Optimizing the US Navy’s Combat Logistics Force

Gerald G. Brown, W. Matthew Carlyle

Operations Research Department, Naval Postgraduate School, Monterey, California 93943

Received 18 February 2007; revised 14 July 2008; accepted 19 July 2008
DOI 10.1002/nav.20318
Published online 21 October 2008 in Wiley InterScience (www.interscience.wiley.com).

Abstract: We study how changes to the composition and employment of the US Navy combat logistic force (CLF) influence our ability to supply our navy worldwide. The CLF consists of about 30 special transport ships that carry ship and aircraft fuel, ordnance, dry stores, and food, and deliver these to client combatant ships underway, making it possible for our naval forces to operate at sea for extended periods. We have modeled CLF operations to evaluate a number of transforming initiatives that simplify its operation while supporting an even larger number of client ships for a greater variety of missions. Our input is an employment schedule for navy battle groups of ships operating worldwide, extending over a planning horizon of 90–180 days. We show how we use optimization to advise how to sustain these ships. We have used this model to evaluate new CLF ship designs, advise what number of ships in a new ship class would be needed, test concepts for forward at-sea logistics bases in lieu of conventional ports, demonstrate the effects of changes to operating policy, and generally try to show whether and how the CLF can support planned naval operations. © 2008 Wiley Periodicals, Inc.

Keywords: naval logistics; optimization; combat logistics force

My logisticians are a humorless lot... they know if my campaign fails, they are the first ones I will slay. Alexander

1. WHAT IS THE COMBAT LOGISTICS FORCE, AND WHY MODEL IT?

Our combat logistics force (CLF) is a fleet of transport ships that sustains US Navy combatant ships at sea worldwide. Each transport carries some combination of four basic commodities: ship fuel, aircraft fuel, ordnance, and dry stores and food. An underway replenishment (UNREP) rendezvous of a transport with a client ship (or simultaneously with more than one) demands superb seamanship to approach, rig transfer lines and hoses, convey commodities and, perhaps, personnel, unrig, and depart company. Transports also use helicopters for vertical replenishment (VERTREP) of client ships that may be some distance away. The special hardware and procedures for these operations have been developed and improved since the 1930s, and permit our navy today to operate continuously for extended periods at sea without returning to any port.

Correspondence to: W.M. Carlyle (mcarlyle@nps.edu)
2. **CLF CUSTOMERS: US NAVY COMBATANT SHIPS**

Most US Navy deployments are groups of ships assembled with a particular mission. Some frequent examples are as follow:

- A carrier strike group consists of a nuclear-powered aircraft carrier (CVN), a guided-missile cruiser (CG), two guided-missile destroyers (DDG), and a fast combat replenishment ship. Accompanying attack submarines are completely autonomous.
- An expeditionary strike group transports a Marine expeditionary unit on an amphibious assault ship (LHA or LHD), with a dock landing ship (LSD), amphibious transport dock (LPD), a CG and two DDGs.
- A surface strike group consists of ships equipped with missiles and missile defense weapons, such as a CG and two DDGs.
- A Littoral Combat Squadron will employ a new class of small ships where larger ships cannot safely navigate, engaging in anti-surface warfare, mine countermeasures, intelligence, surveillance and reconnaissance, homeland defense and maritime interdiction, and special operations forces support. For logistic planning purposes, we treat this new, small ship as a frigate (FFG).

To us, any such deployed group of ships in company is a CLF customer. We call such a customer a battle group (BG).

3. **SCENARIOS: TRANSIT AND BATTLE PLANS**

For our purposes, a scenario is set of exogenous, scripted deployment plans that tells us, day by day, where each battle group will be and what it will be doing. This daily fidelity is in keeping with navy practice, where each ship captain transmits a daily situation report including position and state. Our scenarios are filtered from larger, much more detailed contingency plans for a wide variety of missions.

A typical scenario consists of multiple BGs, and for each BG specifies last-minute in-port preparations and/or predeployment workup training in preparation for deployment, a high-speed transit to an area where we will show our military presence, a surge into combat operations to achieve a given objective, a sustainment phase to hold that objective, and perhaps a postcombat period where we stand guard and provide humanitarian assistance when diplomacy and other nonmilitary measures unfold.

Of course, we do not believe that any one of our planning scenarios will ever be followed verbatim. Rather, we use a wide variety of these to see how we will need to support such operations, region-by-region, mission-by-mission, worldwide.

4. **DEFINING DEMAND: LOGISTICS PLANNING FACTORS**

Standard deployment scenarios used by navy planners include all the client ships, where they will be day by day, and what they will be doing, but do not tell us what logistics support they will need. That’s our problem to estimate.

Eccles [13] provides a classic document with lessons learned from World War II, and advises “all logistics planning is based on usage factors, which are average figures computed in many various ways.” Today, we call such consumption estimates logistics planning factors. For purposes of estimating demand, we specify the employment state of each ship as, for example, in port, in transit, operating on station, or in combat. We aggregate demand into four categories: food and dry stores (STOR), ship fuel (DFM), aviation fuel (JP5), and ordnance (ORDN). The number of personnel aboard determines consumption of STOR, regardless of ship employment. DFM (distillate fuel, marine) consumption is fairly easy to estimate from ship engineering publications (e.g., see Brown et al. [6]) and employment state. Ship power consumption is stated in kilowatts, with a basic “hotel load” required to support the ship and her crew and systems, and propulsion plant demand as a function of speed. Some JP5 is consumed by helicopters, but the overwhelming volume is required by carrier aircraft. Although some ORDN is consumed in, for example, gunnery training, most weight consists of air-dropped munitions delivered in combat.

5. **CLF SHIPS: FLEET COMPOSITION**

The combat logistics force is being consolidated to just three ship types, with 30 total ships (see Fig. 1).

- The TAO187 (Henry J. Kaiser) class was introduced in 1986 as the first US Navy UNREP ship designed for operation by civil service mariners. With a crew of about 82 civilians and 21 navy personnel, it can carry about 180,000 barrels of fuel oil and 271 tons of cargo lube oil, dry stores, and refrigerated containers, at about 20 knots.
- The T-AOE6 (Supply) Class was introduced in 1994, and with a crew of about 176 civilians and 59 navy personnel, it can carry about 180,000 barrels of fuel oil, and 271 tons of cargo lube oil, dry stores, and refrigerated containers, at about 20 knots.
- The T-AKE1 (Lewis and Clark) joined the fleet in 2006, and with a crew of about 123 civilians and 49 navy personnel, it can carry 18,000 barrels of fuel oil, and...
Figure 1. Combat logistics force ship classes. The CLF is shifting from five to just three classes of support ship, but expects to serve a fleet growing from 284 to 310 ships. Navy ship class names offer telltales of function: “T” means Military Sealift Command transport, commanded and crewed by civilian mariners accompanied by some uniformed navy crew, “A” auxiliary, “O” fuel oil, “E” explosive ordnance, “F” refrigerated, and “K” general cargo. The respective crew complement and steaming speed for each T-AO is 103 and 20 knots, T-AOE 235 and 26 knots, and T-AKE 172 and 20 knots. The T-AOE is faster, has defensive armaments, and is favored as a station ship. The slower T-AO and T-AKE may pair up as station ships, but are more often used as shuttle ships. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]

5,900 tons of ordnance, dry stores, and refrigerated stores at up to 20 knots. Customarily, each storage hold is designed to carry either ordnance or dry stores, but T-AKE storage holds can be converted between the two.

Other ship classes (e.g., T-AE, T-AFS, T-AOE(X)) are either scheduled to leave active service for the reserve fleet, or are still on the drawing boards.

Generally, each ship type is characterized by size, speed and flexibility. Cost increases with each of these attributes, especially speed [e.g., [16]].

CLF ships fill one of two roles: a station ship accompanies a BG group of customer ships, acting as a local storage facility for the BG, while a shuttle ship transits between BGs and replenishment ports. A station ship may not be fast enough to keep up with its BG customers at their top speed, but it needs to be fast enough to periodically rendezvous with and resupply these customers. The standard term for a shuttle ship UNREP of a station ship, or serving an entire BG through several UNREPS, is a consolidation, or CONSOL.

6. SEA ROUTES: NAVIGATING THE WORLD’S OCEANS

Because where we will need to navigate our CLF ships worldwide is an output of our planning, rather than an input, we need an “automated sea routes” model. We could find no such tool, so we built our own. A key feature of our sea routes model is that it takes a basic set of worldwide waypoints and feasible transits between them, and integrates each route followed by the BGs in a given scenario. This provides a navigable network for transports to follow in service of the BGs.

This sea routes network construction proceeds in four phases.

1. A a node is defined for each “port” (i.e., a forward logistics site or an at-sea, pre-positioned modular cargo delivery system ship) and for each of a number of at-sea waypoints frequently used by ships navigating worldwide (e.g., Gibraltar gate). A “fast arc” connects each adjacent pair of these nodes between which full-speed transit is feasible, and nodes are positioned such that each fast arc is navigable along a great circle route.

2. A “slow arc” connects any node pair with a fixed transit time (e.g., a canal or restricted passage). This

Figure 2. Worldwide sea route network. This particular network is for a case with 13 battle group customers operating over a 90-day planning horizon. Figure from Doyle [12]. [Color figure can be viewed in the online issue, which is available at www.interscience.wiley.com.]
7. PLANNING CLF EMPLOYMENT SCHEDULES: AN INTEGER LINEAR PROGRAM

We use an integer linear program to plan optimal employment of CLF ships to minimize policy penalties accruing from any commodity shortage. An exact formulation follows.

7.1. Indices [~cardinality]

\[ s \in S \quad \text{Shuttle ship} \quad [\sim 25] \]
\[ p \in P \quad \text{Port available to load shuttle ships} \quad [\sim 35] \]
\[ bg \in BG \quad \text{Battle group} \quad [\sim 13] \quad \text{(alias bx, by)} \]
\[ d \in D \quad \text{Day} \quad [\sim 181] \quad \text{(alias dx, dy, dh)} \]
\[ c \in C \quad \text{Commodity (DFM, JP5, STOR, ORDN)} \quad [\sim 4] \]
\[ \hat{c} \subseteq C \quad \text{Dry commodity subject to load fraction restrictions (STOR, ORDN)} \quad \text{(alias } \hat{c} \text{)} \]

7.2. Provided Data [units]

\[ \text{spdSHUTTLE}_s \quad \text{Speed of shuttle ship } s \quad [\text{nm/day}] \]
\[ \text{inptrTAT} \quad \text{Time to reload shuttle ship in port} \quad [\text{days}] \]
\[ \text{portok4s}_{s,p} \quad \text{Binary indicator that shuttle ship } s \text{ can reload at port } p \quad [\text{binary}] \]
\[ \text{legdays}_{s,bg,d,p} \quad \text{Shuttle ship } s \text{ transit time at speed } \text{spdSHUTTLE}, \text{ from } bg \text{ position on day } d \text{ to port } p \text{ following given sea routes and/or BG tracks} \quad [\text{days}] \]
\[ \text{useBG}_{bg,d,c} \quad \text{Consumption by } bg \text{ during day } d \text{ of commodity } c \quad [\text{c-units}] \]
\[ \text{mxload}_{bg,c} \quad \text{Maximum capacity of } bg \text{ to carry commodity } c \quad [\text{c-units}] \]
\[ \text{safety}_{c} \quad \text{Minimum desired fraction of } \text{mxload}_{bg,c} \text{ to be held at all times} \quad [\text{fraction}] \]
\[ \text{extremis}_{c} \quad \text{Extreme minimum desired fraction of } \text{mxload}_{bg,c} \text{ to be held at all times, } \text{extremis} \leq \text{safety}_{c} \quad [\text{fraction}] \]
\[ \text{hitOK}_{bg,d} \quad \text{Logical indicator if } bg \text{ can CONSOL on day } d \quad [\text{binary}] \]
\[ \text{capacity}_{s,c} \quad \text{Shuttle ship } s \text{ capacity to deliver commodity } c \quad [\text{c-units}] \]
\[ \text{mnfrac}_{c}, \text{mxfrac}_{c} \quad \text{Minimum, maximum fraction of T-AKE dry capacity that must be loaded with dry commodity } \hat{c} \quad [\text{fraction}] \]
\[ \text{safety\_penalty}_{c} \quad \text{Penalty per deficit unit of desired storage below safety-stocks held by any BG} \quad [\text{penalty per c-unit}] \]
\[ \text{extremis\_factor} \quad \text{Multiplier (>1, e.g. 10) for penalty per deficit unit of desired storage below extremis held by any BG} \quad [\text{dimensionless}] \]
\[ \text{negative\_factor} \quad \text{Multiplier (>extremis\_factor, e.g. 1000) for penalty per deficit unit of desired storage below zero held by any BG} \quad [\text{dimensionless}] \]

7.3. Derived Data

\[ \text{mxconsol}_{s,bg,c} \quad \text{Maximum delivery shuttle ship } s \text{ can make to } bg \text{ on any day of commodity } c \quad [\text{c-units}] \]
\[ \text{mxconsol2}_{s,bg,by,c} \quad \text{Maximum delivery shuttle ship } s \text{ can make in one voyage to CONSOL } bg \text{ and } by \text{ with commodity } c \quad [\text{c-units}] \]

Naval Research Logistics DOI 10.1002/nav
In addition, for T-AKE shuttle ships and dry commodities \( \hat{c} \) sharing dry storage, and subject to limits on the minimum and maximum fractions of dry capacity that must be carried in every T-AKE load, this is restricted to:

\[
\min \begin{cases} 
mxload_{bg,c}, \min[mxfrac_c], \\
1 - \sum_{c \neq \hat{c}} \text{mnfrac}_c \times \text{capacity}_{s,d} 
\end{cases}
\]

or, the maximum permitted T-AKE load of dry commodity \( \hat{c} \), or the amount of commodity \( \hat{c} \) that can be loaded after the minimum loads of other dry commodities \( \hat{c} \neq \hat{c} \) sharing dry storage are loaded.

\( \text{cycledays}_{s,bg,bx,dx} \) If shuttle ship \( s \) departs \( bg \) on day \( d \) to reload at some port \( p \), the minimum number of days before a rendezvous with \( BG bx \) on day \( dx \) is

\[
\min \begin{cases} 
\infty, \min_{\text{provides}_p} \left[ \min_{\text{supplies}_{bx,dx,p}} \{ \text{legdays}_{s,bg,d,p} + \text{inptTAT} \geq \text{cycledays}_{s,bg,bx,dx} \} \right] 
\end{cases}
\]

Note that this admits a cycle with slack time (or, "shuttle waiting time") \( dx - d - \text{cycledays}_{s,bg,bx,dx} \geq 0 \), and that because of the relative motion of a shuttle ship and a BG over navigable sea routes, and their daily proximity to ports and to each other, there will be cases in which planning for a shuttle to wait for this amount of time is better than restricting plans to have no such slack.

\( \text{directdays}_{s,bg,bx,dx} \) The number of steaming days for shuttle \( s \) to transit from the position of \( bg \) on day \( d \) directly to the position of \( bx \) on subsequent day \( dx \) (i.e., without reloading in any port) (policy limits may govern the minimum or maximum days allowed between these planned events).

### 7.4. Decision Variables

\( \text{HIT}_{s,bg,d} \) Binary indicator of shuttle \( s \) CONSOL visit to \( bg \) on day \( d \) (depends on \( \text{hitOK}_{bg,d} \))

\( \text{HIT2}_{s,bg,bx,dx} \) Binary indicator of shuttle \( s \) CONSOL visit to \( bg \) on day \( d \), followed by a second CONSOL visit to \( bx \) on day \( dx \) before returning to port (depends on \( \text{hitOK}_{bg,d} \))

\( \text{CONSOL}_{s,bg,d,c} \) Amount of shuttle \( s \) delivery to \( bg \) on day \( d \) of commodity \( c \) \([c\text{-units}]\)

\( \text{CONSOL12}_{s,bg,bx,dx,c} \), \( \text{CONSOL22}_{s,bg,bx,dx,c} \) Amount of shuttle \( s \) deliveries of commodity \( c \) to respectively, \( bg \) on day \( d \) ("12") and \( bx \) on subsequent day \( dx \) ("22") \([c\text{-units}]\)

\( \text{SHORTAGE}_{bg,d,c} \) amount of inventory deficiency of \( c \) for \( bg \), at end of day \( d \) \([c\text{-units}]\)

\( \text{EXTREMIS}_{bg,d,c} \) amount of extreme deficiency of \( c \) for \( bg \), at end of day \( d \) \([c\text{-units}]\)

\( \text{NEGINV}_{bg,d,c} \) magnitude of negative inventory of \( c \) for \( bg \) at end of day \( d \), has this \([c\text{-units}]\)

### 7.5. Formulation

\[
\text{s.t.} \quad \sum_{s, dh \leq d} \text{CONSOL}_{s,bg,dh,c} + \sum_{s, dh \leq dx} \text{CONSOL12}_{s,bg,bx,dx,c} + \sum_{s, dh \leq dx} \text{CONSOL22}_{s,bx,dx,bg,c} \leq \sum_{dh \leq d} \text{useBG}_{bg,dh,c} \forall bg, d, c \quad (1)
\]

\[
\sum_{s, dh \leq d} \text{CONSOL}_{s,bg,dh,c} + \sum_{s, dh \leq dx} \text{CONSOL12}_{s,bg,bx,dx,c} + \sum_{s, dh \leq dx} \text{CONSOL22}_{s,bx,dx,bg,c} + \text{SHORTAGE}_{bg,d,c} + \text{EXTREMIS}_{bg,d,c} + \text{NEGINV}_{bg,d,c} \leq \sum_{dh \leq d} \text{useBG}_{bg,dh,c} - (1 - \text{safety}_{c}) mxload_{bg,c} \forall bg, d, c \quad (2)
\]

\[
\text{CONSOL}_{s,bg,d,c} \leq mxconsol_{s,bg,c} \text{HIT}_{s,bg,d} \forall s, bg, d, c \quad (3)
\]

\[
\text{CONSOL12}_{s,bg,bx,dx,c} + \text{CONSOL22}_{s,bg,bx,dx,c} \leq mxconsol_{s,bg,c} \text{HIT2}_{s,bg,d,bx,dx} \forall s, bg, d, bx, dx, c \quad (4)
\]

\[
\text{HIT}_{s,bg,d} + \sum_{dy(dy \geq \text{cycledays}_{s,bg,bx,dx})} \text{HIT2}_{s,dy,by,bg,d} + \text{HIT}_{s,bx,dx} + \sum_{dy(dy \geq \text{cycledays}_{s,bg,bx,dx})} \text{HIT2}_{s,bx,dx,by,dy} \leq 1 \\
\forall s, bg, d, bx, dx \mid dx - d < \text{cycledays}_{s,bg,bx,dx} \quad (5)
\]
Inequalities (1) limit day-by-day cumulative CONSOL volumes of each commodity to the cumulative usage of each BG through the end of that day. We assume that on the first day, each BG is full to capacity with every commodity. Thereafter, daily use is deducted, and replenishments are accounted from shuttle CONSOLs. Elastic inequalities (2) reckon cumulative inventory state of each commodity at the end of each planning day, and compare this to the cumulative usage less desired safety-stock level at the end of that day, representing any shortage, extreme shortage, or negative inventory required to reconcile this state. Each inequality (3) limits the CONSOL volume transferred from a shuttle ship, to a BG, on some given day, to be zero unless a replenishment event takes place. Similarly, each inequality (4) controls the successive CONSOL volumes transferred from a shuttle to a BG on some given day, followed by a second CONSOL on a BG on some given later day, to be zero unless a replenishment event takes place for that shuttle on BG on that day, followed by the second BG on the second day. Constraints (5) restrict successive shuttle rendezvous with battle groups so that each such visit is followed by sufficient time to cycle to a port for re-supply. Each constraint (6) permits a shuttle to engage in at most one activity on a given day. Variable domains are stated by constraints (7)–(14). The objective (15) expresses a penalty with a component for any shortage below safety-stock, and extreme shortage below minimum stock, and any negative inventory, less rewards for commodity volume delivered; the rewards here are ten percent of the safety stock shortage penalties, and attract maximal delivered volumes, rather than merely deliveries to avoid shortages.

Our model can schedule a single shuttle ship sortie from port to make two separate CONSOL visits, perhaps to two different battle groups. It turns out that allowing multiple CONSOLs does not help in our large scenarios, and it increases the solve times significantly, so we do not use this feature in those scenarios. For a small 30-day scenario in the Arabian Gulf, with three battle groups being supported by one T-AKE, we find that allowing multiple CONSOLs per sortie increases the overall minimum inventory levels seen, but that the difference is modest. We include this feature to allow the model to represent a situation that could occur in the real world, but we conjecture that it is useful in a few circumstances where many battle groups are close to each other for extended periods, and have low to moderate consumption of the relevant commodities. The two-C CONSOL sorties can be toggled on and off, therefore, for completeness, we display in our formulation the fully general model we have implemented.

8. DISCUSSION

9. PRIOR MODELS OPTIMIZING NAVAL LOGISTICS

Dantzig and Fulkerson [9] present what we would now call a pure network formulation to minimize the number of identical tanker ships required to deliver a fixed slate (schedule) of naval fuel shipments. Each shipment is characterized by load day and location, unload day and location, and times for loaded outbound, and empty return voyages to the next load location.

Brown, et al. [5] plan crude oil tanker voyages with a set partition model selecting for each vessel the best employment schedule among all those feasible over a 60–90 day planning horizon. The sorties carry full loads of crude oil on various-sized tankers from Middle East terminals to refineries in Europe and the Americas.
Bausch, et al. [2] schedule lighter and barge operations conveying multiple distilled and refined petroleum products among coastal port facilities. Tides and complex operating and safety rules govern hours of operation, each vessel has distinct cargo capacities and operating rules, and vessels must adjust their speeds to arrive at destinations when they can dock and transfer cargo.

10. RESULTS: CLF INSIGHTS

The integer linear optimization model (or, if you prefer, mixed-integer program, or MIP) presented here is the latest in a series that has evolved to answer a number of questions. Following are abstracts of our results.

Borden [3] presents seminal work on the history of CLF, recounts prior analyses and, anticipating decisions to procure the T-AKE, shapes the fundamental questions:

- How many T-AKEs will be enough?
- What is the optimal T-AKE load of ordnance and dry stores for its convertible-storage holds?
- How should we operate the T-AKEs?

He develops from scratch three single- and three multiple-battle group 90-day scenarios variously directed at the Baltic, Arabian Gulf, Philippines, Panama, and Korea, and ranging in scale from a minor contingency to a major theater war. He develops logistics planning factors, a global sea route model, and a MIP to plan CLF CONSOLs.

Borden answers that:

- We need 11 T-AKEs, plus one to allow for maintenance availability and shipyard periods;
- Rather than a single, static, optimal T-AKE load, we simply need to load what is needed each time we load it; and
- T-AKE can not only shuttle to CONSOL faster BGs, but can also join with a T-AO to serve as a station ship pair for a BG, even though this pair is not as fast as its BG customer.

Borden offers a serendipitous insight, discovered by the optimization: forward pre-positioning of a T-AKE to make a timely first CONSOL of an emergent deploying battle group as it speeds by still permits the slower T-AKE to head to a forward logistics site, reload, and follow the faster battle group in time to join it in the destination area of operation. Once there, T-AKE is fast enough to shuttle to and from CONSOL rendezvous with the faster battle group. With multiple battle group deployers, and more than one T-AKE, even more interesting chess moves arise, but all with the same essence: anticipate the position of the BGs, top them off as they pass, then follow them to their area of operation and serve them there.

Borden also evaluates the effects of improving port loading time, decreasing the distance to forward logistics sites and/or at-sea station ships (resupply ships prepositioned in advanced locations to reload shuttle ships), and either increasing shuttle ship speed or slowing planned BG speed.

We initially distinguished between a station ship and its companion BG ships, with shuttle ship consolidating the station ship, and the station ship, in turn, providing UNREPs to its companions in the BG. This turns out to be more detail than we need, so we now just consider the station ship as organic with its BG, and plan CONSOLs of the BG.

Subsequently, the navy announced plans to purchase 12 T-AKEs. (This is one more than shown in Figure 1 for the 2020 force plan.)

Givens [15] evaluates a proposed new T-AOE(X) ship, each of which would replace both a T-AKE and a T-AO with a faster (and much more expensive) station ship.

Givens refines logistics planning factors by ship type and employment state, including details of UNREP approach, rig and unrig times, and transfer rates. Givens highlights the influence of the minimum inventory levels for combatants that we use to trigger extraordinary efforts to CONSOL. Givens also introduces restrictions on shuttle access to ports, to preclude consideration of silly trans-global transits and limit the sheer size of our planning problems.

Givens concludes that we can support his scenarios without T-AOE(X), but that the cost is an increase in “off station time,” when station ships must break company with their customer ships to resupply.

Cardillo [7] examines a 90-day scenario deploying every available naval combatant. He investigates how CLF can best support forces concentrating on one major theater conflict while holding back a secondary contingency, and then turning to deal with the secondary action. His scenarios orchestrate CLF ships moving to one theater, and then transitioning to another. He also anticipates activating and deploying navy reserve-fleet tankers to supplement the active CLF fleet.

Even in the basic scenario, where all ports in both theaters are open to our CLF transports, several BGs get uncomfortably close to running out of fuel in an optimal solution. One BG arrives in the second theater and gets to within one day of running out of DFM, and another gets within three days of a DFM runout. This is a completely unacceptable situation for a BG commander, who prefers to maintain at least ten to twelve days of fuel in reserve. The result points to an urgent need for more logistical support in a two-theater scenario, especially during the swing between theaters.

DeGrange [10] models CLF operations with a forward sea logistics base—an at-sea logistics facility made up of ships that can support direct operations inland without amphibious assault or permissive access to nearly port facilities. He also evaluates navy conversion to a single distillate fuel,
embarrassment.

Wisdom” to save ourselves time, frustration, and (maybe) data bases, errors happen. We have built in a lot of “tribal immediately. Even (perhaps especially) with sophisticated planning factor, say BBL instead of KBBL for DFM con-

CLF to keep up with. Similarly, a unit error for a logistics at 100 knots for a couple of days, and this will be tough for graphical interface sea route map—might make that BG move daily BG longitude—one too small to see right away in a

tative GAMS script totals about 7000 source lines, including writing) [14] on WINTEL personal computers. A represen-
tive GAMS script about 7000 source lines, including

an imported scenario data script.

Our cascade is defined with three terms: days in planning horizon, days in planning window, and days advanced per solve. For the simple example in Fig. 3, these are, respectively, 30, 10, and 5 days. As we advance the planning window through the number of days comprising the planning horizon, we divide the optimization into three components: history, current planning window, and future. In the initial step, the first MIP solves only the current planning window, returning a solution when the integer tolerance is satisfied. The second MIP then advances to the next planning window, fixing the last-determined values for those variables in our history, and relaxes all historic constraints save those that still have influence on the new current planning window. We pay no
Figure 3. Example of a time-myopic problem cascade. We solve a 30-day planning horizon by considering a sliding planning window of 10 days, and advancing this planning window 5 days at a time. As we advance, we fix our history at that last seen in a planning window. For example, in the third integer program, we have 10 days of decisions that are fixed (days 1–10), ten days of decisions available to the model (days 11–20), and ten days that do not yet appear in the model (days 21–30). Figure from Doyle [12].

attention to the variables and data for future time periods until they comprise part of the current planning window. This iteration repeats until the final day of the planning horizon is included in the current planning horizon.

We add another key feature to our cascade: When we cannot solve a current planning window in a specified amount of time, our solver memorizes the last, “goal day” of this solve window, then halves the window length and the number of the days to advance to solve this new, and now smaller, planning window. Despite the reduced planning window, the MIP advances from where we last started and attempts to once again solve the current cascade window. If necessary, this halving continues recursively until a planning window of only two days, and an advance of just one day might fail, in which hypothetical case we would abnormally terminate. When we finally solve a planning window that ends on or after the goal day, we restore the days in the current planning window and the days advanced per solve to their original values until we either reach the end of the planning horizon, or need to repeat the recursive steps when we cannot solve a subsequent current planning window.

In practice, with an initial planning window spanning the full planning horizon, if we allow reasonable maximum solve time and interval of uncertainty, the automatic, emergent planning window reduction rarely activates. But, when it does, we get an alarm, and still reliably get a planning solution. This is a robust solution scheme. And, an alarm is a valuable telltale of model trouble.

When the planning window is a subset of the planning horizon, the variables we fix during the early periods have an impact on the later decision variables as the history period grows. For example, a T-AO replenishment on day 3 of a 30-day scenario may offer the optimal solution for this current planning window. However, establishing this same T-AO replenishment on day 3 of the 181-day scenario could result in a sub-optimal solution for the complete scenario, because the day 3 replenishment does not “anticipate” necessary later requirements in the complete planning horizon. We might see this same effect in the initial prepositioning of CLF shuttles. We allow the model to locate shuttles based on the initial planning window regardless of later requirements in the planning horizon.

Admittedly, when our cascade planning window is (or becomes) shorter than the planning horizon, this returns a restricted solution, and we forfeit the certificate of solution quality we would otherwise attain.

Nevertheless, a time-myopic optimization may be more realistic than the omniscient, global monolithic one. Our scenario, dependent on known consumption and capacity data, assumes deterministic demand, allowing us to anticipate every future battle group nuance. Such omniscience is arguably “too optimal.” The temporal cascade more closely mimics CLF planning that considers recent history and a reasonable forecast of near-term demands to develop shuttle schedules for upcoming sorties. While we concede formal optimality, and admit that the current planning window does not consider possible future spikes in demand, actual experience reveals that a cascade returns feasible solutions that are not far from omniscient-optimal. The cascade offers us a reliable solution strategy and can potentially highlight unusually challenging windows of the planning horizon, through the need to recursively halve the planning window, to alert CLF and individual fleet planners to the need for added shuttle capacity.

For exploratory optimization to merely assemble and filter scenario data for errors—preparatory exercises we admit take much more of our time than making subsequent model plays for the record after we have the problem shaped and debugged—the cascade can solve the largest problems in a minute or two on a personal computer. For important plays where we really need a solution quality certificate, or for cases where we must compare two alternatives and come to an unambiguous choice of the better one, we may spend hours solving a monolith model.

An example planning scenario includes 13 battle groups served by nine TAO and seven T-AKE shuttle ships over a
Logistics Force. The planning factors and ancillary tools developed to support this work provide a reliable foundation upon which fleet planners can base a comparative analysis. Clearly-stated modeling and data assumptions combine with mathematical optimization to render advice with two distinguishing advantages: optimization has earned its reputation for teasing some surprising insights from the scenarios, and each monolithic solution comes with a quality certificate assuring that no better solution remains undiscovered. These advantages convey an unusual level of confidence, especially in comparison to ubiquitous simulation tools.

We have been studying these problems long enough now to see some of our prescriptions come to life in the CLF fleet. The basic question is always “Can we logistically support this plan?” The plans, and there are a lot of these we constantly tend, express our navy’s commitments to support current defense doctrine (e.g., see the latest Quadrennial Defense Review [11]).

ACKNOWLEDGEMENTS

The authors are grateful to OPNAV N42 (Navy Operational Logistics), CAPT Jim Stewart, USN-SC, and CDR Frank Futcher, USN-SC, who have tirelessly helped dig up every obscure detail that they have asked for, and offered on-call expert judgment. By direction of N42, the authors can provide modeling code and an illustrative, unclassified scenario.

REFERENCES


