine which combinations of ASRs fit on a given helicopter model, the planner would need to input the dimensions of the helicopter interior and the dimensions of each component of each ASR. If all of this data was available, a complex enumeration algorithm would need to try all spacing arrangements of the cargo to determine if the cargo fits inside the helicopter.

To simplify the cubic capacity check, the MASHPAT algorithm only considers a set of standard load templates. The load templates are planner-defined to

describe the capacities of each helicopter available. Planners must categorize the cargo for each ASR into passengers, seabags, triwalls, pallets and external loads as detailed in chapter one. Load templates store a series of common maximum cubic loads. MASHPAT holds a list of load templates for each helicopter model and considers only these options when determining if a particular load fits. This reduces data input and improves run time. An example of the format for several planner-designated load inputs on the "Load Templates" worksheet is depicted in Figure 4 below.



LOAD_TEMPLATES

Validate Data | Add a helo type | Rer

notes	CH46	CH53D	MV22	CH53E	PXWB	BAGS	TRIW	PALS	EXTL
t09	n	y	y	y	16	10	2	0	0
t06	n	n	y	y	18	10	0	0	0
t13	y	y	y	y	8	16	0	0	0
t16	n	y	y	y	16	16	2	0	1
t01	n	n	n	y	24	10	4	0	0
t02	n	n	n	y	24	24	0	0	0
t03	n	n	n	y	20	40	0	0	0
t04	n	n	n	y	20	20	4	0	0
t05	n	n	n	y	20	20	0	1	0
t07	n	y	n	y	16	10	0	2	0

Figure 4. MASHPAT uses load templates to simplify a complex cubic capacity planning problem. The planner inputs various numbers of units in various cargo categories and marks which helicopter types have the cubic capacity for the designated load template.

c. Aircraft ASR Assignments Using a Modified Greedy Heuristic

The MASHPAT algorithm cannot consider every possible load plan to select the best solution. Considering a single route without allowance for throughput (ASRs that remain on an aircraft for more than one leg), an optimal solution for that route may be found by considering each feasible load plan for each leg individually and comparing the routes with a pre-determined objective function.

Allowing throughput (ASRs carried through more than one hop) increases complexity due to the added interactions between consecutive legs, because an ASR that remains on a helicopter for several legs before arriving at the requested drop-off affects

the weight and cubic capacity for each leg that it remains onboard. To identify an optimal load plan for a route with throughput consideration, the effect of scheduling an ASR must, therefore, be considered for the route *as a whole*.

When considering the selection of multiple routes to form a plan, the complexity increases exponentially due to the interaction between routes. Because an ASR is either completed or rolled, assigning an ASR to multiple aircraft does not improve the plan. If the plan is examined as a whole, there may be ASRs, which could be moved to a different route with remaining space and weight on the necessary legs. This adjustment could free space and weight for additional ASRs to be scheduled. For this reason, finding an optimal plan requires evaluating the interaction of route selections for each helicopter assigned.

The MASHPAT algorithm uses a modified greedy heuristic to assign ASRs to aircraft. The heuristic considers each available helicopter individually in a pre-determined order set by the planner (e.g., smallest helicopter first), tries to create an optimal load plan for each feasible route created for that helicopter, and then selects the route achieving the highest objective function score. The solver does not consider scheduling an ASR already assigned to another helicopter.

A different ordering of aircraft can yield a different (possibly better) solution. MASHPAT maintains a list of ASRs exceeding a designated size threshold and prioritizes these ASRs higher than others, in that the solver attempts to schedule these large ASRs first. Occasionally, planners will split ASRs that require a long-distance movement to reduce impact of the ASR on the plan. The first part of a split ASR receives priority handling. After the prioritized list is considered, the remaining ASRs are considered per planner priorities. Handling priorities in two separate classes (i.e. difficult and easy) increases the chance of completing hard-to-schedule ASRs and improves overall planning efficiency. The re-ordering of any of the inputs to the greedy heuristic can produce better solutions.

2. Meeting Planner Priorities for Optimization Using Prioritized Weighting in the Heuristic

A simple objective function with a series of bonuses quickly evaluates routes to identify plans that best meet the planner's priorities. The base objective for the greedy heuristic is to move as many prioritized pounds of passengers and cargo as possible with each route. The planner may input variable bonuses to meet certain criteria and to focus the solver on certain aspects of a proposed plan. The planner may adjust priorities for:

- Completing all remaining ASRs for a given pick-up and drop-off combination,
- Clearing all cargo into and out of an LZ,
- Scheduling higher-priority ASRs,
- Completing the first part of an ASR split into two parts during the day to allow follow-on transportation at night for the second part, or
- Completing a high volume (as defined by the planner) ASR.

The local search technique of the heuristic makes it undesirable to place too much focus on any one aspect of the objective. If the bonuses are set too high, the plan created may perform worse in the desired category than with a lower bonus level. For example, if the bonus used to prioritize the planner-specified ASR priorities is set too high, the MASHPAT algorithm creates routes specifically tailored to schedule the ASRs in order of priority. A helicopter that could carry the first, third, fourth and fifth priority ASR instead carries the first and second priority ASR if feasible. The result over several helicopters is an inefficient schedule that may carry less of the top priority ASRs than if the priority bonus is set lower.

If the planner appropriately balances priorities, the MASHPAT algorithm identifies a plan that meets the planner's objectives. Appropriate bonus levels may vary from one operation to another, but once a planner has identified bonuses appropriate to the operational goals, the bonuses will need very little if any adjustment for day-to-day operations.

III. MASHPAT REQUIRES ACCURATE INPUT DATA FOR COMPARISON WITH CURRENT PLANNING METHOD

A. SELECTING INPUT DATA FOR MASHPAT

Ten consecutive days of helicopter tasking for Operation Iraqi Freedom (OIF) were used to test the effectiveness of MASHPAT. This data set represents realistic sized problems with all of the constraints discussed in chapter one. The actual plans manually created for these ten days of tasking provide a baseline for comparison.

B. SIMULATING INPUTS REQUIRED FOR MASHPAT

1. Scenario Setup

The head planner for Marine helicopters in Iraq, Captain Christopher Schumann, USMC, provided the majority of the inputs required to complete the scenario setup section of MASHPAT. Because over 80 landing zones are set up in Iraq, receiving a manually created time matrix is unrealistic. To overcome this hurdle, the distance calculator built into MASHPAT creates an approximate time matrix based on latitude and longitude for each LZ. Because route legs are rarely flown in a straight line, the airspeeds used to approximate leg times are less than the actual cruise speed of a helicopter. The resulting time matrix used for this test is conservative to ensure the MASHPAT algorithm does not create infeasible routes. Figure 5 shows a distance worksheet display.

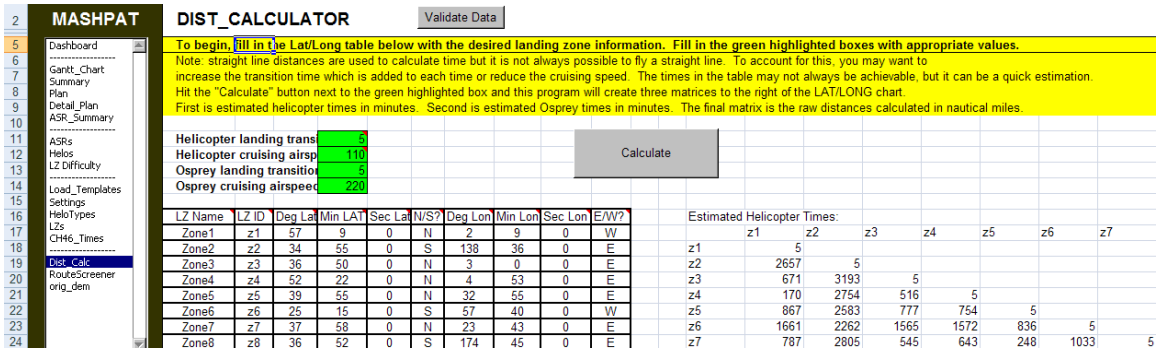


Figure 5. The distance calculator built into MASHPAT assists planners in creating the large time matrix necessary to generate feasible routes. The planner can adjust airspeed and landing transition time to compensate for helicopter routing considerations. This calculator produces a time matrix that can be directly copied for each helicopter's time matrix or the planner can adjust specific entries in the matrix that have different leg times due to the routing for that leg.

Setting up MASHPAT for use in a new theater of operations can be completed in less than three hours. A navigation bar on the left side of each worksheet (see Figure 6) breaks the worksheets into logical groupings. The fourth section consists of all worksheets containing scenario setup data. The planner enters a sufficient variety of load templates for each helicopter type in the "Load Templates" worksheet as depicted in Figure 4. The "Settings" worksheet accepts user input for handling large ASRs. The "Helo Types" worksheet shown below in Figure 6 accepts data necessary to handle helicopter-specific constraints.

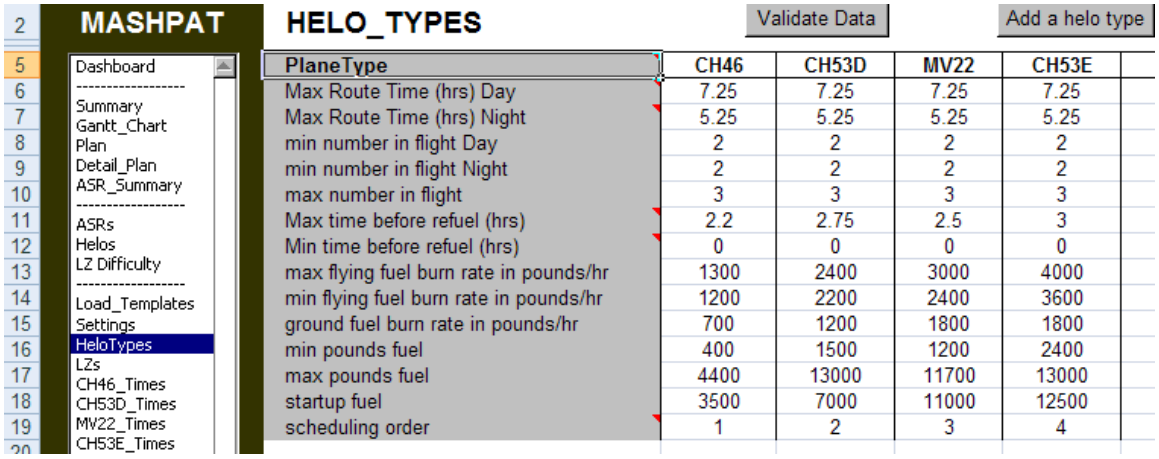
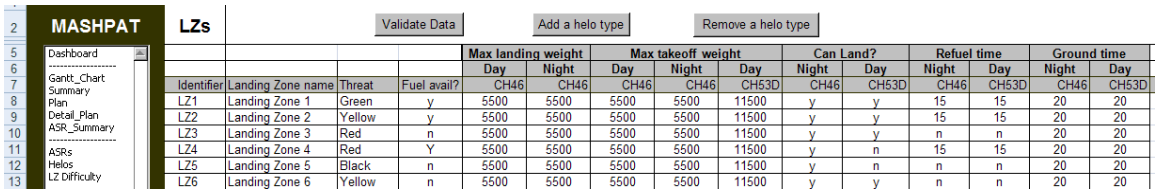


Figure 6. Planners enter information specific to each helicopter type in the "Helo Types" worksheet.

Planners input all information necessary to describe an LZ in the "LZs" worksheet. This worksheet (see Figure 7) holds information about which LZs have fuel available, the LZ's threat level, and which helicopters can land there during the day and at night. Additionally, the planner enters expected ground time for cargo loading, time to refuel (if fuel is available) and the maximum weights for takeoff and landing at each LZ.



				Max landing weight		Max takeoff weight			Can Land?		Refuel time		Ground time	
				Day	Night	Day	Night	Day	Night	Day	Night	Day	Night	Day
Identifier	Landing Zone name	Threat	Fuel avail?	CH46	CH46	CH46	CH46	CH53D	CH46	CH53D	CH46	CH53D	CH46	CH53D
LZ1	Landing Zone 1	Green	y	5500	5500	5500	5500	11500	y	y	15	15	20	20
LZ2	Landing Zone 2	Yellow	y	5500	5500	5500	5500	11500	y	y	15	15	20	20
LZ3	Landing Zone 3	Red	n	5500	5500	5500	5500	11500	y	y	n	n	20	20
LZ4	Landing Zone 4	Red	Y	5500	5500	5500	5500	11500	y	n	15	15	20	20
LZ5	Landing Zone 5	Black	n	5500	5500	5500	5500	11500	y	n	n	n	20	20
LZ6	Landing Zone 6	Yellow	n	5500	5500	5500	5500	11500	y	y	n	n	20	20

Figure 7. The "LZs" worksheet holds data that varies by LZ. The planner inputs the threat level (used only for threat depiction on Gantt chart output), maximum weights for each helicopter and light condition, expected cargo loading time and fuel availability. Additionally, the planner marks which helicopters can land at each LZ.

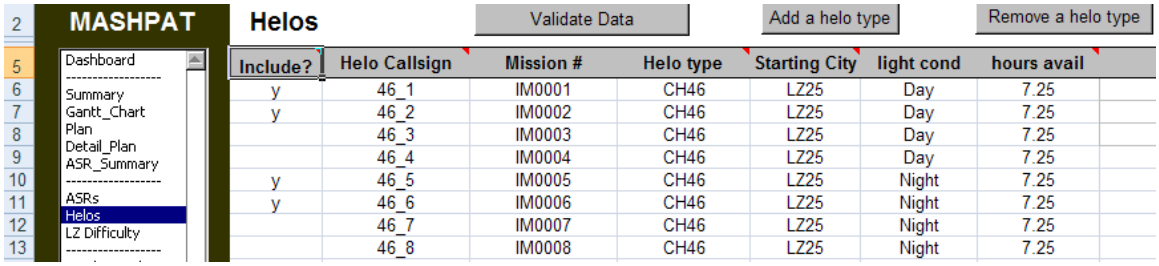
Finally, the planner enters a time matrix for each helicopter type. Each LZ combination in the matrix requires a time in minutes for the specified helicopter type to transit this leg. MASHPAT assumes that blank entries in the matrix denote legs that cannot be flown by that helicopter type. The planner may rely primarily on the distance calculator described above to generate these times.

2. Daily Inputs

To test MASHPAT's ability to create a plan, only the basic features of MASHPAT are used. The ASRs and helicopter availability are entered based on the plan executed. While MASHPAT offers many opportunities for planner interaction, only maximum route time and helicopter scheduling order are varied to develop plans for this test.

Because the scenario data should rarely change, daily modifications to MASHPAT should take less than thirty minutes for most planning days. The third grouping in the navigation bar contains the three worksheets that may require daily

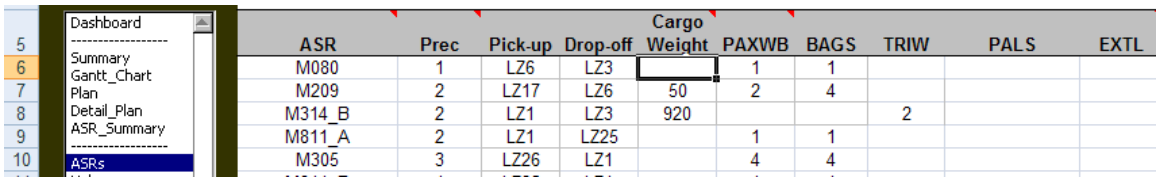
manipulation. For this test, only the first two worksheets in this group were use. First, the planner selects which helicopters will be available each day (see Figure 8). A helicopter has a callsign, mission number and type associated with it. A "y" in the first column of the "Helos" worksheet represents a helicopter available for tasking. Leaving this column blank for a helicopter ensures the MASHPAT algorithm will not assign tasking to that helicopter.



Include?	Helo Callsign	Mission #	Helo type	Starting City	light cond	hours avail
y	46_1	IM0001	CH46	LZ25	Day	7.25
y	46_2	IM0002	CH46	LZ25	Day	7.25
	46_3	IM0003	CH46	LZ25	Day	7.25
	46_4	IM0004	CH46	LZ25	Day	7.25
y	46_5	IM0005	CH46	LZ25	Night	7.25
y	46_6	IM0006	CH46	LZ25	Night	7.25
	46_7	IM0007	CH46	LZ25	Night	7.25
	46_8	IM0008	CH46	LZ25	Night	7.25

Figure 8. Planners select which helicopters will be available for tasking by placing a "y" in the first column for each available helicopter.

Next, the planner enters all of the ASRs requiring movement that day. After entering the ASR name, the priority of the ASR, the pick-up LZ and the drop-off LZ, the planner enters information necessary to describe the cargo requiring movement (see Figure 9).



ASR	Prec	Pick-up	Drop-off	Cargo Weight	PAXWB	BAGS	TRIW	PALS	EXTL
M080	1	LZ6	LZ3		1	1			
M209	2	LZ17	LZ6	50	2	4			
M314_B	2	LZ1	LZ3	920			2		
M811_A	2	LZ1	LZ25		1	1			
M305	3	LZ26	LZ1		4	4			

Figure 9. The planner specifies all ASRs in the "ASRs" worksheet. The first four columns must be filled in. The remaining entries are only filled in if they apply to the ASR for that row.

IV. MASHPAT DEMONSTRATES IMPROVEMENT OVER MANUALLY CREATED PLANS

A. COMPARING MASHPAT RESULTS TO MANUAL FLIGHT PLANS

During the ten-day test period, MASHPAT outperformed the manual planners eight days, tied once and was outperformed once. The total flight hours planned, the number of helicopters required, and the number of rolled ASRs provide metrics to compare MASHPAT results to manually created plans. MASHPAT is generally more effective at reducing the number of helicopters required and reducing the number of rolled ASRs than reducing overall flight hours. Additionally, MASHPAT creates a plan in less than one hour while manually creating a plan typically takes several hours. Full test results are in the appendix.

1. Comparison of Overall Flight Hours

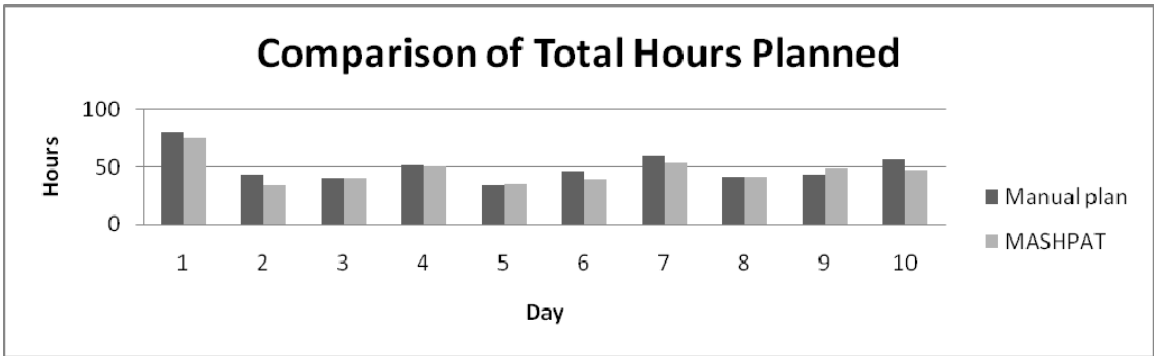


Figure 10. Comparison of total flight hours planned. The differences range from -21% to +12% with an overall average decrease of 6%.

On average, MASHPAT produces plans with 3.3 less flight hours than the manual planners do. This equates to a 5.9% improvement. Six days have reduced hours, two days are unchanged, and two days use more flight hours (see Figure 10).

2. Comparison of Total Helicopters Required

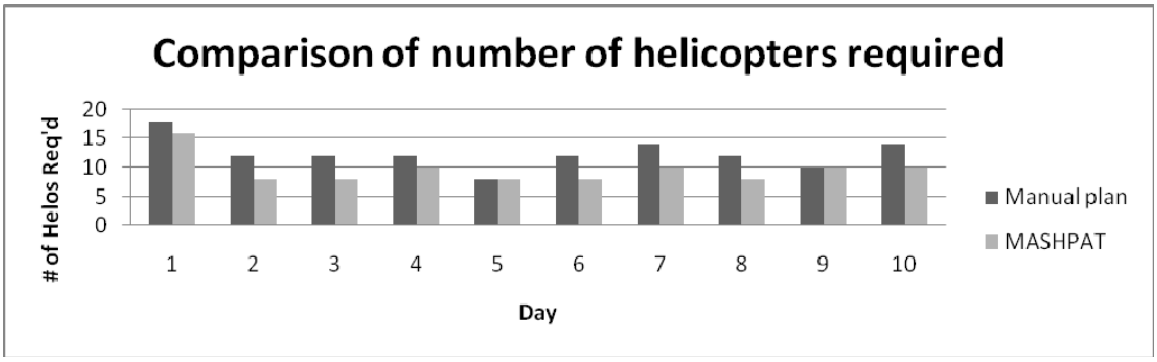


Figure 11. Comparison of total helicopters required. Results range from no improvement to a 33% reduction in number of helicopters required with an average reduction of 22%.

MASHPAT uses an average of 2.8 fewer helicopters than the manual planners do. This equates to a 21.8% improvement. Eight days have reduced helicopters required and two days are unchanged (see Figure 11).

3. Comparison of Rolled ASRs

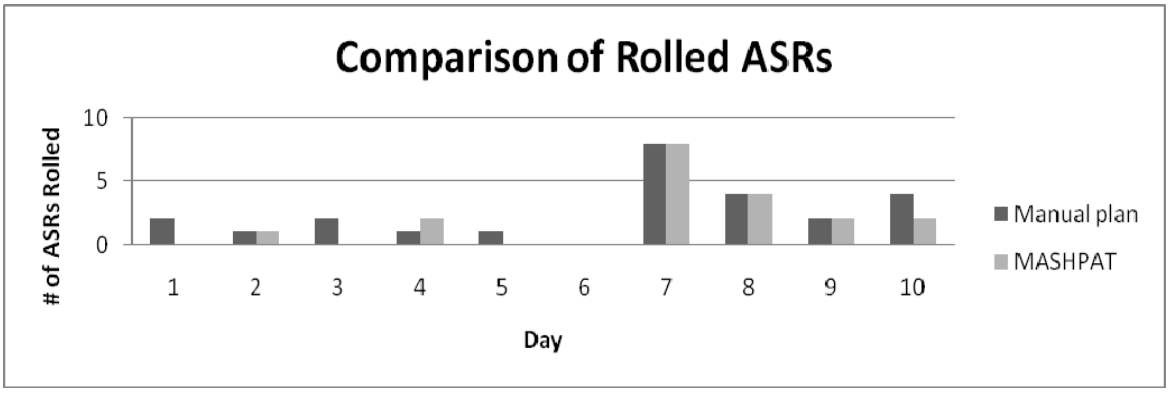


Figure 12. Comparison of rolled ASRs

On average, MASHPAT rolls a total of 0.6 ASRs less than the manual planners do. Four days have less rolled ASRs, five days are unchanged, and one day rolls more ASRs (see Figure 12).

B. MASHPAT AND PLANNERS WORKING TOGETHER

MASHPAT allows for varying levels of planner interaction to capitalize on planner knowledge and overcome shortfalls. Planners can adjust a series of bonuses to overcome some of the weaknesses of the greedy heuristic at the heart of the MASHPAT algorithm (see Figure 13). Because the MASHPAT algorithm considers total weight lifted as the metric to evaluate a route's effectiveness, specific ASR weights can be adjusted for the purpose of route scoring or a set number of pounds can be added to a route after loading is complete. Each time an incumbent route clears all ASRs for a given pick-up and drop-off combination, a "leg clearing bonus" adds a set number of pounds to the incumbent route score. A "priority bonus" increases the adjusted weight for ASRs with high planner set priorities. Occasionally an ASR is split into two sequential legs due to a long distance from pick-up to drop-off. To complete a split ASR in one day, MASHPAT must schedule the first part during the day and the second part at night. A "multi leg bonus" increases the adjusted weight for completing the first part of a split ASR. An incumbent route that clears all ASRs coming in or going out of an LZ receives an "LZ clearing bonus" which adds a set number of pounds to the incumbent route score. The "improvement requirement" is a number of pounds per minute required for MASHPAT to increase flight time on a route. To reduce flight hours, planners can increase the "improvement requirement." Increasing the "improvement requirement" setting may reduce the number of ASRs scheduled. The "LZ difficulty" set on the "LZs" worksheet increases the adjusted weight for completing an ASR that goes into or out of an undesirable (due to distance, enemy threat, etc.) LZ to improve the chances of the effected ASRs being scheduled (see Figure 14).

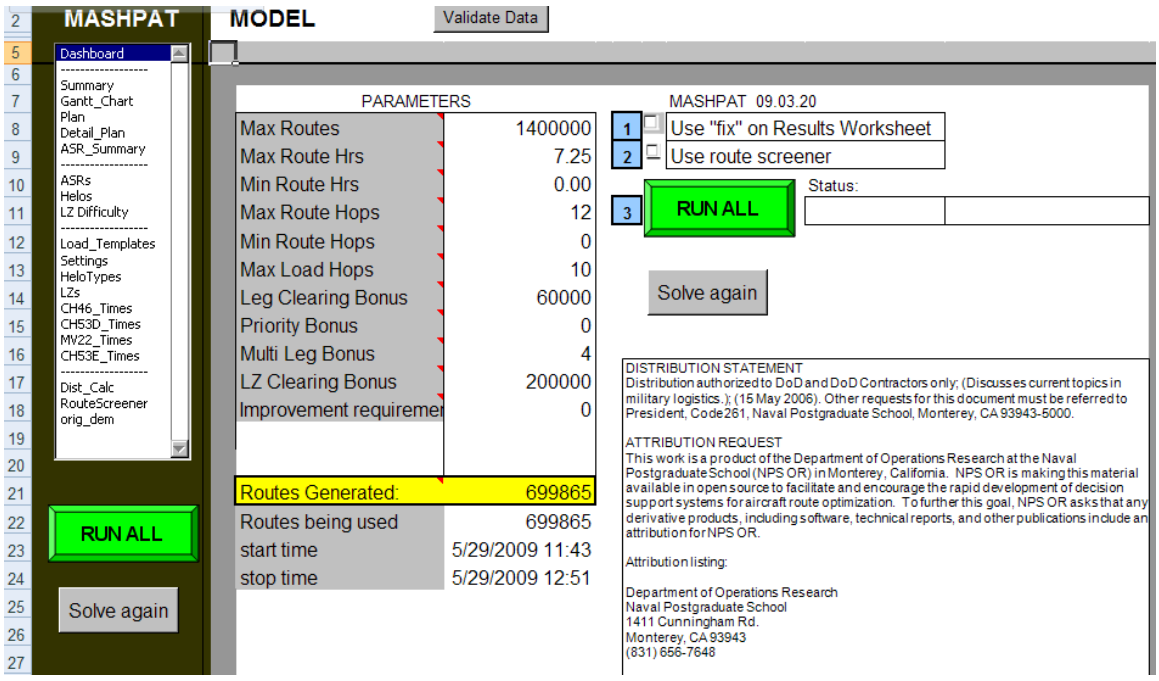


Figure 13. The "Dashboard" worksheet allows planners to influence MASHPAT selections. The bonuses entered at the bottom of the "parameters" section change scores assigned to incumbent routes in the solver based on specific aspects of route performance.

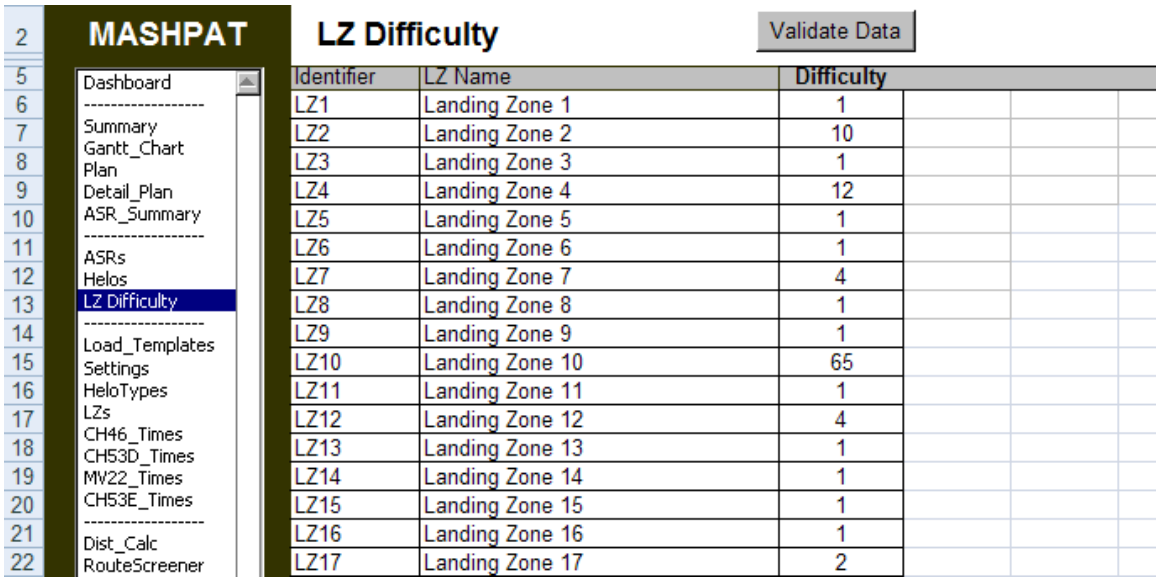
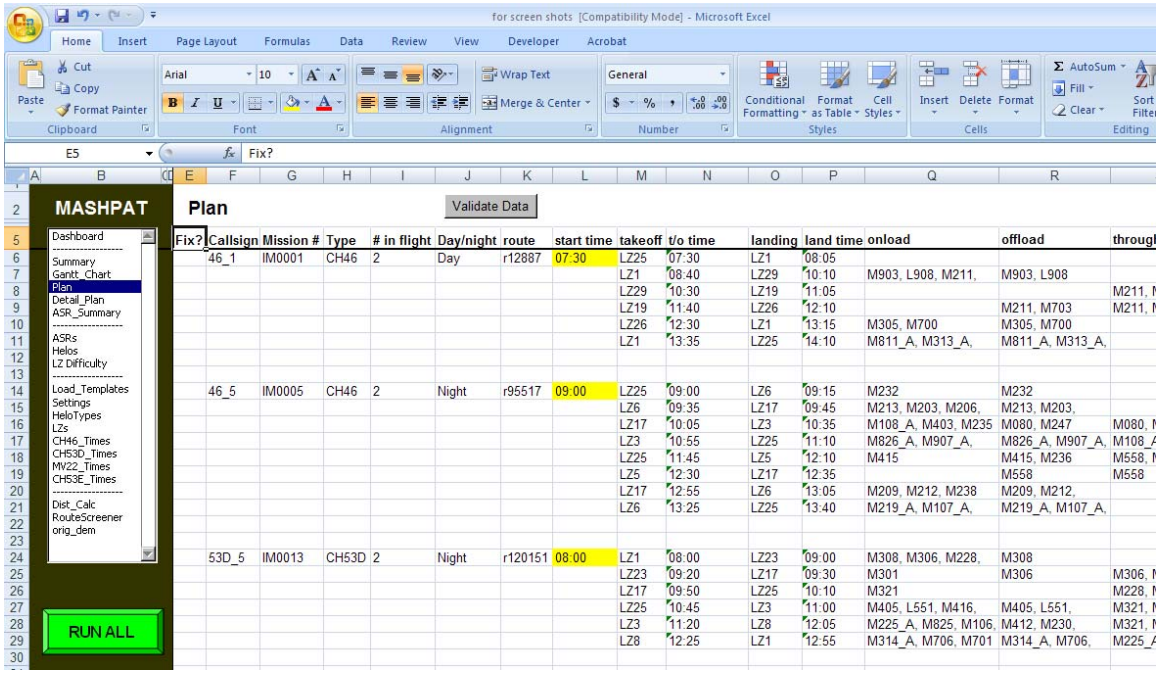


Figure 14. The planner can compensate for undesirable (due to distance, enemy threat, etc.) LZs by increasing their "Difficulty" rating on the "LZ Difficulty" worksheet. The total ASR weight is multiplied by the "Difficulty" factor for the pick-up and drop-off LZ to calculate the adjusted weight added to a route's score for completing the ASR.

Planners can force MASHPAT to use specific routes and ASR assignments (see Figure 15). The perspective of a planner looking at the plan as a whole may allow him to choose a better route or load plan than the MASHPAT algorithm's local search. Planner experience and judgment are valuable and MASHPAT takes advantage of this.



Fix?	Callsign	Mission #	Type	# in flight	Day/night	route	start time	takeoff	t/o time	landing	land time	onload	offload	through
	46_1	IM0001	CH46	2	Day	r12887	07:30	LZ25	07:30	LZ1	08:05			
								LZ1	08:40	LZ29	10:10	M903, L908, M211,	M903, L908	
								LZ29	10:30	LZ19	11:05			M211,
								LZ19	11:40	LZ26	12:10		M211, M703	M211,
								LZ26	12:30	LZ1	13:15	M305, M700	M305, M700	
								LZ1	13:35	LZ25	14:10	M811_A, M313_A,	M811_A, M313_A,	
	46_5	IM0005	CH46	2	Night	r95517	09:00	LZ25	09:00	LZ6	09:15	M232	M232	
								LZ6	09:35	LZ17	09:45	M213, M203, M206,	M213, M203,	
								LZ17	10:05	LZ3	10:35	M108_A, M403, M235	M080, M247	M080,
								LZ3	10:55	LZ25	11:10	M826_A, M907_A,	M826_A, M907_A,	M108_A
								LZ25	11:45	LZ5	12:10	M415	M415, M236	M558,
								LZ5	12:30	LZ17	12:35		M558	M558
								LZ17	12:55	LZ6	13:05	M209, M212, M238	M209, M212,	
								LZ6	13:25	LZ25	13:40	M219_A, M107_A,	M219_A, M107_A,	
	53D_5	IM0013	CH53D	2	Night	r120151	08:00	LZ1	08:00	LZ23	09:00	M308, M306, M228,	M308	
								LZ23	09:20	LZ17	09:30	M301	M306	M306,
								LZ17	09:50	LZ25	10:10	M321		M228,
								LZ25	10:45	LZ3	11:00	M405, L551, M416,	M405, L551,	M321,
								LZ3	11:20	LZ8	12:05	M225_A, M825, M106,	M412, M230,	M321,
								LZ8	12:25	LZ1	12:55	M314_A, M706, M701	M314_A, M706,	M225_A

Figure 15. The second group on the navigation bar contains worksheets displaying the MASHPAT-generated plan. The "Plan" worksheet displays the route and ASR assignments MASHPAT selects. The planner may force certain routes to be selected by entering a desired route and entering a "y" in the "fix?" column on the left. Additionally, the planner may force certain ASRs to be scheduled on fixed routes by entering them in the columns on the right.

In addition to the "Plan" and "Detailed Plan" worksheets which give specific information about the selected plan, the planner can also see a broad overview of the plan by selecting the "Summary" (see Figure 16) or "Gantt Chart" (see Figure 17) worksheets. The "Summary" worksheet provides statistics on the overall performance of the plan. This includes the number of flight hours planned, number of helicopters required and the level of ASR completion. The "Gantt Chart" worksheet gives a visual representation of the flight time and what threat levels are encountered on each route.

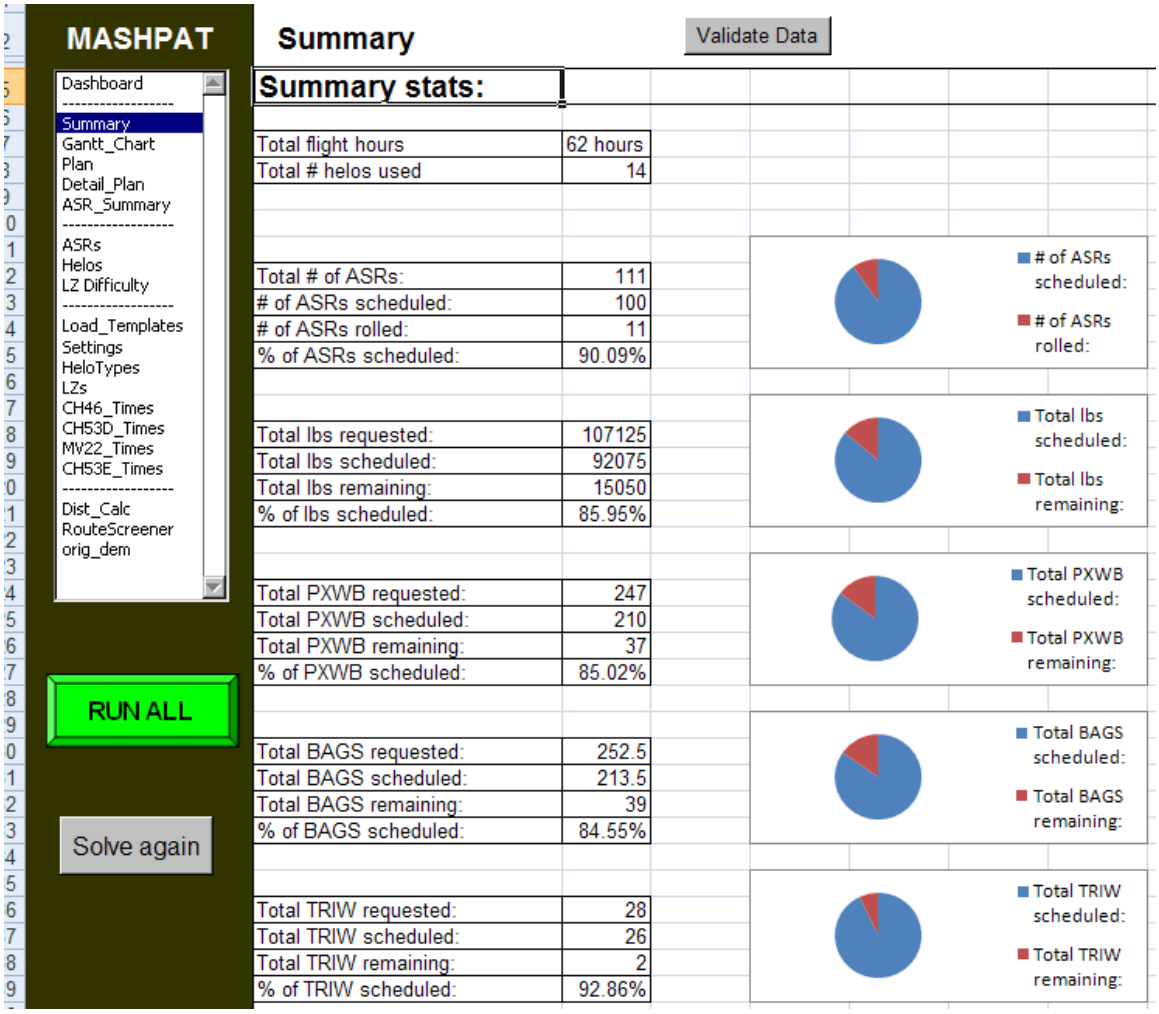


Figure 16. The "Summary" worksheet displays a brief overview of the selected plan's performance. In addition to displaying flight hours planned and the number of helicopters required, the planner can see what portion of the ASRs are scheduled.

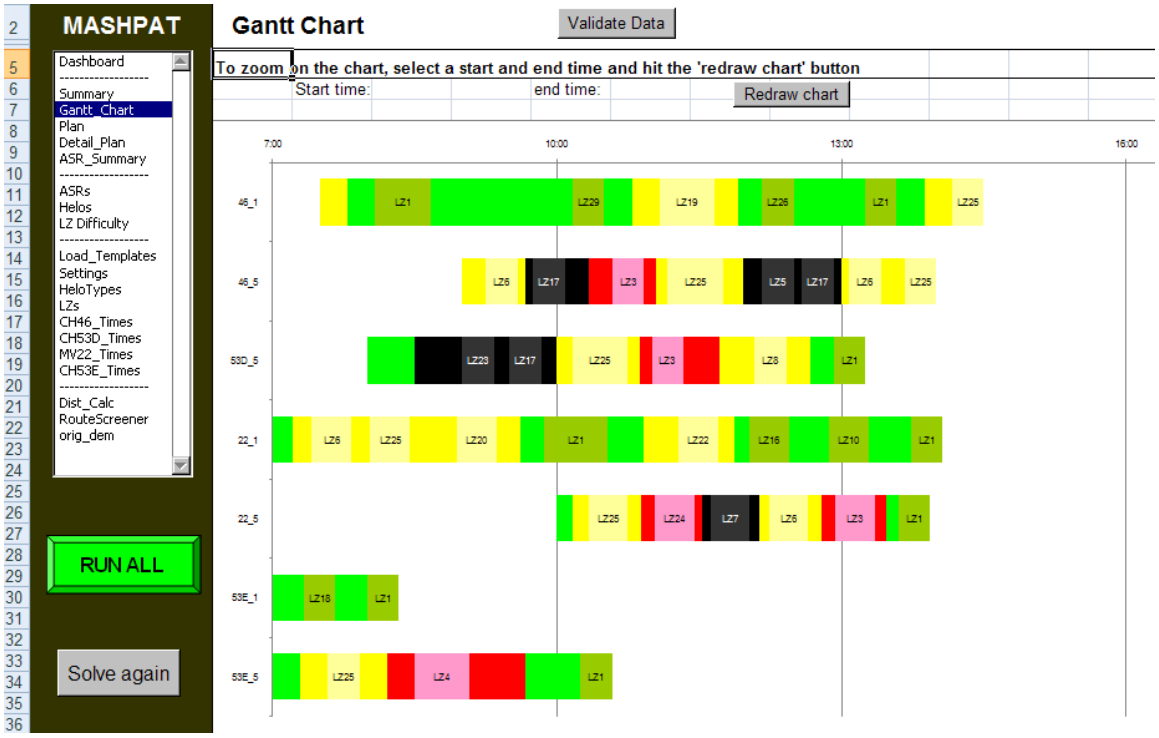


Figure 17. Planners can use the gantt chart generated by MASHPAT to visually display the routes and threats encountered along each route. Threats are categorized by color with black being the highest threat.

C. MASHPAT'S UTILITY IN REAL WORLD SCENARIOS

MASHPAT is free, adaptable to most high demand operations and ready for use. A 45-minute training video is available to introduce planners to all aspects of the MASHPAT interface. Because this formulation captures the generic challenges of any assault support-planning problem, the same concepts apply to operations in any theater. MASHPAT's scenario setup allows planners to input data necessary to capture the peculiarities of any operation and handle them appropriately. Because run time and memory requirements are heavily dependent on the number of LZs and the proximity of the LZs to each other, MASHPAT may require structural changes to accommodate a significantly larger planning problem in which many LZs are in close proximity. While the efficiency for manual planning greatly decreases as the number of required helicopters and the number of ASRs increases, MASHPAT becomes more efficient in these same conditions.

In his role as the lead planner in Iraq, Captain Christopher Schumann, USMC, has already demonstrated initiative and adaptability typical of Marines. Since completion of MAHSPAT 1.0, planners have encountered a new requirement dictated by the aviation element commander requiring two helicopters to fill a standby role each day. Standby helicopters are capable of handling last minute, high priority tasking (e.g. emergency evacuation). To fulfill this role, the commander requires such helicopters to remain within 60 miles of their home base and perform no more than four hours of tasking. To model this new constraint in MASHPAT, Captain Schumann created new helicopter types with "hours avail" annotated in the "Helos" worksheet reduced to 4 and LZs outside the 60 mile ring marked "n" in the "can land?" column of the "LZs" worksheet for the standby helicopter types. Additionally, Captain Schumann added the Marine C-130 cargo plane to the model as a helicopter type allowing MASHPAT to schedule ASRs moving from one runway to another on a C-130. A cargo plane is accurately modeled in MASHPAT by placing an "n" in the "can land?" column of LZs that do not have a sufficient runway. These simple changes exercise MASHPATs flexibility.

MASHPAT accommodates ASR and helicopter changes. Last-minute ASR changes, weather delays and maintenance delays are frequent. MASHPAT can quickly rewrite an entire plan or maintain current tasking and exploit open space on scheduled helicopters to source additional ASRs. Handling these changes manually is time consuming and often inefficient due to the minimal planning time available.

MASHPAT is consistent and reliable and does not have a steep learning curve. Current planners in OIF benefit from planning techniques built over several years. Additionally, the quality of plans produced varies with the ability and experience of the planner. MASHPAT embodies "tribal wisdom" of planners, and offers this legacy to new planners.

Because MASHPAT quickly produces consistent plans, planners can use this tool to forecast assault-support helicopter asset requirements for various phases of an operation. By creating distributions of expected ASRs, MASHPAT could be run over

hundreds of simulated days to provide sensitivity analysis regarding asset availability. This output could aid commanders in determining desired asset allocation for a future operation.

D. RECOMMENDED MASHPAT IMPROVEMENTS

1. Closing the Optimality Gap with Heuristic Improvements

Improvements to the MASHPAT algorithm's solver might greatly affect the quality of plans produced. An omniscient algorithm capable of considering the plan as a whole better serves this complex planning problem. A simpler but less effective approach would be to consider local changes after the plan is completed. By reconsidering one or two routes at a time after the plan is created, adjustments can be made to improve overall efficiency.

2. Simplifying the ILP

Fixing some variables to simplify route selection may make a commercial optimization solver a feasible approach to finding an optimal solution. The first effort at solving the planning problem as an ILP in GAMS failed due to the complexity of the problem. A preprocessing step to fix complex variables such as fuel state at reasonable levels may simplify the problem enough to attain an optimal solution to the remainder of the problem in a reasonable amount of time. Alternately, one could formulate a slightly less detailed version of the problem, following the successful experience with the MASHPAT heuristic.

3. Reducing Run Time

Run time must be reduced before a more advanced solver can be implemented. Daily planning must be completed in a timely manner. Because a more advanced algorithm requires additional run time, fewer routes are considered in the same amount of time. An intelligent filtering during route generation will reduce time required to generate routes and the magnitude of the solver's task.

4. Adjusting Cargo Loading Time

MASHPAT requires correct cargo loading times to produce accurate route time estimates. Cargo loading times vary significantly with the magnitude and type of cargo. MASHPAT accepts a single time for cargo loading based on helicopter type, light condition and landing zone. In reality, this time also varies with what cargo is loaded and unloaded. MASHPAT accuracy would increase if historical trends for cargo-loading times were used to predict load times based on what cargo is scheduled for pick-up and drop-off.

APPENDIX. TEST RESULTS

		Day										
		1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**avg**
Manual plan:	**hours**	80	43	40	52	34	46	60	41	43	57	49.6
	# of helos	18	12	12	12	8	12	14	12	10	14	12.4
	rolled ASRs	2	1	2	1	1	0	8	4	2	4	2.5
MASHPAT:	**hours**	75	34	40	50	35	39	54	41	48	47	46.3
	# of helos	16	8	8	10	8	8	10	8	10	10	9.6
	rolled ASRs	0	1	0	2	0	0	8	4	2	2	1.9
raw comparison:	**hours**	-5	-9	0	-2	1	-7	-6	0	5	-10	-3.3
	# of helos	-2	-4	-4	-2	0	-4	-4	-4	0	-4	-2.8
	rolled ASRs	-2	0	-2	1	-1	0	0	0	0	-2	-0.6
pct comparison:	**hours**	-6%	-21%	0%	-4%	3%	-15%	-10%	0%	12%	-18%	-6%
	# of helos	-11%	-33%	-33%	-17%	0%	-33%	-29%	-33%	0%	-29%	-22%

Table 1. Test results comparing ten days operations manually planned in Iraq with MASHPAT plans.

The results in Table 1 cover a ten-day test period used to compare MASHPAT results to manually created plans. MASHPAT produces dominant plans for all but days 4 and 9. Day 4 is essentially a tie with the manual plan completing one more ASR but using two more hours than the MASHPAT-generated plan. On day 9, the manual plan uses five fewer flight hours to provide the same level of service as MASHPAT.

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