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Optimizing Schedules for Maritime Humanitarian Cooperative Engagements from a United States Navy Sea Base

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This paper introduces Global Fleet Station Mission Planner (GFSMP), an optimization tool to aid in mission planning and the scheduling of humanitarian assistance missions for the US Navy. GFSMP helps fleet staffs to examine how one naval ship, which was deployed for an extended period (e.g., six months), with embarked teams can best provide humanitarian assistance. We illustrate the application of GFSMP using notional data from the fall 2007 Gulf of Guinea African Partnership Station demonstration, which the Commander, US Naval Forces Europe–Commander, Sixth Fleet developed, and by its use in the Trident Warrior 2009 exercise, which the Commander of the US Second Fleet conducted. In contrast to manual planning GFSMP's solutions significantly improve total mission value achieved and reduce costs. Equally important, GFSMP quickly provides decision makers with courses of action, including partial rescheduling of existing plans, in response to exigent changes.

"Do good with what thou hast, or it will do thee no good." *William Penn, American colonial leader (1644–1718)*

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A Cooperative Strategy for the 21st Century Seapower (Allen et al. 2007) elevated humanitarian assistance to a core capability for the United States Navy (USN), United States Coast Guard (USCG), and United States Marine Corps (USMC). It encourages forward maritime forces to establish global maritime partnerships and to engage in humanitarian assistance and crisis response, in addition to their traditional roles such as maintaining the capability to win our nation's wars.

The establishment of the African Partnership Station (the "station") by the Commander, US Naval Forces Europe–Commander, Sixth Fleet (CNE-C6F) demonstrated the ability of a ship to support humanitarian engagements. The station consists of a ship or ships deployed to African nations to host engagement teams to conduct military training, humanitarian efforts, and, if called upon, theater security operations. Henceforth, we refer to all these efforts as theater security cooperation missions.

The station may be supported by several types of ships with different capabilities. For example, in early 2009 the station consisted of a large amphibious ship, the USS *Nashville*, along with a smaller frigate, the USS *Robert G. Bradley*. In October 2007, the dock landing ship USS *Fort McHenry* departed for a six-month deployment to the Gulf of Guinea (GoG) (Figure 1), forming a station with the high-speed vessel *Swift*. This station performed multiple humanitarian assistance missions, including delivery of supplies to various clinics and schools off the coast of Monrovia, Liberia (Navy Office of Information 2008) and construction projects for schools in São Tomé and Principe and Port Gentil, Gabon. As US Navy Captain John Nowell, Commander of the African Partnership Station, stated, "We will always make the point that we are not here for APS just to do humanitarian assistance kinds of actions. We are here to do maritime safety and security but we have the ability to do a lot with respect to humanitarian assistance and community outreach. It is very good for promoting goodwill and forming relationships" (Goyak 2008).

Scheduling activities supported from a sea base is a complex planning problem with considerations such

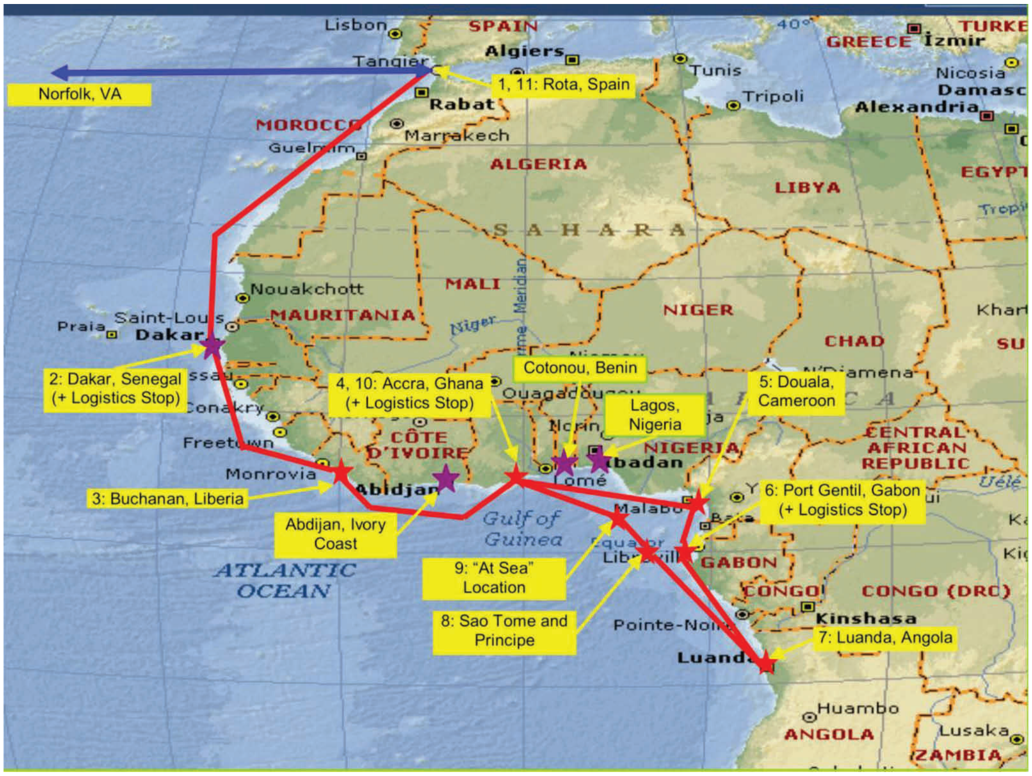

Figure 1: The map shows the Gulf of Guinea (GoG) region and original CNE-C6F's dock ship demonstration proposed route (after an e-mail from Commander Michael Fulkerson to the authors on January 26, 2007).

as ship capacity to host engagement teams, length of deployment, logistics support for the ship and teams, budget, mission selection tailored for specific countries, and individual mission lengths. Currently, because most of this planning is done manually, it requires extensive effort and constant adjustments when new missions are added to a proposed deployment or when an exigency occurs that necessitates rescheduling. CNE-C6F's deployment problem for the station is particularly demanding in the GoG region, where long distances stress logistics capabilities, and multiple and varying engagement mission teams are needed in various countries.

This paper presents the Global Fleet Station Mission Planner (GFSMP), an optimization tool to aid in mission planning and scheduling. GFSMP is a prototypic planning tool that allows fleet staffs to examine the feasibility of future deployments and activities. The GFSMP model identifies how one naval ship with embarked teams can best meet the logistical requirements necessary to provide training and support in an area of responsibility such as the GoG. It suggests solutions, i.e., a deployment schedule and a combination of teams required to perform the missions, to guide planners in optimally using the naval resources available in the region, and it provides insights for future planning.

GFSMP is applicable in all theaters using afloat basing (i.e., naval platforms that form a sea base of operations) to support engagement teams; for example, planners can use it to consider many scenario-specific constraints and thus to understand how different ship types may be used to accomplish similar missions. Changing deployment time, team availability, budget, and other data allows planners to understand where trade-offs can be made. GFSMP simultaneously allocates training teams to a ship and schedules its voyage and the missions' execution to achieve maximum theater security cooperation. This achievement is assessed as the aggregate value of missions carried out during the planning horizon, where each mission's value represents an informed, numerical specification of its contribution to theater security cooperation should the mission be performed.

To evaluate GFSMP and illustrate its application, we use notional data from the fall 2007 GoG African Partnership Station demonstration, which the CNE-C6F GoG regional planning team developed and the Commander, US Second Fleet (C2F) used during its Trident Warrior 2009 exercise.

Relationship to Other Routing and Scheduling Models

Ship routing and scheduling have been the subjects of multiple scholarly articles since Dantzig and Fulkerson (1954) introduced their elegant tanker scheduling problem in which a shipping company requires a fleet of ships of minimum size to meet service requirements among six ports. The authors convert this apparently complex problem into a standard transportation-problem formulation for which there are well-known, specialized solution methods.

Christiansen et al. (2004) present a comprehensive review of recent literature on ship routing and scheduling. They also discuss models at the strategic level, such as fleet and sea-network planning, which usually overlook the tactical or operational details present in such planning.

Although military applications involving sea routing and scheduling abound, few are formally documented in the literature; humanitarian assistance applications are rarely documented partly because most USN humanitarian missions use little formal routing and scheduling. Ward (2008), based on his experience aboard the US hospital ship *Comfort* during its humanitarian deployment to Latin America and the Caribbean (The White House 2007), describes how medical teams and other personnel may benefit from optimized ship-to-shore transportation scheduling using the ship's helicopters, watercraft (both owned and rented), and ground transportation provided by the host nation. Ward (2008, p. 58) also highlights the potential for improving operations for the ashore mission sites "which are dynamic, unique, and involve queuing and optimization issues, and definition and inventory management of a customized allowance list of pharmaceuticals," and strategic decisions "involving the selection of countries and duration of stay... [and] modeling of the personnel assignment... with consideration of the possibly unique mix of skills required." The latter is a design component present in GFSMP, where the ship's configuration (composition of teams) is optimized along with other operational decisions.

The lack of operations research analysis in US Navy humanitarian assistance operations is apparent from our interviews with CNE-C6F's regional planning team leader, Commander Michael Fulkerson. In a conference with the authors on October 19, 2006, he reported that current naval presence in the GoG can be adequately supported for a limited time, but extended deployments over several months "prove problematic." Operational planners usually recommend an initial proposal that follows the commander's intent for the overall mission. Then, logisticians (e.g., supply officers) analyze the proposal's feasibility and recommend adjustments to the planners until both groups reach a consensus in terms of both operational goals and logistic requirements. Currently, however, the planning for these missions and associated ship schedules is being carried out "the best that we [planners] can, but without the support of any formal operations research analysis," according to Fulkerson.

Like GFSMP, many navy scheduling applications perform certain tasks to maximize their effectiveness. Brown et al. (1990) discuss the employment schedule (involvement in major operations, exercises, maintenance, etc.) of a fleet of military ships, guaranteeing a high level of combat readiness. Nulty and Ratliff (1991) formulate a large-scale integer program to model the deployment of a fleet of ships, where the primary goal is to satisfy the largest possible number of requirements. Darby-Dowman et al. (1995) and Brown et al. (1996) pursue the same goal for the schedule of a fleet of US Coast Guard cutters. Unmet requirements are penalized, establishing a trade-off between the requirement's importance and the resources it consumes. Cline et al. (1992) use the solution of a travelling salesman problem to develop a fast, good-quality heuristic solution for the problem of routing and scheduling Coast Guard buoy tenders.

Psaraftis et al. (1985) study the problem of assigning cargoes to available navy (i.e., Military Sealift

Command) ships in an emergency so that they can reach their destinations within prescribed time limits. Brown and Carlyle (2008) model the routing and scheduling of a logistics force (i.e., a fleet of 30 auxiliary ships carrying fuel, ammunition, dry cargo, and food) in support of US Navy combatant groups worldwide. Salmerón et al. (2009) use stochastic optimization to discuss the timely delivery of cargo in a hostile environment that could disrupt port availability.

Most routing and scheduling problems at the operational level fall in the broad category of the well-known vehicle routing problem (VRP), which entails designing the optimal set of routes for a fleet of vehicles and the vehicles' schedules to serve a given set of customers. The interest in this type of problem is motivated by its practical relevance and by its considerable difficulty (Toth and Vigo 2002). GFSMP has requirements not typically found in a standard VRP. For example, it determines an optimal ship–team configuration; it then allows any team to be dropped off at a location for the duration of its mission and be recovered again later when the mission is complete, allowing the ship to carry out other missions in other ports in the meantime.

Problem Details and Modeling Assumptions

GFSMP posits a navy vessel that is equipped with teams to carry out theater security cooperation missions in its area of responsibility during a planning horizon. Its primary objective is to devise both an optimal route and mission schedule that maximizes the total mission value earned. The simultaneous optimization is the key complication here for planners. Because the total port visit fees incurred while conducting the missions can be substantial, GFSMP's secondary objective is to minimize these fees. We use the term *country* and *port* interchangeably to refer to locations where the ship may conduct missions and (or) obtain fuel or provisions (e.g., food and replacement parts). One or several fictitious *at-sea* ports represent locations where the ship may, for example, conduct multicountry training missions or exploit opportunities to schedule replenishments (fuel or commodities) at select times when supply ships are in the area.

While underway, the ship must stay at or above its minimum fuel level and maintain sufficient provisions for all its personnel. We plan for a fixed amount of provisions to be consumed every day per person. However, the amount of fuel consumed depends on the ship's activity; three burn rates may be selected: underway (i.e., at a nominal transit speed), at anchor, and moored pier-side. Travel days between any pair of ports are precalculated based on feasible sea routes and the vessel's nominal transit speed. The ship incurs a port-dependent charge for each day it remains in port.

For each mission–country pair, we assume that adequate support, transportation, and (or) training facilities to conduct the mission have been verified. In addition, we assume that the team resources and physical requirements needed to conduct the missions, including storage space, communications, etc., can be met by the ship or host nation. Teams are self-sufficient while conducting their missions ashore; i.e., the ship does not have to remain in port unless the mission is specifically so restricted. In addition, some missions may require the ship to be moored pier-side (e.g., to load or unload heavy equipment) during the first and last days of the mission, whereas other missions may allow the ship to remain at anchor.

Every candidate mission in each country has a predetermined value (the higher the better), a cost, and a fixed duration, and it can be completed by one of several potential teams. Some missions have a precedence requirement; i.e., a mission may require one or more other missions to be completed before it can be carried out. Each mission requires the ship to deliver a qualified team to the respective country to complete the mission and to recover the team immediately upon the mission's completion. Each team may have the capability to complete several missions, but only one at a time.

Each type of team has limited availability and a specified number of personnel; in addition, the amount of berthing space to provide for all personnel of all teams assigned to the ship is limited. Thus, in addition to selecting the optimal routing and scheduling, GFSMP must determine the deployment's optimal team configuration.

We present the optimization model used to solve this problem in the appendix. In the next section, we describe the planning scenarios we used with that model.

Description of Resources and Constraints

Overview of Scenarios

The baseline scenario is based on a 2007 GoG demonstration developed by the CNE-C6F GoG regional planning team, which assumes a dock landing ship (dock ship—LSD in Table 1) as the station during a six-month planning horizon and Rota, Spain as the origin and destination port. The available budget of $10 million must cover all mission and port costs in all countries.

The C2F subsequently adopted the baseline scenario for the Trident Warrior 2009 exercise, replacing the Dock ship with the amphibious assault ship USS *Kearsarge* (Amphib—LHD in Table 1). The planning horizon for the exercise is April 10, 2009 (day 1) through October 6, 2009 (day 180). The exercise also adds new missions and logistic requirements as well as surprise exigencies, e.g., a ship suffering a propulsion casualty and a replacement of the Amphib large deck by a high-speed vessel ship (Speed—HSV in Table 1).

Ship and Team Characteristics

Table 1 displays the ship characteristics we used in our scenarios. We observe that Amphib has a fuel capacity of approximately 43,000 barrels (bbls)—42 gallons—of marine diesel fuel. To mitigate the risk of poor weather or other unforeseen circumstances, such as a sudden mission reassignment, naval regional commanders can establish minimum fuel levels at any time. For Amphib, we set this level at 60 percent of its capacity. This level also helps maintain the best stability because under certain levels the ship's rolling motion becomes problematic and may reduce overall performance. Given that underway consumption at 14 knots is 1,071 bbls per day, Amphib's endurance is approximately 16 days while in transit. Burn rates at anchor and at dock are estimated at 214 bbls per day for auxiliary steaming. In addition, this station must obtain general supplies at least every 25 days.

Table 2 describes the available teams, the maximum number of teams available at any one time, and the size (i.e., number of personnel) of each team; it also defines abbreviated team names for later reference. All team sizes reflect the various teams predicted by the Naval Expeditionary Combat Command, except for the ship crew (CREW) team. CREW describes any number of personnel assigned to the ship (rather than ashore) to carry out an onboard mission. These missions often include military-to-military training, which

Team	Available (No. of teams)	Size (persons/team)
Coast Guard Detachment (USCG)	2	4
Navy Warfare Command Component (NWC)	4	25
Explosive Ordnance Detachment (EOD)	3	12
Naval Construction Force (NCF)	4	13
Maritime Civil Affairs Group (MCAG)	2	6
Expeditionary Training Command (ETC)	4	4
Maritime Expeditionary Security Force (MESF)	4	24
Medical Support (EXMED)	2	5
Other Reserve Unit (RES)	2	4
Maritime Domain Awareness (MDA)	2	4
Ship Crew (CREW)	3	1
Marines	1	150

Table 2: The number available and size are shown for GFSMP teams.

Ship	Beds	Resupply time (days)	Underway speed (knots)	Fuel consumption (bbls/day) underway	at anchor	docked	Fuel capacity (bbls) (min. level)
LSD							
Dock ship	414	25	12	277	69	69	13,045 (60%)
LHD							
Amphibious ship	1,670	25	14	1,071	214	214	43,091 (60%)
HSV							
Speed ship	142	10	20	400	100	0	3,700 (20%)

Table 1: Ship characteristics, as assumed in GFSMP scenarios, are shown for Dock, Amphibious (Amphib), and Speed ships.

subject matter experts or senior enlisted personnel usually conduct, or community relations projects. Larger numbers of personnel contribute to the community relations projects or preplanned humanitarian assistance missions with the communities ashore. GFSMP currently limits the simultaneous number of these missions to three at any given time. For the smaller ships, e.g., Speed or Dock ships, this is a realistic number. Planners can adjust this number to suit requests by the host nations.

Mission Data

Table 3 describes the initial set of countries, missions, and mission–country demand pairs. Missions can be classified into several categories (e.g., medical, infrastructure) with the following attributes: duration, cost, mission value (i.e., theater security cooperation (TSC) value), and mission-capable team types. Countries have associated daily port costs. Some ports can refuel and (or) resupply the station ship. The at-sea port represents a location off the coast of Nigeria, approximately 175 nautical miles south of Lagos. Norfolk, Virginia is the origin and return port for the station.

The missions are a subset of those designated by CNE-C6F's long-term plan to be carried out between 2007 and 2016. Although the mission values shown are estimates based on information from previous-mission feedback, they are ultimately subjective. The total mission value for the 66 mission–country pairs is 377. Individual values range from one point for band lessons, which several countries require, to 30 points for the 21-day "theater security task force" mission in Nigeria, involving a 150-person marine team. This mission is the only one with a required starting date on planning day 62 (June 10). Some missions are *in-port* missions. For example, community relations requires the station to remain in-port while the mission is conducted. Mission-duration estimates are based on experience in previous deployments.

Distances between ports are calculated using direct, port-to-port, great-circle routes (if navigable), or shortest-path distances through sea-way points to avoid land. At a constant speed of 14 knots, Amphib needs approximately 10 days to travel from its home port of Norfolk to Dakar, Senegal, in West Africa. This port is only a refueling and resupply port in our baseline scenario. Distances between ports with assigned missions range from 0.18 days to travel from Port Gentil, Gabon to São Tomé, São Tomé, and Principe (a nation later referred to as STP) to 4.95 days to travel from Buchanan, Liberia, to Luanda, Angola. We use GFSMP with daily time fidelity, so we have adopted the convention that all travel times exceeding one-tenth of a day will be rounded up to a full day. For example, 6.08 days of travel from Senegal to Cameroon are treated as 6.00 days in GFSMP, and 5.13 days from Senegal to Nigeria are conservatively rounded up to 6.00 days.

The countries listed in Table 3 can provide both fuel and supplies. However, countries can sometimes provide one but not the other.

The 1,670 beds for teams on Amphib exceed the space needed. However, bed space is more restrictive on other ships. GFSMP favors fewer teams on board when possible, i.e., in the presence of multiple optima.

Results

CNE-C6F Demonstration

First, we evaluate a preliminary version of GFSMP to confirm the feasibility of carrying out all possible missions during a six-month deployment, following the manual schedule (Figure 1) created by CNE-C6F planners; it assumes the Dock ship for the 2007 station and Rota, Spain as the Dock ship's origin and destination. Numbered ports indicate the sequence of stops provided by CNE-C6F planners.

For this scenario, GFSMP shows that the maximum mission value can be accomplished in only five months and at a lower cost.

In addition, we conducted excursions to assess trade-offs; for example, we found the following:

(1) Reducing the total mission value by 10 percent reduces costs by 27 percent;

(2) within a reduced mission time of only three months, we can still achieve 85 percent of the total mission value; and

(3) replacing the Dock ship with the smaller, faster, but less fuel-efficient Speed results in significant cost savings. This is partly because of reduced in-port costs as well as Speed's fast-transit capability between ports; this allows it to drop off teams ashore and leave for another port more frequently than the Dock ship can. On the downside, reduced bed space may become problematic for a larger mission set.

	Accra (GHANA)	Port Gentil (GABON)	São Tomé and Principe (STP)	Douala (CAMEROON)	Luanda (ANGOLA)	Norfolk, VA	Buchanan (LIBERIA)	At sea	Lagos (NIGERIA)	Dakar (SENEGAL)	TSC value	Duration (days)	Cost ($)	Capable team(s)
Port with fuel and supplies	Yes	Yes	No	No	No	Yes	No	No	Yes	Yes				
LSD/LHD port costs ($ × 1,000 per day)	72	190	45	145	200	0	115	0	100	185				
Medical														
Medical OPS/Readiness	×	×									3	5	5,000	EXMED
Infectious diseases	×										4	3	7,500	EXMED
Infrastructure														
Dig wells and eng. reconstruction	×	×	×	×			×				5	10	65,000	NCF
Renovate medical clinics	×	×									2	3	10,500	NCF
Renovate schools	×	×									2	3	10,500	NCF
Road improvement	×	×	×	×							4	10	6,500	NCF
Utility improvement	×	×	×	×							5	10	6,500	NCF
Infrastrucutre analysis →	×	×	×	×							5	5	32,500	NCF
→ airport improvement	×										6	15	97,500	NCF
→ port improvement							×				9	20	13,000	NCF
Civil/Communications														
Public affairs	×	×	×	×	×		×				5	3	9,000	MCAG
Band lessons	×	×	×	×							1	2	4,000	RES
Community relations*					×		×				3	2	1,000	CREW
Surface maritime activities														
Port security MTT	×						×				8	5	45,000	USCG, NWC, MESF
Multinational exercise*								×			10	5	2,500	CREW
Shiprider embarks*								×			7	5	2,500	CREW
Small boat/Boat patrol maint.*	×		×								6	5	7,500	CREW, ETC
ISPS assist/CERT visit	×	×	×	×							8	10	20,000	USCG, RES
Hydro survey	×		×								8	10	20,000	USCG
Mine clearance					×						7	10	60,000	EOD
Military and leadership training														
Communications	×	×		×							4	5	10,000	ETC
Officer leadership	×			×							7	5	7,500	CREW, ETC
NCO professional development	×										6	3	1,500	CREW
Maritime domain awareness activities														
Ship visit*					×		×				5	5	2,500	CREW
AIS receive sites	×		×				×				9	10	65,000	NCF
Cooperative security	×										10	5	10,000	MDA
GFS demo*								×			7	3	6,000	CREW
MDA site survey →											7	5	10,000	MDA
→ MDA demo*								×			7	2	4,000	MDA
Theater security task force														
Theater security task force (TSTF)									×		30	1	400,000	Marines
TSC value by country (Total 377)	104	41	63	44	20	0	44	31	30	0				

Table 3: Mission data, port (country) data, mission–country pairs, and mission–team pairs are shown. An asterisk (*) indicates that the mission requires the ship to remain in-port or at the at-sea location if the mission is at sea. Arrows (→) specify mission prerequisites. TSC value refers to the mission value.

Spitz (2007) gives details for the CNE-C6F demonstration.

C2F Trident Warrior Exercise: Baseline Scenario

The first phase of the Trident Warrior 2009 exercise uses the data described in the previous section and Amphib as the station. Despite the addition of a costly and lengthy mission in Nigeria and the longer distance from Norfolk, GFSMP schedules all missions during the 180-day horizon, achieving all 377 mission points and spending less than the $10 million budget.

Figure 2 shows a snapshot of the recommended schedule for a subset of planning days covering one month of the deployment. The two top rows represent the calendar and deployment days, respectively. The row labeled "Country" indicates the country where the ship is in-port; blue indicates that the ship is underway.

The chart shows GFSMP's flexibility for accommodating multiple concurrent missions. Specifically, the station comes from recovering three teams in Cameroon, where it left four other teams ashore and then sailed for Nigeria. It drops off the marines for their theater security task force mission on planning day 62 and returns to Cameroon to recover the four teams who have just completed their missions. While the theater security task force mission is still ongoing, several other missions take place in Gabon; the station then sails back to Nigeria to recover the marines upon completion of their mission. The subsequent set of missions is at sea and requires the station to remain at the at-sea location.

The team composition of the station consists of 252 personnel, divided as follows (an asterisk indicates that the maximum number of teams available is used; team codes are listed in Table 2): two USCG*, one EOD, four NCF*, one MCAG, one ETC, one EXMED, two RES*, one MDA, a large Marines* team of 150 USMC personnel, and three CREW* teams.

C2F Trident Warrior Exercise: Underway Replenishment

The "X" marks in Figure 2 indicate refueling and resupply opportunities over time. Although GFSMP produces a self-sustained schedule for the station ship by just taking fuel and supplies from designated

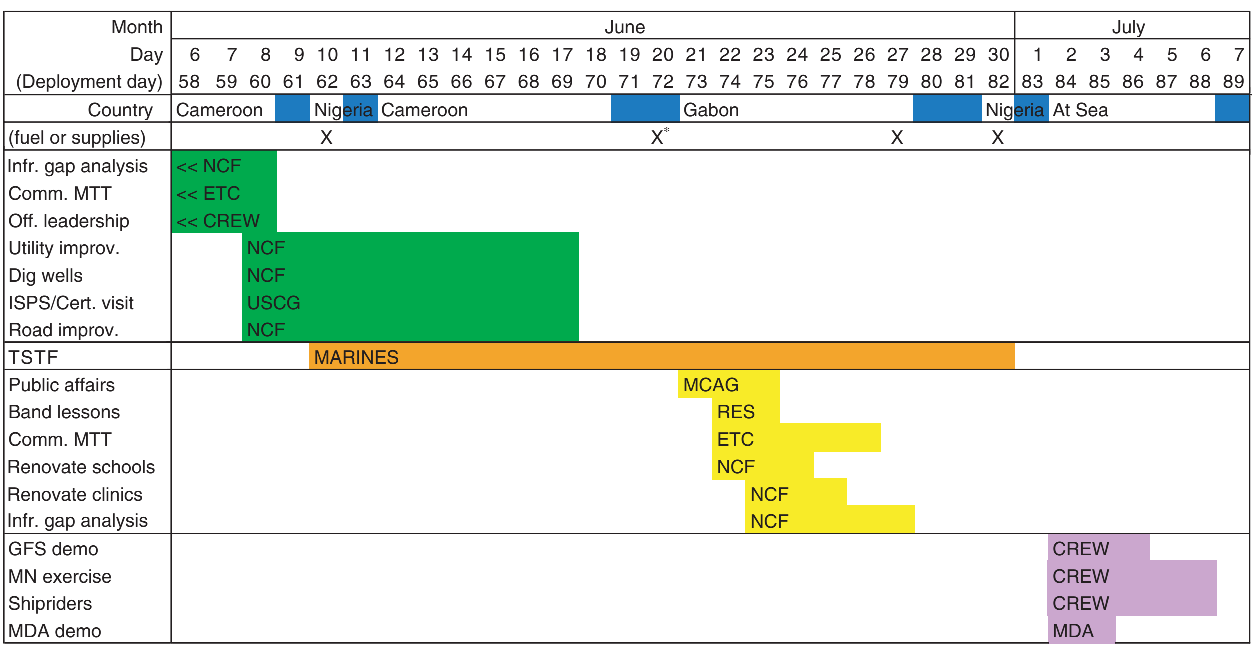

Figure 2: The GFSMP schedule for planning days 58–89 of 1–180 is displayed. Multiple missions are planned around the three-week duration of the mandatory theater security task force mission carried out by a marine team.

ports, navy planners typically ensure that a station ship deployed for an extended period will receive support by the combat logistic force (CLF). Thus, taking GFSMP's schedule as an input, we use a CLF planner (Brown and Carlyle 2008) to schedule an underway replenishment date and location schedule. The CLF planner recommends this on day 72 (indicated by an "X*" mark), shortly before the station arrives at Gabon. The replenishment would allow the station to skip the refuel and resupply port call originally planned in that country on day 79.

One exigency analyzed by planners using GFSMP during the first phase of Trident Warrior exercise consists of a casualty suffered by the CLF supply ship on June 18, two days before its meeting with the station. One of its engines has been damaged, reducing its speed and preventing it from carrying out the underway replenishment of the station at the planned date and location. The C2F planners used GFSMP to produce several possible responses to this exigency and presented these to the fleet commander for consideration.

Examples of these courses of actions (in brief) include the following.

(1) Primacy of theater logistics: The supply ship is positioned for the most expeditious repairs and central theater position, the underway replenishment is cancelled, and the supply ship returns to either the port of Dakar, Senegal or the port of Rota, Spain for repair. The station obtains fuel and supplies in Gabon as in the baseline scenario.

(2) Primacy of station mission: The supply ship continues at the lower speed to meet the station at the initial location but at a later time. This is still feasible given the current location of the supply ship, the new meeting time on day 80 (June 28), and CLF planner verification that the supply ship's later return to the Mediterranean would not adversely impact overall CLF requirements elsewhere. This option causes no impact on the station schedule but requires the supply ship to travel further east into the GoG with a damaged engine.

(3) Compromises between CLF and station missions: These compromises include several possible courses of action in which the station travels to new meeting locations on certain dates saving the supply ship from traveling to Gabon. This may have an impact on the station schedule, requiring some missions to be advanced or postponed to maintain the mission's value.

The fleet commander must ultimately decide the best course of action that serves the joint interest of the station mission and the navy. GFSMP ensures the best solution for the new exigency, according to the commander's intent. The revised plan also adheres to a "persistence" specification made by the commander that missions carried out at the at-sea location starting July 2 had to remain within the prescheduled time windows because of their multinational character. The concept of optimization with persistence (Brown et al. 1997) is used, for example, in the recent work by Fagerholt et al. (2009), who reschedule and reroute ships ensuring that, given the new information available, their solutions are near optimal and close to a prespecified baseline plan. In GFSMP, we do not implement persistence based on relative penalties for deviations with respect to a baseline plan. However, we implement persistence for port calls and mission execution as requested by the commander, as in the above example.

C2F Trident Warrior Exercise: Amphib Loitering at Anomie Oil Platform

The second phase of the Trident Warrior exercise hypothesizes three scenarios requiring the station to remain loitering in the vicinity of the Anomie Oil Platform (Anomie-OPLAT) off the coast of Nigeria to engage in a special anti-piracy and security mission.

Scenarios 1 and 2: Amphib continues with its missions after Anomie-OPLAT.

Two scenarios assume that on day 73 (June 21) the large-deck Amphib receives orders to interrupt its current visit to Gabon so it may begin its new mission at Anomie-OPLAT on day 77 (June 25). The duration of this mission is 31 days for Scenario 1 and 45 days for Scenario 2. We assume that CLF support for fuel and supplies can be provided to Amphib during those days and that it will be released to continue its deployment after that period.

Several missions in Gabon must be cancelled to allow Amphib to recover the last team on day 75 and sail for Anomie-OPLAT in time. The scenarios also assume the marine team currently in Lagos, Nigeria, with an ongoing theater security task force mission, will be flown by helicopters to Amphib upon completion of its mission, which is scheduled to finish on day 82.

Because of its exclusive dedication to the Anomie-OPLAT mission, a disruption to the incumbent schedule is inevitable. To assess the loss in mission value, we must again plan for the remaining days of the schedule in each scenario. Planning personnel may be tempted to use the schedule in place as the basis for such a reassessment. For example, one may assume that missions scheduled for the blocked days are simply forfeited. Skipping such missions has the advantage that the rest of the schedule is unchanged after the station is released. However, if some are high-value missions, planners may need to seek other alternatives.

Another strategy could be shifting the scheduled missions. Amphib would continue with the same mission sequence as in the original schedule, from the point where it left before the Anomie-OPLAT requirement. Of course, the station must still return to its home port by day 180; therefore, the last missions in the original schedule would be skipped. Although these back-of-the-envelope alternatives may sound appealing to planners, who are under great time pressure as the new requirements unfold, they may produce suboptimal solutions, as we show using counterexamples.

Instead, we use GSFMP to reschedule the station after it has been released from its duties at Anomie-OPLAT for the remaining days in the planning horizon. As in the first phase of the Trident Warrior exercise, the commander could impose any additional conditions to limit the flexibility of the new schedule. However, we were directed to perform a comparison assuming no other restrictions.

The comparative results of the three strategies follow. To put these numbers in perspective, although the maximum mission value achievable over 180 days is 377 points, by planning day 77 only 137 points are pending to be collected. Thus, for each scenario and strategy, we indicate the absolute mission value lost, the percentage with respect to the 137 maximum, and the number of missions cancelled by country.

Scenario 1. Thirty-one days blocked (planning days 77–107):

—Skipping: 72 points (53 percent). All missions in Angola, at-sea, and Gabon, and one in STP.

—Shifting: 43 points (31 percent). Three missions in Liberia, two in Ghana, two in STP, and one in Gabon.

—GFSMP: 23 points (17 percent). Two missions in Ghana, two in STP, and one in Angola.

Scenario 2. Forty-five days blocked (planning days 77–122):

—Skipping: 87 points (64 percent). Same as in Scenario 1, and four more missions in Liberia.

—Shifting: 64 points (47 percent). Same as in Scenario 1, and all missions in Liberia.

—GFSMP: 39 points (28 percent). All missions in Angola, two in Ghana, and one in Liberia.

As we can see in both scenarios, GFSMP achieves significant improvements over back-of-the-envelope strategies.

Figure 3 shows the chart for the scenario with 45 days blocked. The chart starts on day 124 (August 20) when the ship reengages in conducting missions. We observe that there are multiple simultaneous missions in Gabon, STP and the at-sea locations. A 10-day, non-in-port, ashore mission is scheduled in Gabon between days 140 and 149, allowing us to use the intermediate days to carry out several missions that require the station to remain at the at-sea location. We also notice the optimized use of naval construction force teams to perform multiple missions simultaneously in different countries; they never exceed the four embarked teams at any given time. For example, during the first visit to Gabon, the road improvement mission must wait until day 131 to begin because all four naval construction force teams are engaged in two other missions in Gabon and two in STP.

Scenario 3. Speed replaces Amphib to provide mission value.

In the third scenario, Amphib receives notice on planning day 74 (June 22) that it will need to rejoin its combatant group at sea by the end of July 8 (day 90). Planners decide to allow Speed to assume the station for the remaining days. That is, a subset of the current teams currently embarked on Amphib will be transferred to Speed. Specifically, Speed is expected to take aboard the teams on July 10 (day

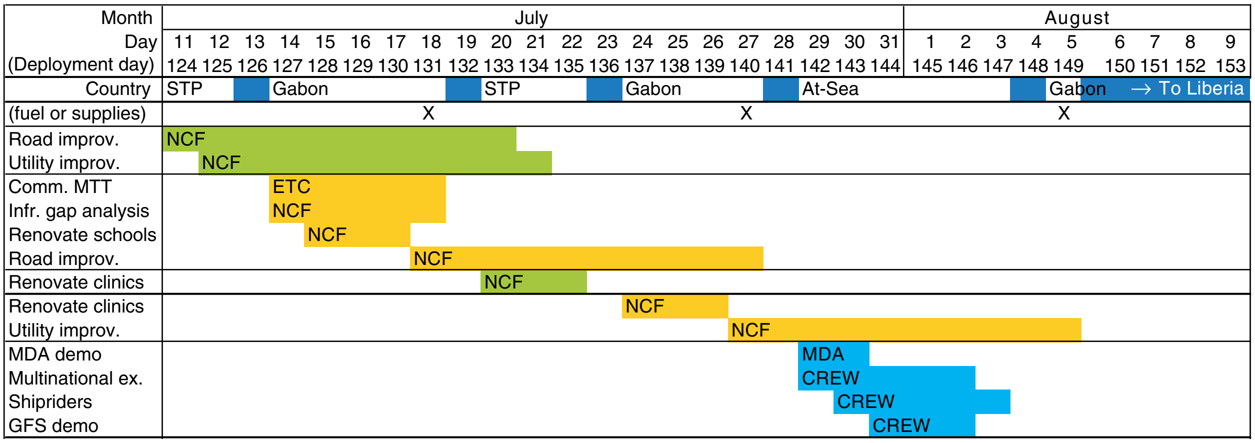

Figure 3: The chart displays GFSMP rescheduling for planning days 124–153 of 1–180 after Amphib is required to remain at sea during days 77–122.

92) at the at-sea location and will employ them until September 21 (day 165), when they should be returned to Amphib at the same location. This should give Amphib enough time to return to its home port in Norfolk by planning day 180 with all of its crew and teams.

We make certain assumptions for Speed (Table 1). For example, we assume a nominal speed of 20 knots. Although Speed can travel much faster, this capability is weather-dependent and incurs much higher fuel consumption that is not routinely approved by the navy; this also implies less endurance and more frequent refueling needs in an area of operation where fuel availability is limited. The required resupply duration of 10 days is also an important limitation compared to the endurance of either the Dock or Amphib ships.

We also assume that Speed has 142 beds available (97 permanent plus 75 temporary, minus 40 for its crew). Because the teams embarked on Amphib total 252 people, we limit the transfer of personnel according to the current Amphib configuration of teams.

Other data for Speed include, for example, port costs with respect to those displayed in Table 3 for Amphib. The updated costs range approximately from 10 percent lower in Douala and Dakar to 35 percent lower in Luanda, Port Gentil, and Buchanan.

Given that there is sufficient time between the notification and the station transfer days, planners also consider adding new missions to the schedule to take advantage of the speed of Speed. Also, to have more flexibility to add demand requirements involving the large Marines team, this is split into five Marines groups (see Table 4), which can now engage in different missions independently.

The requirements for this scenario add 29 mission–country pairs as follows: 3 in Dakar, 13 in Lagos, 8 in Cotonou, Benin, and 5 in Abidjan, Ivory Coast. The purple stars in Figure 1 indicate ports that have new missions added. The new missions add 158 points to the original value of 377, making a maximum of 535 points possible. At the team hand-off date (day 92), Amphib has already mustered 283 points, leaving 252 as the maximum that Speed can achieve. The GFSMP solution achieves 212 points (84 percent of the possible points) between days 92 and 165, for a

Mission	Mission value	Duration (days)	Cost ($)	Capable teams (size)
Theater security task force (TSTF)—Original	30	21	400,000	Marines (150)
Theater security task force—New	8	21	366,000	Marines-1 (120)
Marine leadership—New	5	3	1,500	Marines-2 (2)
Marine ground security training—New	7	5	10,000	Marines-3 (13)
Marine HA/DR—New	5	10	15, 000	Marines-4 (5)
Marine reconnaissance—New	5	5	7,500	Marines-5 (5)

Table 4: We show how the original theater security task force mission and marine team used in Scenarios 1 and 2 are broken down for Speed replanning in Scenario 3. HA/DR, humanitarian assistance/disaster relief.

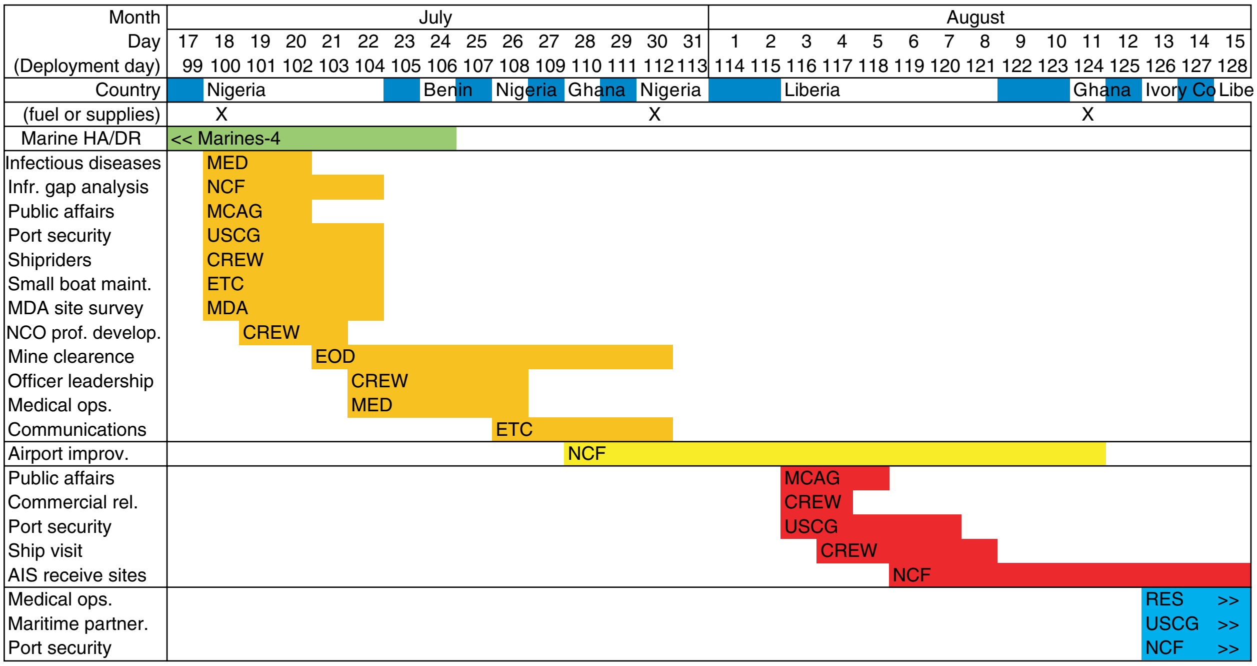

Figure 4: The chart displays GFSMP rescheduling for planning days 99–128 of 1–180 after Amphib is required to remain at sea starting on day 90 and Speed takes over starting on day 92.

combined total of 495 points. During this short period, Speed makes a total of 21 trips. Figure 4 shows the schedule details for days 99 to 128. All countries are visited except Cameroon, where all missions had already been performed, and Senegal.

Conclusions

GFSMP is a mission-planning and scheduling optimization tool designed to provide fleet staffs with the ability to examine the feasibility of future deployments and activities in support of the Global Fleet Station concept. In this paper, we have illustrated its application to exercises developed by the Commander of CNE-C6F and the C2F for humanitarian and other theater security cooperation missions in GoG.

GFSMP can be used for long-term planning and sudden exigencies requiring rescheduling. We have demonstrated significant improvements over manual planning in total mission value achieved and costs.

After its initial demonstration and use by CNE-C6F staff, GFSMP was selected by Navy Warfare Development Command and C2F staff to be used in the US Navy's 2009 Trident Warrior series of exercises for planning and further evaluation as a potential tool for fleet-wide use. This exercise was mainly devoted to maximizing the effectiveness of humanitarian assistance to African nations bordering GoG. Schedule outputs from GFSMP have been used inside this exercise series by the C2F to meet emerging demands from the GoG.

GFSMP is applicable in all theaters using afloat basing to support engagement teams. However, it is not intended to be a stand-alone decision aid. Instead, as it continues to be used by navy staffs and modified with their suggestions, the longer-range intent is for it to be integrated into a suite of decisions aids supporting maritime planning staffs.

Appendix

This appendix describes GFSMP's basic model formulation.

Indices and Sets

T: time periods (days), $t \in T = \{1, 2, \ldots, |T|\}$.

C: countries, including "at-sea" predesignated locations, $c \in C$; c^0 is the home port.

M: missions, $m \in M$.

U: team types, $u \in U$.

$C^F, C^P \subset C$: subset of countries that can provide fuel and provisions, respectively.

$M^W \subset M$: subset of in-port missions.

$B \subset M \times M$: subset of (m, m') pairs where mission m must precede mission m'.

$J \subset M \times U$: subset (m, u) pairs where mission m can be carried out by team type u.

$K \subset M \times C$: subset of (m, c) pairs where mission m is solicited by country c.

Parameters and Units (units are in parentheses)

r: number of beds available for all team personnel (persons).

p_u: number of people in each team of type u (persons per team).

$\underline{n}_u, \bar{n}_u$: minimum and maximum number of teams of type u onboard the ship (teams).

d_m: duration of mission m (whole days).

$s_{c,c'}$: duration of trip from country c to country c' (whole days).

$f^0, \underline{f}, \bar{f}$: initial, minimum, and maximum fuel onboard, respectively (bbls).

b^Q, b^W: fuel burn rate when underway and waiting in port, respectively (bbls per day).

p: maximum time between ship resupply for provisions (days).

v_m: mission value earned for accomplishing mission m (mission-value units).

g_m^M: cost of mission m ($).

g_c^C: in-port cost at country c ($ per day).

b: budget allocated for all missions and port costs ($).

$\alpha, \varepsilon_1, \varepsilon_2$: small penalties to discourage unnecessary use of ports when a cost is incurred, unnecessary transits, and unnecessary use of teams, respectively (set to $\alpha, \varepsilon_1, \varepsilon_2 = 0.01$ in all our runs).

Decision Variables and Units (units, if applicable, are in parentheses)

$X_{m,c,t,u}$: 1 if mission m in country c starts in day t by team u, 0 otherwise.

$W_{c,t}$: 1 if the ship is waiting in port at country c in day t, 0 otherwise.

$Q_{c,c',t}$: 1 if the ship starts a trip from country c to country c' in day t, 0 otherwise.

F_t: amount of fuel onboard the ship at the end of day t (bbls).

E_t: amount of fuel supplied to the ship at the beginning of day t (bbls).

N_u: number of teams of type u onboard the ship (whole number of teams).

Formulation

$$\max_{X,W,Q,F,E,N} \sum_{\substack{m,c,t,u \mid \\ (m,u)\in J \\ (m,c)\in K}} \nu_m X_{m,c,t,u} - \sum_{c,t \mid g_c^C>0} \alpha W_{c,t} - \sum_{c,c',t} \varepsilon_1 Q_{c,c',t} - \sum_u \varepsilon_2 N_u, \quad (1)$$

$$\sum_u p_u N_u \le r \quad \forall t, \quad (2)$$

$$\sum_{\substack{m,c,t,u \mid \\ (m,c)\in K \\ (m,u)\in J}} g_m^M X_{m,c,t,u} + \sum_{c,t} g_c^C W_{c,t} \le b, \quad (3)$$

$$W_{c,t} + \sum_{c' \mid c'\neq c} Q_{c',c,t-s_{c',c}+1} = W_{c,t+1} + \sum_{c' \mid c' \neq c} Q_{c,c',t+1} \quad \forall c, t \mid t < |T|, \quad (4)$$

$$\sum_{\substack{m \mid (m,u)\in J \\ (m,c)\in K,}} X_{m,c,t,u} \le W_{c,t} \quad \forall c, t, u, \quad (5)$$

$$\sum_{\substack{m \mid (m,u)\in J \\ (m,c)\in K}} X_{m,c,t,u} \le W_{c,t+d_m-1} \quad \forall c, t, u, \quad (6)$$

$$\sum_{t'\in\{t-d_m+1,\dots,t\}} X_{m,c,t',u} \le W_{c,t} \quad \forall m, c, t, u \mid (m,u)\in J, (m,c)\in K, m\in M^W, \quad (7)$$

$$\sum_{\substack{c,m \mid \\ (m',c')\in K \\ (m',u')\in J}} \sum_{t'\in\{t-d_m,\dots,t\}} X_{m,c,t',u} \le N_u \quad \forall t, u, \quad (8)$$

$$\sum_{u \mid (m,u)\in J} \sum_{t'\in\{t-d_m,t\}} X_{m,c,t',u} \ge \sum_{u \mid (m',u)\in J} X_{m,c,t,u} \quad \forall t, m, m', c \mid (m,m')\in B, (m,c)\in K, (m',c)\in K, t > d_m, \quad (9)$$

$$\sum_{c\in C^P} \sum_{t'\in\{t-p,\dots,t\}} W_{c,t'} \ge 1 \quad \forall t \ge p, \quad (10)$$

$$E_t \le \bar{f} \sum_{c\in C^F} W_{c,t} \quad \forall t, \quad (11)$$

$$F_t = f^0 + \sum_{t'\in\{1,\dots,t\}} E_{t'} - \sum_c \sum_{t'\in\{1,\dots,t\}} b^W W_{c,t'} - \sum_{c,c'} \sum_{t'\in\{1,\dots,t\}} \sum_{n=1}^{\min\{s_{c,c'},t-t'+1\}} b^Q Q_{c,c',t'} \quad \forall t, \quad (12)$$

$$W_{c^0,t} = 1 \quad \forall t \in \{1, |T|\}, \tag{13}$$

$$Q_{c,c't} = 0 \quad \forall t \in \{1, |T|\}, \tag{14}$$

$$X_{m,c,t,u}, Q_{c,c',t}, W_{c,t} \in \{0, 1\}$$

$$\forall m, c, c', t, u \mid (m, c) \in K, (m, u) \in J, \tag{15}$$

$$\underline{n}_u \le N_u \le \bar{n}_u \quad \text{and integer} \quad \forall u, \tag{16}$$

$$E_t \ge 0 \quad \forall t, \tag{17}$$

$$\underline{f} \le F_t \le \bar{f} \quad \forall t. \tag{18}$$

Formulation Description. The first term in the objective function (1) maximizes the total mission value from all missions accomplished. The second term discourages incurring any unnecessary port costs. The in-port penalty can be left as a constant or be replaced by a function of the actual in-port cost, g_c^C; in this case, we would be creating a trade-off between the port cost and the mission value it generates. The third and fourth terms discourage solutions in which the ship transits unnecessarily or brings onboard more teams than needed, respectively.

Equations (2) and (3) represent knapsack-like constraints for berthing space and budget, respectively. Equation (4) is a balance equation for the ship's location. The left side of the equation becomes one when the ship waits at port c in period t, or when the ship is underway to c with arrival date t. Only when either of these conditions is met can the ship wait at or depart c during the next period, $t+1$.

Equations (5) and (6) ensure that each team is dropped off on the day it starts performing the mission and is picked up immediately after completion. Equation (7) enforces the ship to remain in-port during the entire execution for missions so designated.

Equation (8) restricts each team to accomplishing only one mission simultaneously; Equation (9) provides mission precedence between associated missions.

Equations (10)–(12) account for replenishment needs. Equation (10) ensures that the ship obtains provisions and other supplies within no more than p days apart at ports that can provide these commodities, Equation (11) ensures that fuel is obtained from allowed ports and only if the ship is in-port, and Equation (12) keeps track of the fuel at time t through all that has been used and taken on in refueling.

Equations (13) and (14) establish the initial and final conditions, which include the ship leaving from and returning to its home port.

Constraints (15)–(18) establish the domain for all decision variables in the model.

The formulations described above depict the kernel of the GFSMP model. Other decision variables and constraints, which we did not list for brevity reasons, are used to represent the following operational and logistical requirements: in-port locations for the ship, including docked, at anchor, and at an offshore aviation position; associated port costs and fuel burn rates at each of these locations; fuel costs; missions requiring the ship to offload troops and equipment in a docked position; in-port missions that can be sustained while the ship is at anchor and (or) at an offshore aviation position; other aviation constraints; time windows for mission execution; time windows for replenishment availability at ports or for underway replenishment (i.e., at sea); mandatory ports of call and dates of visit; and ongoing missions and teams involved during replanning activities.

In addition, GFSMP incorporates other logical valid inequalities to speed up convergence, such as avoiding trivial cycle trips or eliminating impossible trips early and late in the deployment, given the origin and destination ports.

Model Size Details. GFSMP is a large-scale mixed-integer program. The full 180-day problem, including the missions, teams, network, and other data described in this paper, has over 150,000 constraints and 60,000 variables, of which 25,000 are binary.

We typically solve GFSMP using a rolling-horizon, heuristic scheme (Bostel et al. 2008, p. 517) with a *block* of approximately 50 days, about 43,000 constraints, and 7,300 binary variables. CPLEX 11.2 preprocessing reduces this to about 6,400 constraints and 5,800 binaries and obtains a solution that is within 5 percent of optimal within one hour.

After the first block, subsequent blocks start shortly before the end of the preceding block (rather than on the following day) to cope with possible "end effects," such as missions that could have started (but not be completed) during that block. Earlier blocks are usually harder to solve because there are more missions to complete. Overall, a complete solution for a 180-day planning horizon using this heuristic is achieved within three hours, which is acceptable to planners. For reschedules caused by exigencies while the station is underway, solution time is significantly reduced because the time horizon is shorter and some missions have already been performed.

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Sanford D. Lansing, CAPT, USN, Director, Experimentation Directorate, Navy Warfare Development Command, Sims Hall, 686 Cushing Road, Newport, RI 02841, writes: "It is my pleasure to acknowledge the participation of the Naval Postgraduate School's Global Fleet Station Mission Planner (GFSMP) and validate its contribution to the Trident Warrior 2009 (TW09) Operational Level Command and Control (OLC2) Experiment.

"An interdisciplinary team of researchers from the Naval Postgraduate School Maritime Operational Planner research program traveled to Norfolk, VA to facilitate use and evaluation of GFSMP in support of TW09 OLC2. The GFSMP was utilized by US Navy logistics planners to initially prepare a deployment plan for the Global Fleet Station ship and its embarked Expeditionary Partnership Teams. Additionally, logistics planners were able to utilize the GFSMP's outputs to quickly develop and evaluate proposed courses of action in support of the exercise scenario.

"The Naval Postgraduate School's participation and the use of GFSMP proved to be very timely as there is currently no other automated aid that can produce optimized courses of action for a Global Fleet Station deployment. GFSMP had a significant impact on the operational planning of OLC2 and the experiment as a whole."

Mel Williams Jr., Vice Admiral, Commander US Second Fleet, 1751 Morris Street, Building D29, Norfolk, CA 23511, writes: "It is my pleasure to acknowledge the participation of the interdisciplinary team of researchers from the Naval Postgraduate

School Maritime Operational Planner Research Program and validate their contribution to TW09 OLC2.

"The NPS team traveled to Norfolk, VA on three occasions to facilitate use and evaluation of two of your operational level optimization planning aids. Both the Global Fleet Station Mission Planner (GFSMP) and the Combat Logistics Force (CLF) Planner proved to be extremely timely as there is currently no other automated aid that can produce optimized courses of action for a Global Fleet Station deployment or CLF deployment. Both of these decision aids greatly enhanced the ability of the Seabasing Logistics team to develop initial deployments plans and quickly produce optimized varying courses of action for consideration as situations changed during the experiment.

"Both of these decision aids proved to be valuable assets that could be of use in the fleet today. My thanks to you and your team for their initiative and support to the success of TW09. Hopefully we can work together to bring these valuable decisions aids into production for fleet-wide use in the future."