OPERATIONAL PLANNING TOOLS FOR U.S. NAVY MARITIME COMMANDERS

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ABSTRACT

This work presents recent research to develop a series of optimization- and simulation-based decision support tools to aid in operational maritime mission planning for integration into the Globally Networked Maritime Headquarters with Maritime Operations Center. We present three tools: Global Fleet Station Mission Planner recommends route and mission scheduling for a naval contingent embarked with training teams and sustainment requirements. Combat Logistic Force Planner recommends how to employ special transport ships that carry ship and aircraft fuel, ordnance, dry stores, and food, to sustain navy battle groups operating worldwide for 90-180 days. Container Port Simulation models individual container vessels approaching the west coast of the U.S., starting with their required notice of arrival 96 hours out in the Pacific and, in case of closure of the intended destination port, suggests an alternate destination port in accordance with the shipper's economic self-interest to minimize time and cost to the ultimate destination.

Keywords: maritime optimization models, port simulation models.

1. INTRODUCTION

The Operations Research Department at the Naval Postgraduate School has over fifty years of experience applying scientific, mathematical, and systems tools to planning military operations. In this paper, we introduce representative current planning tools in development by faculty and operationally-experienced military officer students. Specifically, we tap the most recent research in optimization and simulation to describe a series of decision support tools to aid in operational maritime mission planning for integration into a Globally Networked Maritime Headquarters with Maritime Operations Center (Department of the Navy 2008).

The specimen planning tools chosen for illustration are Global Fleet Station Mission Planner (GFSMP), "Navy Combat Logistic Force" (CLF) planner, and "Container Port Simulation Model" (CPSM). Spitz (2007), Brown and Carlyle (2008), and Pidgeon (2008), respectively, document earlier, prototypic versions of these planning tools, and references therein further document the needs leading to their development.

2. GLOBAL FLEET STATION MISSION PLANNER

2.1. Overview

GFSMP is a mission planning and scheduling optimization tool designed to provide fleet staffs the ability to examine the feasibility of future deployments and activities in support of the Global Fleet Station (GFS) concept, Maritime Domain Awareness, and the Global Maritime Partnership initiative.

GFSMP identifies how one naval ship with embarked Expeditionary Partnership Teams (EPTs) can best meet logistical and other requirements (such as berthing space, budget, re-supply needs, transit times, mission requirements, etc.) to provide navy strategic priorities in Maritime Security and Theater Security Cooperation (TSC).

A typical solution would include a deployment schedule and the combination of EPTs required to perform the missions. These results can guide planners in best utilizing current naval resources available in the region and provide insights for future planning, offering opportunities to understand where tradeoffs can be made.

GFSMP is applicable in all theaters using afloat basing to support engagement teams. Changing limitations on deployment time frame, ship or EPT availability, and budget, offer opportunities to understand where tradeoffs can be made. GFSMP can also be used by planners to understand how different ship types may be used to accomplish similar missions. Exploration into EPT constraints can help the navy to determine team requirements: GFSMP optimally allocates training teams to a ship, and schedules the ship route to achieve the maximum, aggregate TSC "value" for all executed missions. Here, mission value refers to an informed, quantitative assessment of contribution to TSC if the mission is performed.

2.2. The Problem

GFSMP posits a Navy vessel, equipped with EPTs, carrying out TSC activities in its area of responsibility during a continued period of time referred to as the planning horizon. GFSMP's primary objective is to devise an optimal route and mission schedule that maximizes the TSC value collected. As a secondary objective, GFSMP seeks to minimize the total port cost

incurred while conducting the missions. (We use the term "country" and "port" interchangeably to refer to locations where the ship may conduct missions, and/or obtain fuel or provisions.)

During operations, the ship must maintain at least its minimum fuel level as well as maintain sufficient provisioning supplies for all personnel. A fixed amount of provisions is consumed every day, depending on the personnel deployed. However, the amount of fuel consumed, in barrels per day, depends on the ship's activity, and three burn rates are used: while underway (at a nominal transit speed), while at anchor (supporting "hotel load" power requirements), and moored pier-side receiving shore power. Travel times (in days) between any pair of ports are pre-calculated based on feasible sea routes and the nominal transit speed of the vessel.

Each ship incurs a port-dependent charge for each day it remains in-port. This charge also depends on whether the ship stays at anchor or docked. One or several fictitious "At Sea" ports represent locations at sea where the ship may, for example, conduct multi-country training missions, or have opportunities to schedule underway replenishments (of fuel or commodities) at select times when auxiliary fleet ships are present in the area (see CLF planner in Section 3).

Every candidate mission in each country has a pre-determined TSC value, a cost, a fixed duration, and can be completed by one (among potentially several) EPTs. Some missions have precedence requirements in relation to other missions such that one mission may require one or more other mission(s) to be completed before it can be carried out.

Every mission requires the ship to deliver a qualified EPT to the respective country to complete the mission and to pick up the team immediately upon completion of that mission. Additionally, some missions may require the ship to stay in-port for the duration of the mission. Also, some missions require the ship to be moored pier-side (e.g., in order to load or unload heavy equipment) during the first and last days of the mission, while other missions may allow the ship to remain at anchor. Each EPT can only participate in one mission at a time, but once finished it is assumed to become available to perform other missions immediately.

There is limited availability of each type of EPT. Each one has a varying number of personnel, and there is limited amount of berthing space to provide for all the personnel of all EPTs assigned to the ship. Thus, in addition to selecting the optimal routing and scheduling, GFSMP must determine the optimal EPT configuration for the deployment.

2.3. Modeling, Scenario and Results
GFSMP model's key decision variables are:

- EPT configuration, i.e., how many teams of each type should be embarked on the GFS
- Mission schedule by country
- GFS schedule: When the GFS stays in a given port (conducting missions or resupplying), or is underway between countries
- Fuel and supply levels

To evaluate GFSMP, we use notional data from the Fall 2007 Gulf of Guinea (GoG) African Partnership Demonstration developed by CNE-C6F GOG Regional Planning Team (Spitz 2007), which have also been utilized by Second Fleet during Exercise Trident Warrior 2009 (TW09). The original Demonstration assumed an amphibious ship LSD-43 and/or a High Speed Vessel HSV-2 as the platforms to accomplish 66 missions over six months. However, for TW09, LSD-43 is replaced by USS Kearsarge, LHD-3 (U.S. Navy 2009).

Figure 1 is an example of the recommended route and mission schedule for select dates. (The snapshot covers approximately two of the six month's deployment of the GFS.) Bars indicate the period of execution of each mission, with names inside indicating the team performing the mission (for example, "NCF" refers to a "naval construction force" team). We can observe, for example, that no more than the four available NCF teams are used, and that the GFS transit between ports while missions are still ongoing, in order to maximize mission accomplishment. Overall, GFSMP shows that the GFS can complete all missions in substantially less time (only five months) than originally planned by CNE-C6F (Spitz 2007), and at a much lower cost (by incurring in lower port costs).

In addition to its capability as a planning tool, during the TW09 Exercise GFSMP also proved useful by helping planners to deal with a variety of exigencies. These included rescheduling the GFS in the middle of the deployment due, for example, to the unexpected failure of a CLF asset originally scheduled to resupply the GFS, or to new requirements for the GFS to engage for an extended period (several weeks) in an anti-piracy emerging situation. These disruptions to the baseline schedule may require rescheduling or cancelling some of the original missions.

As U.S. Navy CAPT Lansing, Director, Experimentation Directorate, Navy Warfare Development Command states, "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 Operational Level Command and Control and the [TW09] Experiment as a whole."
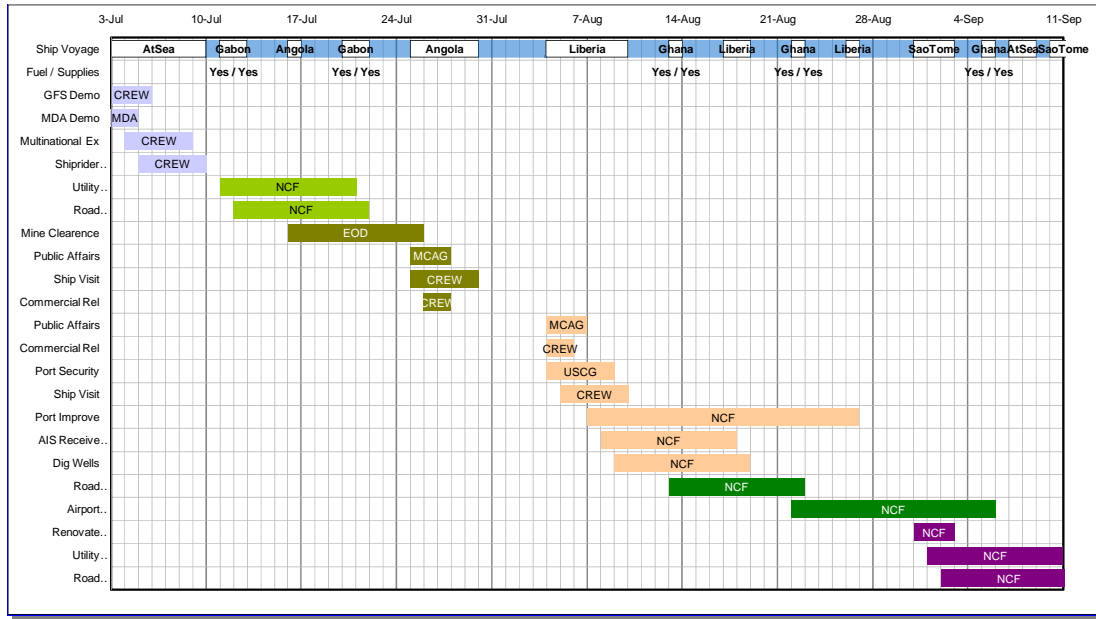
Figure 1: This is a snapshot of, approximately, two of the six months for which GFSMP plans the routing and scheduling of an LHD in the Gulf of Guinea. During the recommended deployment, the LHD transits through different ports ("Ship Voyage" line on top) while accomplishing missions listed on the left. Bars indicate the execution period of each mission and the performing team.

3. COMBAT LOGISTIC FORCE PLANNER

3.1. Overview

The Navy 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 U.S. naval forces to operate at sea for extended periods.

The CLF is being transformed to a fleet with fewer different types of transports, and no more total transports, but it expects to have to serve more clients for a greater variety of deployments in the next decade. Conventional planning has relied on steady-state, average-rate-of-consumption models and rules-of-thumb to assess CLF ability to re-supply our fleet operations. Details matter, and we want to determine whether or not, and how, the new CLF can actually support its anticipated missions.

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 use optimization to advise how to sustain these ships.

Most U.S. Navy deployments are groups of ships assembled with a particular mission. Some frequent examples of these "Battle Groups" (BGs) are a Carrier Strike Group (a nuclear-powered aircraft carrier, CVN, a guided-missile cruiser, CG, two guided-missile destroyers, DDG, and a fast combat replenishment ship), an Expeditionary Strike Group (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 (ships equipped with missiles and missile defense weapons, such as a CG and two DDGs); and a Littoral Combat Squadron (new class of small ships where larger ships cannot safely navigate, engaging in anti-surface warfare, mine counter measures, intelligence, surveillance and reconnaissance, homeland defense and maritime interdiction, and special operations forces support, each of which we treat as a frigate FFG). Combatant classes are available from Jane's (2008, pp. 873-943).

The Combat Logistics force is being consolidated to just three ship types, with 30 total ships: The TAO187 (Henry J. Kaiser) which 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, which can carry 156,000 barrels of fuel oil, 1,800 tons of ordnance, 250 tons of dry stores, and 400 tons of refrigerated stores, at speeds exceeding 26 knots; And, the T-AKE1 (Lewis & Clark), which can carry 18,000 barrels of fuel oil, 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), etc.) are either scheduled to leave active service for the reserve fleet, or are still on the drawing boards.

We evaluate new CLF ship designs, advise what number of 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.

3.2. Modeling, Scenario and Results

We use an integer linear program to plan optimal employment of CLF ships to minimize policy penalties accruing from any commodity shortage. Decision variables for the CLF model account for:

- Indicators of whether or not at least one shuttle visits a given BG on a particular day, and the port from where the shuttle is coming
- Taking stock of each shuttle's daily commodities, and the amounts delivered to a BG
- Taking stock of each BG's commodity levels, and categorizing these by levels of deficiency (if any)

The CLF model can schedule a single shuttle ship sortie from port to make many separate consolidation (CONSOL) visits, perhaps to different battle groups.

Our model takes into account changing daily consumption of each of four basic commodities classes for each client ship, navigational issues such as slow passages through canals, and the possibility of several client ships, or groups of ships, running low on the same commodity at the same time. Given a deployment scenario and a current configuration of the CLF fleet of transports, a solution to our model is a face-valid logistical plan for the CLF that minimizes shortfalls of any commodity for any customer, highlighting any unavoidable low-inventory events, and maximizing the utilization of transports by maximizing the total volume delivered over the scenario.

A typical scenario consists of multiple BGs, and for each BG specifies last-minute in-port preparations and/or pre-deployment 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 post-combat period where we stand guard and provide humanitarian assistance while diplomacy and other non-military measures unfold.

An example planning scenario includes 13 battle groups served by nine TAO and seven T-AKE shuttle ships over a 90-day planning horizon. Some of the larger battle groups are accompanied by station ships (supply ships that serve as accompanying inventory vessels). Five of the battle groups are deployed on day one, and the rest deploy on day 10, 12, etc., until all are underway to their various areas of operation worldwide. Figure 2 depicts totally automatic world sea-route model for estimating times and positions of optimally-deployed CLF ships worldwide.
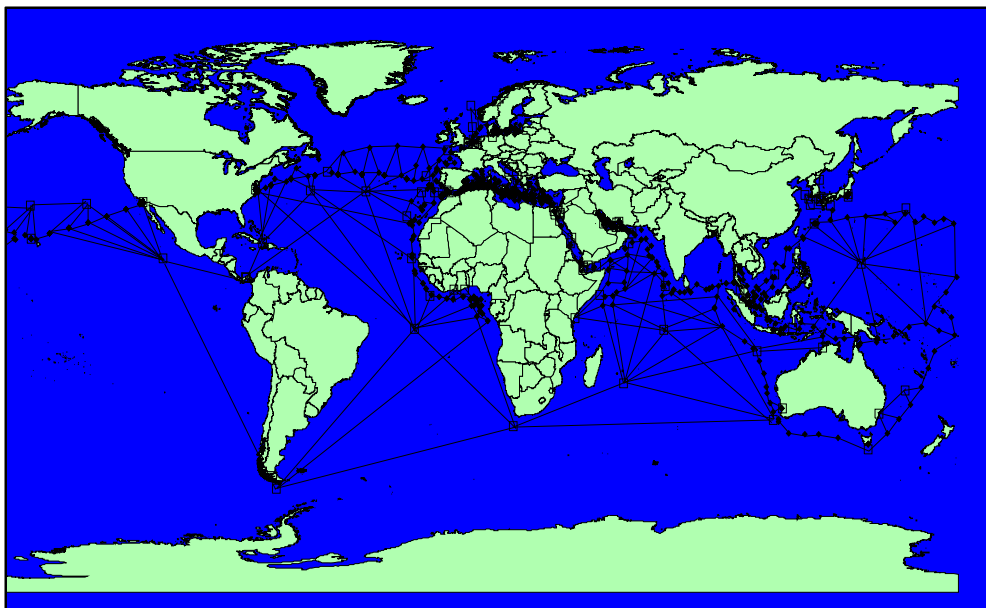

Figure 2: Worldwide sea route network. The static searoutes shown here (as a connected network of ports and at-sea location nodes and arcs indicating navigationally adjacent nodes) connect all ports and trans-oceanic routes a CLF ship might use at the discretion of the optimization (that the shuttle movements are *outputs* rather than inputs is a key innovation of CLF). Transit of most arcs can be made at any speed desired, but some arcs (e.g., canals) require a fixed transit time. CLF merges the tracks of combatant customers with these static searoutes to produce the full, worldwide maneuver network. When needed, local operating areas can be embellished with even more at-sea locations and arcs for finer fidelity. Each at-sea location can be coded with an administrative restriction that permits access only to compatibly-coded CLF ships. Each port may accommodate only a subset of CLF ships by type or by hull number, and each port may offer only a subset of commodities.

A monolithic (i.e., omniscient) solve of this situation generates an optimization model with about 367,000 constraints and about 23,000 variables. A cascade (i.e., myopic) solve using a 30-day planning windows advanced 15 days at a time yields a sequence of problems with between about 37,000 and 75,000 constraints and between 6,000 and 9,000 variables. The monolith takes several hours to solve on a 2-GHz laptop, while the cascade takes a few minutes. For this particular case, the two solutions compare closely. The CLF fleet conducts a total of 101 CONSOLs (i.e., deliveries). The availability in this scenario of forward (i.e., close to the areas of operation) supply base ports is key: our average cycle times from a CONSOL back to a port and on to the next CONSOL is only just over five days, two of which are spent pierside loading the shuttle ship.

A cumulant inventory constraint, combined with an elastic violation device for a shortage, and another for extremis shortage, combine to signal a deficiency, and carry this forward, paying a daily penalty, until this deficiency is remediated. The distinction between shortage and extremis penalties is important: CLF ships are equitably assigned to CONSOL all customers by maximizing deliveries, to preferentially serve needy customers by CONSOL to avoid shortage, and to energetically serve customers in extremis.

CLF (Brown and Carlyle 2008) is a strategic planning model to assess our ability to supply about a dozen large carrier battle groups. The Trident Warrior 09 Exercise includes many operations in the Gulf of Guinea, a long way from resupply ports, and CLF has been generalized to be an *operational* planning model serving individual ships worldwide. CLF shuttle employments can now include unlimited consolidations between port calls for reloading ─so may consolidations that a shuttle ship may end up resembling a station ship (i.e., a ship that accompanies a deployed battle group), though our shuttles may switch customers as advantageous). There are now many more ports, and each port may only offer some subset of commodities. Deployed combatants can now be scheduled to make port calls for resupply pierside. To enhance operational planning, CLF now runs faster, and features a graphical user interface offering geographic views of the world, hemispheres, or operating areas with high close-up resolution. The display now includes animation of moving shuttles and their moving customers to better help planners understand the prescribed ballet. CLF became a centerpiece for TW09, providing quick, trustworthy advice in response to the exigent events that inevitably disrupt operational plans already in execution.

4. CONTAINER PORT SIMULATION MODEL

CPSM models the effects of a transportation security incident on one or more of the U.S. West coast marine container ports. Operation of the container ports on the U.S. west coast is critical to ongoing national commerce. We built a simulation model of the seven major West-coast container ports to study their ability to process container throughput, and especially to measure what would happen system-wide were one or more ports taken out or degraded due to a natural or human-caused event.

We modeled individual container vessels starting with their Notice of Arrival 96 hours out in the Pacific. Vessels then travel to their intended port, or to an alternate port if the intended port is closed. In the case of closure of the intended port, an alternate port is advised in accordance with the shipper's own economic self-interest, with an eye toward minimizing time and cost to the ultimate destination. Once at a port, either intended or diverted, the vessel unload time is accounted for, and the shipment is broken into ten pieces bound for each one-digit ZIP code in the continental United States. These landside shipments then travel to their designated aggregate destinations.

We have collected data on vessel arrival patterns by intended port, unload time, port capacities (berths), landside travel times, and various costs, including demurrage costs for freight. These real data were then used to specify inputs to the model, both deterministic constants like distances and speeds, as well as probability distributions from which uncertain elements like arrival times, number of containers on a ship, and unload times were generated.

We have built several alternate versions of the model, treating different scenarios of port transportation security incidents. We built models both with and without the proposed port at Punta Colonet, Mexico, to see how the presence of that port might help maintain operations in the face of U.S. port closures. The model was run for a one-year planning horizon in each of several configurations, with thousands of replications to assure adequate statistical precision. The model has been streamlined to be general and scalable in the number of ports, and an animation has been used to help with model verification and establishing credibility CPSM was validated by modeling the ten-day closure in 2002 when members of the International Longshoremen's and Warehousemen's Union (ILWU) were locked out in retaliation for a labor slowdown on the part of the union.
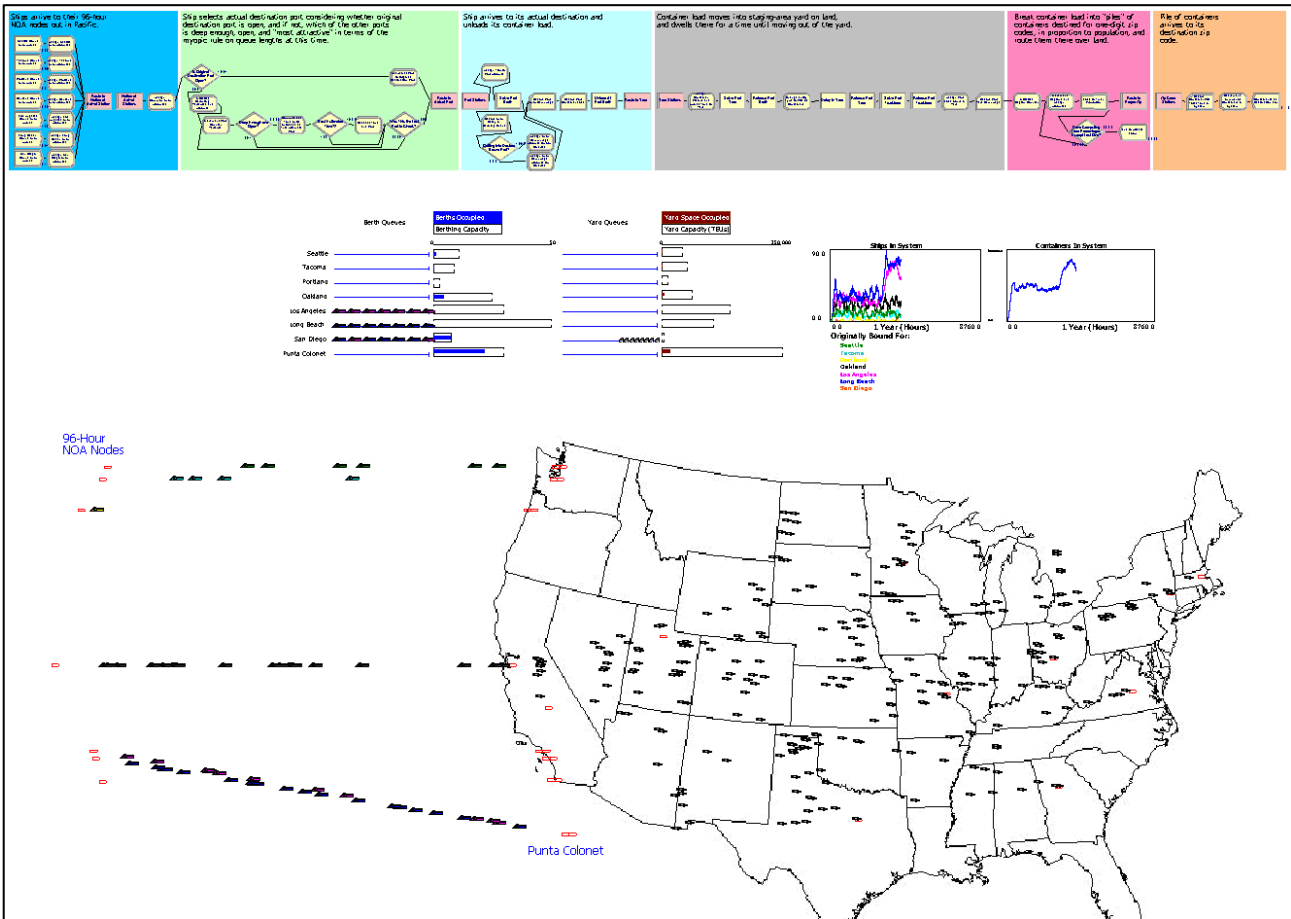
Figure 3: Screenshot of Arena CPSM (top flowchart) and animation (bottom) of West-coast container-port operations. At the time of this screen shot, both the ports of Los Angeles and Long Beach are closed, so vessel traffic is being diverted to other ports, mostly to the proposed port in Punta Colonet, Mexico.

Figure 3 is a screenshot of the model implemented in the Arena simulation software (Kelton, Sadowski, and Swets 2010) to illustrate both the logic (the flowchart at the top) and the animation at the bottom. The logic flowchart at the top proceeds from left to right: the first blocked-out area is arrival of ships to their Notice of Arrival positions, the next block is the port-selection logic including choosing the next-best port if the intended port is closed, next is unloading operations at the berth (including any necessary queueing), next is landside storage at the port, next is overland transit, and finally arrival of a shipment to its destination ZIP code. The map animation at the bottom shows movement of ships as well as the ZIP code loads once the ship is unloaded and broken into ten loads. The queue and plot animations in the middle depict queues of ships for berths, utilization levels of berths, and graphs of both the number of ships and number of containers in the system at any given time. This particular situation shows a point near the middle of the year a few weeks after the ports of Los Angeles and Long Beach were taken out, so ships bound for those ports are being diverted mostly to Punta Colonet to the south, and the graphs show significant spikes of both the number of ships and number of containers in the systems, representing increased congestion and delays

due to the closure of these two major ports. Later in this scenario, the ports of LA and LB were gradually brought back up in groups of berths at a time, and congestion was eventually relieved as these full-capacity ports eventually worked off the backups. Other scenarios without the availability of Punta Colonet resulted in even worse congestion, delays, and costs. In this way, the model quantifies the effects of port closures, and can thus be used as a decision-making aid.

5. CONCLUSIONS
In this paper we have presented the GFSMP, CLF and CPSM optimization- and simulation-based decision support tools. We have illustrated application of GFSMP and CLF to exercises developed by U.S. Commander, Second Fleet, exhibiting significant improvements over manual planning. As these tools continue to be used by Navy staffs and modified with their suggestions, the longer-range intent is that they are integrated into a suite of decisions aids supporting maritime planning staffs.

ACKNOWLEDGEMENTS

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