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Framework for Augmenting Current Fleet with Commercially Available Assets for Logistics Support in Contested Environment

September 2, 2020

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Abstract

China believes logistics in the contested environment is an Achilles's heel for the U.S. Navy (USN). It is therefore critical that we explore ways to develop capabilities to replenish potential combating forces in the Pacific through Next Generation Logistics Ships (NGLSs). In this research, we offer a framework using mathematical models to refuel, rearm, and resupply for future logistics in such contested environments to support the potential combat operations of the USN.

In this research, we first analyze the capabilities for the current fleet and describe the framework used in existing literature. We study various ship platforms and their capabilities. The earlier analysis suggested ships that are most capable for HADR efforts. Bearing in mind the differences between contested and humanitarian environments, we analyze the capabilities of the ship platforms as the background for this research. We then develop the framework for augmenting the current fleet with NGLSs for support in contested logistics. The objective is to study and analyze options for rearming, refueling, and resupplying in the contested and distributed environment.

Feedback from the SME helped us gain insight into the complexity of the problem and its vast scope. We used this input to refine our scenarios. We developed mathematical models based on these scenarios. The top-level requirements of the vessels under consideration, as we understood, incorporate capability of a vessel on certain route based on speed, platform, and capacity. The fuel storage tanks are separate from the storage for ammunition and supplies. Hence, we kept these two commodities separate. Fuel has its own issues, and so do ammunition and supplies. Note that the separate trips for these two commodities could be combined when trying to operationalize these results into a schedule, involving a particular number of ships.

The sponsor did not wish us to model an objective of minimizing costs (which were not available) or the number of ships required to deliver commodities within a certain deadline of under a certain schedule (because deadlines and schedules change based on operational priorities). Measuring the number of deliveries required allowed us to determine a mix of NGLS vessels without addressing cost, deadline, or scheduling

restrictions. We would like to point out that number of deliveries are the deliveries made by a specific vessel, from a supply node to a demand node, on a specific route for a specific commodity. Deliveries, as described in the report, can be interpreted in many ways.

The framework created is flexible in terms of the scenarios. The demand nodes can be modified using amount of demand. They can also be expanded as per the requirement of number of demand nodes. The summary of our results and analysis suggests certain recommendations. We recommend that to negotiate battlespace constraints, the time constraint for PSV (Platform Supply Vessel) engaging with SAG (Surface Action Group) in WEZ should be investigated, since that is the binding constraint on capacity to transfer. The capacity of PSV for carrying fuels is much larger than that, and the same is true for transferring the pallets of ammunition and supplies. It will be necessary to increase the rate of transfer if the time spent in the WEZ (Weapons Engagement Zone) cannot be altered. We also recommend that acquisition of LAWs (Light Amphibious Warship) is preferred to FSVs (Fast Supply Vessel), since it may be prohibitively expensive to maintain a separate maintenance support infrastructure for FSVs, when their range of usefulness is relatively narrow. Finally, we would like to point out that the scenarios we were given excluded a need to replenish water to a DDG (Guided Missile Destroyer), or to replenish a PSV in the WEZ. If these were to be included, we might have gotten a very different answer.

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Introduction and Background

The U.S. government came out publicly with an explicit statement that the so-called “nine-dash line,” which the People’s Republic of China (PRC) asserts delineates their claims in the South China Sea, is contrary to the international law. China claims that the “nine-dash line” encircles as much as 90% of the contested waters. The line runs as far as 2,000 km from the Chinese mainland to within a few hundred kilometers of the Philippines, Malaysia, and Vietnam. The PRC maintains that it owns any land or features contained within the line, which confers vaguely defined “historical maritime rights” (Liu, 2016). It encircles the area where China demands economic rights. Another interpretation is that the line marks the islands and reefs China wants to control rather than the waters inside its boundaries. The PRC has long favored a strategy of ambiguity. It does not openly go against international law but prefers to leave space for its more ambitious claims.

Figure 1. The nine-dash line and surrounding countries

China defiantly lands planes on artificial islands in the South China Sea while U.S. warships patrol in protest. The string of “unsinkable aircraft carrier” islands is an imminent threat to U.S. allies in Southeast Asia. This, plausibly, is where a war with China will likely be fought. When thinking in a geostrategic sense about China, the island-chain formulation is helpful. Since the 1950s, U.S. planners have described a first island chain, running from the Japanese islands through the Philippines and down to the tip of Southeast Asia. Dominating inside that line has been the goal of China’s recent buildup in naval and missile capabilities. But U.S. officials warn that Chinese strategists are becoming more ambitious, set on gaining influence up to the second island chain—running from Japan through the Micronesian islands to the tip of Indonesia.

Figure 2. Chinese dredging vessels in the waters around Mischief Reef in the disputed Spratly Islands in the South China Sea

Figure 3. First and Second Island Chains

As with its initial forays into the South China Sea, China is using so-called scientific missions and hydrographic surveying ships as the tip of the spear. Japan and Singapore essentially serve as anchors at the north and south ends of the island chains. These two nations have been integrating their defense capabilities with the United States through training, exercises, and arms purchases. They are exploring better relations with India as the Pacific and Indian oceans are increasingly viewed as a single strategic entity. This nascent alliance is a crucial element in the U.S. strategy for the region.

China believes logistics in the contested environment is an Achilles's heel for the U.S. Navy (USN). It is therefore critical that we explore ways to develop capabilities to replenish potential combating forces in the Pacific through Next Generation Logistics Ships (NGLSs).

In this research, we offer a framework using mathematical models to refuel, rearm, and resupply for future logistics in such contested environments to support the potential combat operations of the USN. The scenarios developed for this research are based on actual data, but those data are disguised by the authors. At the foundation of the framework are the following research questions:

1. Is the current fleet of vessels adequate to carry out the mission?
2. Are there new vessels that can be modified or produced for the purpose of better sustainment through the three vectors of refuel, rearm, and resupply?
3. If so, what type of vessels, and how many of each kind, should be acquired?

In order to answer these questions, we first look at answers from existing literature on logistics, perhaps derived from a different environment. The capabilities of the new vessels are based on top-level requirements. The first methodology compares the vessels from the perspective of their capabilities. The second methodology considers the supply chain from controlled zone to contested zone, utilizing only the new vessels. We develop and use different scenarios and methodologies to arrive at answers based on different objectives.

Considerable work has been done on the capabilities of USN-owned vessels that supply affected areas for Humanitarian Assistance and Disaster Relief (HADR). Our current research leverages that work. Though war is a manmade disaster, there are distinct differences between the types of support needed in manmade versus natural disasters. The environment in war is contested, and supply includes ammunition. However, the rest of the capabilities for both types of missions have much in common.

In this research, we first analyze the capabilities for the current fleet and describe the framework used in existing literature. We study various ship platforms and their capabilities. The earlier analysis suggested ships that are most capable for HADR efforts. Bearing in mind the differences between contested and humanitarian environments, we analyze the capabilities of the ship platforms as the background for this research.

We then develop a framework for augmenting the current fleet with NGLSs for support in contested logistics. The objective is to study and analyze options for rearming, refueling, and resupplying in the contested and distributed environment.

Existing Framework from Literature Review

In this section, we first analyze platforms and HADR capabilities in the current inventory of combatant ships and noncombatant ships of both the USN and Military Sealift Command (MSC) to understand capability gaps in contested environments. The HADR environment is relevant here since there are similarities in the demands with the contested environment.

USN and MSC Ship Capabilities

Apte et al. (2013) describe each ship class and its HADR-related characteristics and break them down by platform, including the various classes within the platform. The greatest benefit of the MSC fleet is the ability to carry large amounts of cargo to a disaster area and the ability to provide significant medical support. An important benefit of MSC ships for HADR missions is that some of them are self-sustaining for loading and off-loading cargo, rendering outside equipment unnecessary. Appendices 1, 2, and 3 explain the names, platforms, and capabilities of all existing USN and MSC ships.

Landing craft serve as the waterborne transportation link between amphibious platforms and the shore. In HADR operations, landing craft play the critical role of getting supplies, cargo, and personnel to and from the shoreline and supporting ships. USN landing craft were designed not for HADR operations but for combat missions. However, they are valuable assets that can support the HADR mission because of their lift capacity, draft, speed, and range.

When considering specific vessels, a key facet of their capability for HADR missions is the seaborne aircraft. Relevant here are all helicopters utilized by USN and MSC ships. Most military fixed-wing aircraft that play any significant role in HADR operations are too large to land onboard any USN or MSC vessel. Aircraft are evaluated in terms of capabilities, primarily lift capability, personnel transportation capability, and range.

The comparison of the capabilities of USN and MSC platforms to basic mission requests is to identify which USN and MSC vessels are best suited to satisfy the relief requirements. The evaluation of the relative utility of each vessel type uses ordinal-scaled ratings that are assigned by USN surface warfare officers. The three rating values for each of the capabilities for HADR mission requests and their operational definitions are given in Table 1. Some of the capabilities critical in the contested environment are aircraft support, landing craft support, cargo capacity, freshwater production and transit speed.

Apte et al. (2013) conclude that the platforms best suited for HADR missions are amphibious ships of the USN. In the case of the MSC, almost all platforms are capable, except for the Special Mission Ships and T-AGs. (A description of ship platforms is given in Appendix 1 for USN and Appendix 2 for MSC). The USN has significant cargo transfer capabilities due to large numbers of helicopters and landing craft that can be deployed, the ability to bring large numbers of trained personnel to a disaster scene to assist with rescue, berthing space for temporary housing, and the large capacity to provide medical services specifically for HADR missions. The amphibious assault ships have consistently high levels of capability to conduct HADR missions since they can accommodate large numbers of helicopters as well as personnel and have medical and surgical capabilities aboard. Amphibious assault ships also have approximately 2,000 embarked Marines who may be deployed to provide security and assistance to the affected area.

Apte et al. (2013) and Apte and Yoho (2018) state that there are limitations on cruisers, destroyers, patrol craft, and littoral combat ships (LCSs) since they lack storage and berthing facilities, sufficient medical services, freshwater production or storage, and roll-on/roll-off capacity. In short, these ships can traverse the oceans at high speeds but have very few of the other capabilities that are critical to HADR missions. These vessels are effective in their defined warfighting role but may not be effective when employed for supply, even in contested environments.

The capabilities of the MSC fleet, in addition to the ability to carry large quantities of cargo to and from the disaster region, are the two hospital ships that provide high levels of medical support as well as berthing capacity and the ability to produce fresh water. However, lack of embarked helicopters limits conducting search and rescue missions or aircraft support. The ships' crews are small, with the majority being civilian mariners.

Apte et al. (2013) identify an HADR flotilla as follows: "amphibious assault and transport dock ships because of their ability for search and rescue, aircraft and landing support, freshwater production, berthing capacity, and medical support. Nuclear-powered aircraft carriers have the ability to provide aircraft support, freshwater production, berthing capacity, and medical support; these vessels primarily support fixed-wing fighter aircraft that do not have the same level of utility as vertical lift and rotary-wing aircraft, which are abundant on amphibious assault ships." (Apte et al. 2013, page 55)

Table 1. Capability Parameter Definitions for HADR Missions. Source: Apte et al. (2013)

			Capability Rating Defnition
Aircraft support		○	No embarked helo; unable to support helicopter operations
		◑	Single helo embarked; able to support the majority of helo platforms
		●	Multiple helos embarked; able to sustain multiple flight operations simultaneously
Landing Craft support		○	No ability to support landing craft
		◑	Some ability to support landing craft
		●	Landing craft embarked; able to load / off load cargo and store amphibious vehicles
Search and Rescue (SAR)		○	No embarked helo; unable to efficiently conduct SAR missions
		◑	Single embarked helo with communication equipment and night vision
		●	Multiple helos embarked with communication equipment and night vision
Dry goods storage	**Cargo Capacity**	○	No ability to store goods beyond current ship crew use
Refrigerated goods storage			
Fresh water storage		◑	Ability to store supplies beyond ship crew's use
Roll On Roll Off			
Fuel storage & dispensation		●	Ability to store and transfer large quantities of supplies
Self-sufficient			
Personnel transfer		○	No ability to support personnel transfer; slow speed vessel with deep draft
		◑	Ability to support personnel transfer for 15+ personnel
		●	High speed, shallow draft vessel with ability to transport 30+ personnel per voyage
Fresh water production		○	No ability to produce freshwater beyond shipboard usage
		◑	Ability to produce and transfer >2,000 gallons per day (gpd) beyond shipboard usage
		●	Able to produce and transfer > 5,000 gpd beyond shipboard usage
Personnel support		○	Low crew size with minimal ability to support HADR mission (< 50 personnel)
		◑	Medium size crew which can support HADR mission (51 - 200 personnel)
		●	Large crew with ability to support HADR mission (> 200 personnel)
Berthing capacity		○	Little to no excess berthing or facilities (< 30 racks)
		◑	Some excess berthing and facilities (31-50 racks)
		●	Large number of excess berthing and facilities (> 50)
Medical support		○	No ability to conduct inpatient medical treatment; no Medical officer embarked
		◑	Some medical support onboard; ability to support minor medical procedures
		●	Medical officer embarked; ability to perform surgeries and hold several patients
Transit speed		○	0-18 knots max speed
		◑	19-24 knots max speed
		●	25 + knots max speed
Hydrographic survey		○	No ability to conduct hydrographic surveys
		◑	Some ability to conduct hydrographic surveys to include soundings and chart building
		●	Able to conduct hydrographic surveying, soundings and chart development
Salvage Ops		○	No ability to conduct salvage operations
		◑	Some ability to conduct lift and salvage operations in shallow waters
		●	Able to conduct heavy lift and deep water salvage operations
Towing		○	No ability to conduct towing operations
		◑	Ability to conduct emergency towing operations
		●	Designed to conduct push, pull, or alongside towing operations

"Combat ships such as destroyers and cruisers can travel at high speeds, and they have very little utility in the disaster zone because they lack the ability to produce large amounts of fresh water, do not have excess food stores, and generally lack extra berthing capacity. These ships are particularly ill-suited to HADR missions if, in addition, they lack an embarked helicopter. The oilers, prepositioning ships with roll-on/roll-off capability, and hospital ships can also be elements of an HADR flotilla because they have storage capacity and capabilities that other commercial ships and warships lack." (Apte et al. 2013, page 55)

HADR Deployment Issues and the Solution

The vessels deployed by the USN in the 2004 Indian Ocean tsunami consisted of the entire Carrier Strike Group (CSG) 9, which included two fast attack submarines (SSN), one cruiser (CG), three destroyers (DDGs), one fast combat support ship (T-AOE), and nine aircraft squadrons. In 2007, in order to help Bangladesh with the Category 5 cyclone, Sidr, USS Hopper (DDG 70), a destroyer that does not carry any embarked helicopters and has a draft that is not sufficient for getting in close to shore, was diverted to help. Many of these vessels did not play a substantial role in the HADR due to the lack of necessary capabilities (Apte et al., 2013). In spite of this, the ships were tasked with the HADR missions simply because they were available. The experience off the coast of Bangladesh suggests that sometimes ships are diverted or deployed in a suboptimal way, perhaps due to lack of proper decision-making due to time pressure or process constraints (Apte et al., 2013). The USN has frequently supported HADR missions across the globe. However, many times the response is reactionary. Such response in the past has resulted in deploying or diverting ships—at a very high cost—that had no or little capability of delivering disaster relief (Apte & Yoho, 2017). Thus, not only are these particular ships not best to deploy for HADR but sending them creates unavailability if a conflict occurs elsewhere.

Apte and Yoho (2018) develop a mathematical model to optimize the deployment of USN assets for HADR operations based upon the capability rating system used in Apte et al. (2013) under certain assumptions. They suggest an optimal mix of ships that should be sent for HADR based on available supply, demand, and capabilities. The level of specific capabilities of each vessel is based on its capability score (Apte et al., 2013) shown in Table 1 as "little to no capability" (○ or 0), "some capability" (◖ or 1), or "significant capability" (● or 2).

Apte and Yoho's (2018) Optimization Model is as follows:

I = set of resources (vessels), for $i \in I$; *J* = set of capabilities, for $j \in J$

D_j = demand for capability *j*, for $j \in J$

b_i= daily operating cost of vessel $i \in I$

$\{\eta_{ij}\}_{IxJ}$ = capability of vessel $i \in I$ for capability $j \in J$ Where,

$$\eta_{ij} = \begin{cases} 2 \text{ if } i \text{ is capable for } j \\ 1 \text{ if } i \text{ is somewhat capable for } j \\ 0 \text{ if } i \text{ is not capable for } j \end{cases}$$

<u>Decision Variable</u>:

Y_i = number of vessels $i \in I$

The Optimization Model

$$\text{minimize} \quad \sum_{i \in I} b_i Y_i \qquad (1)$$

$$\text{subject to} \quad \sum_{i \in I} \eta_{ij} Y_i \geq D_j \quad \forall j \in J \qquad (2)$$

$$Y_i \text{ integer} \qquad \forall i \in I \qquad (3)$$

The objective function 1 minimizes the cost of a vessel $i \in I$ summed over all vessels, thus yielding the total cost. Constraints 2 ensure that the demand for capability is met by the flotilla of the vessels that are deployed and/or diverted to the affected host country. Constraints 3 guarantee that fractional vessels are not deployed or diverted.

Methodology and Results

The methodology used for studying and analyzing existing vessels for HADR missions gave us insight into which vessels could be used in a controlled zone in a conflict. If one ignores the cost, basing conclusions only on capabilities, the vessels to use will be the slow-moving yet large load carrying LPDs, LSDs, and carriers. However, if cost is considered, then the MSC ships like PM-8 and amphibious vessels come into play. The MSC ships T-As have many capabilities such as fleet replenishment, fast combat support, maritime prepositioning, dry cargo/ammunition transportation, and maritime prepositioning (roll-on/roll-off).

In our scenarios, the Combat Logistics Force (CLF) ships that include L-class/LCS/JHSV/LPD/LSD stay in the controlled zone, whereas the DDGs stay in the contested environment. This suggests that the Offshore Support Vessels (OSV) need to replenish the DDGs and Surface Action Groups (SAGs).

From the perspective of refuel, rearm, and resupply, cheaper, lower capacity vessels and defended assets deliver tonnage much more efficiently than large undefended conventional maritime logistics vessels (Dougherty et al., 2020). The expeditionary vessels—“pullers” such as Expeditionary Transfer Dock (ESD) and the Expeditionary Sea Base (ESB) in the Expeditionary Logistics System (ELS)—can perform these operations. However, it is worth looking at an added option of augmenting the fleet with new vessels, such as Small Auxiliary Logistics Platform (SALP), also called Next Generation Logistics Ships (NGLSs). The purpose here in developing different methodologies and models within those methodologies is to offer choice based on different objectives and different trade-offs among the vessels. In this research, we offer different models for different scenarios involving NGLSs that are flexible with respect to parameters and hence offer choices to decision-makers. But first we describe the motivation for the new vessels (manufactured or refitted), then the actual vessels.

Motivation for the New Vessels

To optimize its future fleet logistics platforms, the USN is exploring the concept of a common hull, multi-mission auxiliary ship design. Navy interest in the multi-mission concept was outlined in a recently released request for information to industry (Gourley, 2018). "'A next generation medium amphibious ship will be a stern landing vessel to support amphibious ship-to-shore operations' while the medium logistics ship 'will be a platform support vessel to support theater lift requirements'" (Abott, 2020, para. 3). Commandant of the Marine Corps, Gen. David Berger, explained his perspective on amphibious forces, including the need for more small ships, at an Amphibious Warship Industrial Base Coalition event.

> I think our amphibious fleet has great capability. It is not enough for 2030. It is not enough for 2025. We need the big decks, absolutely. We need the LPD-17, that is the mothership, the quarterback and the middle. But we need a light amphibious force ship, a lot of them that we don't have today. (Abott, 2020, para. 8)

Abott (2020) continues that the Navy said this non-acquisition program will be one "that designs, develops, and tests the Integrated Naval Force Structure Assessment, to evaluate next generation medium platform solutions for logistics mission requirements in support of Distributed Maritime Operations (DMO) and Littoral Operations in Contested Environment (LOCE)" (para. 11).

The Navy and Marine Corps announced that they will seek a medium amphibious ship that can support the kind of dispersed, agile, constantly relocating force described in the LOCE and Expeditionary Advanced Base Operations (EABO) concepts the Marine Corps has written, as well as the overarching DMO from the Navy (Eckstein, 2020). Marine Corps planners described the features they need on this medium amphibious ship. They not only wanted a ship that could move Marines around with some range, but they also wanted the ship to be able to beach itself, like a landing craft, to help offload gear and vehicles as needed. Presently, there is a new focus on the stern landing vessel designed by Australian company Sea Transport, which could serve as the new inspiration for the medium amphibious vessel as requirements development, EABO wargaming, and simulations take place.

Future Surface Combatant Force is developing alternate surface ship force structure concepts and evaluating their cost and effectiveness, performing force-wide warfighting and mission effectiveness studies, identifying capabilities and characteristics needed to meet future threats, and developing a Technology Investment Strategy to help guide investments for an effective future fighting force. Our research supports this concept.

Some of the vessels, NGLSs, will be commercial ship designs tailored to fit the top-level requirements that can conduct logistics missions in a contested environment. Through these new NGLS vessels, the USN will enable refueling, rearming, and resupply of naval assets, afloat and ashore, in support of LOCE and EABO (Katz, 2020). In a memorandum signed by CNO and Commandant USMC (Congressional Research Service, 2020), Force Structure Assessment (FSA) morphed into Integrated Naval FSA (INFSA), where *Naval* refers to Navy *and* Marine Corps. Acting Secretary of the Navy Modly announced that

> there are certain ship classes that don't even exist right now that we're looking at that will be added into that mix, but the broad message is, it's going to be a bigger fleet, it's going to be a more distributed fleet, it's going to be a more agile fleet. And we need to figure out what that path is and understand our topline limitations. (Congressional Research Service, 2020)

He added that the service is also considering new amphibious ships, as well as new kinds of supply ships and "lightly manned" ships that are "more like missile magazines that would accompany surface action groups." (Congressional Research Service, 2020)

General David H. Berger, the commandant of the Marine Corps, states,

> We must also explore new options, such as inter-theater connectors and commercially available ships and craft that are smaller and less expensive, thereby increasing the affordability and allowing acquisition at a greater quantity. We recognize that we must distribute our forces ashore given the growth of adversary precision strike capabilities, so it would be illogical to continue to concentrate our forces on a few large ships. The adversary will quickly recognize that striking while concentrated (aboard ship) is the preferred option. We need to change this calculus with a new fleet design of smaller, more lethal, and more risk-worthy platforms. (Congressional Research Service, 2020)

We now offer a summary of certain requirements for these vessels that lead to their capabilities since we base our assumptions underlying the developed models on their top-level requirements (TLRs). TLRs are design specifications of performance requirements for future ships.

Description of the New Vessels: Small Auxiliary Logistics Platforms (SALP)

These vessels do not necessarily exist yet but have TLR thresholds defined for each performance dimension.

Platform Supply Vessel (PSV)

In summary, the vessel should have sustained speed of about 11–12 knots. The range of travel for PSV is about 3,500 nm. Its fuel capacity needs to be about 20,000 bbl. Ammunition and cargo capacity needs to be adequate for replenishing cargo, ammunition, and fuel at sea from Combat Logistics Force (CLF), specifically, about 800-900 short tons and deck area being about 10,000 sq ft. A major capability of the PSV is to be capable of delivering about 5,000 bbl of fuel under about 2 hours at sea. In addition, it needs to be able to deliver 15 loads/hour of ammunition and/or cargo in parallel with refueling. This vessel will be unmanned throughout the operational cycle with organic support only when necessary. Autonomously executing the mission is a required capability of PSV.

Fast Supply Vessel (FSV)

Much smaller than PSV but much faster, the sustained speed of an FSV is 23 knots, and the range of travel is about 800–1000 nm. The fuel capacity is required to be about 1,000 bbl. Deck area for ammunition and dry cargo is about 2,500 sq ft. A major capability of the FSV is to replenish PSV in littorals. It also needs to do water transfers with hose reel with roll-on/roll-off capabilities. On shore, FSV needs to be able to refuel at a minimum of about 500 gallons/minute with 2,000 ft hose reel. It also needs to be capable of conducting missions for 2–3 days without replenishment. Finally, it needs to be able to transfer cargo to a pier or ashore.

Light Amphibious Warships (LAW)

These lighter ships will help the Navy and Marine Corps meet new challenges, including sea-control-and-denial operations. The light amphibious warships will serve as maneuver and sustainment vessels to confront the changing character of warfare. The

LAW will have beachability and ability to maneuver shore to shore. It will also be able to provide transfer of fuel and cargo from T-ships on beaches and ports (developed and undeveloped) to forces within contested environment. The idea is to have a risk-worthy vessel (defensible enough that risks are not excessive or cheap enough that we can afford to lose it) with priority for personnel survivability.

Being an amphibious vessel, LAW should deal with 1:40 to 1:100 beach gradients. The loaded LAW should have speed of about 18 knots. Thus, its speed is between the speeds of PSV and FSV. Its minimum operating range is about 5,000 nm. It is capable of transferring 500 gallons/minute fuel at sea or to shore. LAW is capable of conducting up to 11-day missions without replenishment. It is expected to receive, store, and transport up to 90,000 gallons of fuel in port as well as at sea. This fuel can be transferred at the rate of 150 gallons/minute in port as well as at sea. It can have four fueling stations around its cargo deck for filling trucks and vehicles. It has a crane with maximum outreach of about 14 T. It has cargo area of about 10,000 sq ft and deck loading capacity of about 500 lb/sq ft.

Our first methodology derives a mathematical model based on capabilities for resource optimization for humanitarian missions, bearing in mind the distinction between contested environment and uncontested environment, which is that, other than the LAW, neither the PSV nor the FSV can defend themselves. Therefore, if they do not encounter combat, the missions are similar. If they do encounter combat, the PSV and FSV will simply be lost, while the LAW will face an attrition rate. The attrition rates of these vessels have been estimated elsewhere (Dougherty et al., 2020). Since our results can simply be adjusted to account for those already estimated attrition rates, we do not need to model combat attrition in this study. Thus, the HADR inference is relevant in the contested environment.

Methodology I

In this methodology, we minimize operating cost of vessels that deliver fuel, ammunition, and supplies to ships involved in the conflict. The capabilities of the delivery vessels must meet the demand. The model, Model-3.3-1, is given in Appendix A.

For the parameters of this model, the capabilities do not follow an ordinal scale. The capabilities can be computed with an equation based on the influencing factors. Such computation is more objective than ordinal measures, as it is based on actual data. However, it does not necessarily incorporate qualitative or subject matter expert opinions, except in the thresholds those experts have established for the TLRs. Since subject matter experts are more attuned with operations and have considerable experience as well as knowledge, not heeding their advice or opinion could pose a problem. The first model considers daily cost of operations.

The sponsor asked us to ignore costs in some of our models because cost estimates were not yet publishable as developed from the TLRs. With this in mind, we developed the second model. In the second model, the capabilities are on ordinal scale, and the lower the rank, the better the vessel for that capability. If ranks of the vessels based on their capabilities are minimized, the optimal solution from the model will be the vessels that are most capable for said operations. This scale is developed based on knowledge, experience, and opinion of subject matter experts. The model, Model-3.3-2, is given in Appendix B.

Methodology II

The models in the first methodology focus on capabilities. However, we believe transportation for replenishment is critical in contested environment. The capabilities have been drivers of the top-level requirements (TLRs) for PSV, FSV, and LAW. We based this methodology assuming the TLRs are described for the SALP vessels. Therefore, we focused on the supply chain/transportation/transshipment models. These models, based on different scenarios, offer a choice of flexible solutions to decision-makers.

We include the capacities of the vessels and offer two objectives so decision-makers can choose different objectives based on the situations: Objective A minimizes ***time*** for deliveries, and Objective B minimizes ***number*** of deliveries by the appropriate vessels on corresponding route. The time considered was only for transportation and not actual delivery, meaning that load and unload times are not incorporated. However, there was also a time constraint for total unload time to ships in the Weapon

Engagement Zone (WEZ). While we did not explicitly model this unload-time constraint, we modified capacities of the vessels per the time constraint in order to represent the time constraint of delivery. For example, if unload time was constrained to 1 hour, and an NGLS vessel could only unload 10 pallets in an hour, we modified its cargo capacity to 10 pallets, so that would be all it could deliver in one trip.

These transportation/transshipment models consider controlled and contested zones. The assumption is that most of the supplying vessels and Combat Logistics Force (CLF) are in the controlled zone, so there is transfer of commodities in the contested zone from NGLSs to the SAG and transshipment nodes. The transshipment node provides supply for the different Expeditionary Advance Bases (EABs) on the shore in the contested zone. We developed models and analyzed scenarios for the SALP vessels. The modes of transportation in the models and scenarios are PSV, FSV, and LAW. Each of these vessels have certain preferred routes and requirements for capacities, loading/unloading and platforms. These translate into restrictions and constraints for the models.

Given that the goal of our research was to find number of vessels needed, from among PSV, FSV and LAW, we focused on the second objective of minimizing the number of total deliveries by vessels on given routes. We define a delivery as carrying the commodities from a supply node to a demand node, on the given route by a vessel designated to travel on that route. However, we also analyzed the results with the objective of minimizing the transit delivery time, but not the load and unload time (though with modifications to capacity to account for unload time in WEZ as already explained.) The models are executed using plausible but hypothetical numbers in order to maintain the unclassified nature of the report.

The tables list the supply and demand at the nodes of the network. Though the results are based on hypothetical numbers, these numbers can be scaled up or down by using an appropriate multiplier. At this point, we would like to state that the distances between the nodes, demands and supplies at the nodes, and speed and capacities of the vessels for transportation used in this document are approximations and not the real data, again to maintain the unclassified status of the classification of this report.

The distances and time in hours for the scenario in Figures 5 through 7-2 are given in Table 2.

Table 2. Distances Between Nodes (nm) and Delivery Times (Hours)

		Distance in nm between nodes				
		Route				
		1-2	1-3	3-4	3-5	3-6
Vessel	**Speed nm/h**	500	700	300	400	450
PSV	12	42	58	25	33	38
FSV	23	22	30	13	17	20
LAW	18	28	39	17	22	25

Aggregated Multicommodity Transshipment

Scenario

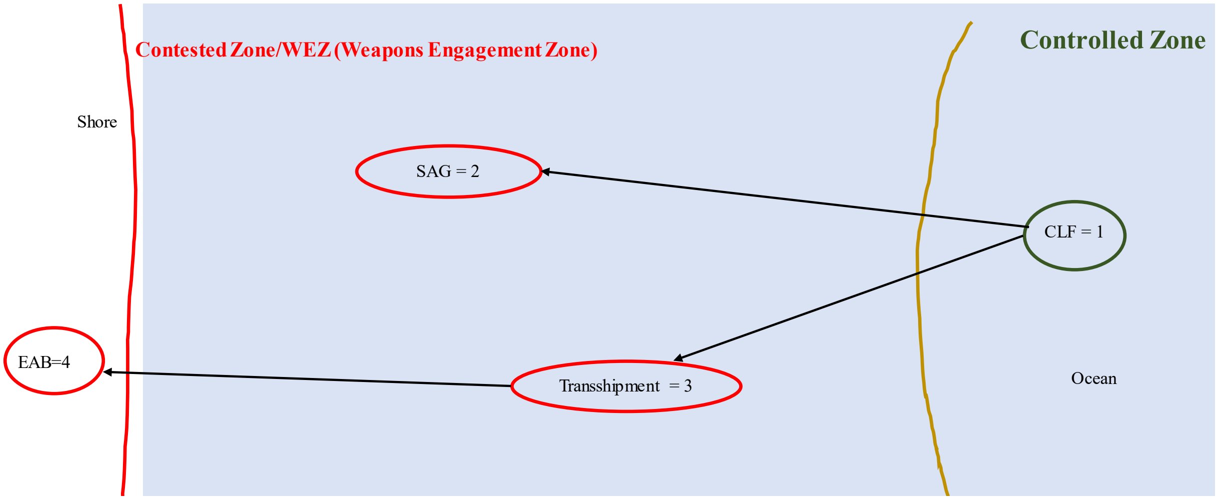

Figure 4. Scenario for Transportation of Fuel, Ammunition, and Supplies

The model, Model-3.4-3, given in Appendix C, is based on the scenario in Figure 4. The supply from CLF designated as node 1, is assumed to be in the controlled zone. The remaining demand nodes are in contested zones. The demand nodes in this scenario are Surface Action Group (SAG) designated as node 2 and Transshipment node designated as node 3. The supply to EAB designated by node 4 originates in CLF but is transferred through Transshipment node 3. We developed this model to understand the interaction within supplies and demands. We also wanted to gain insight into the two objectives of minimizing the time for deliveries (Objective A) and the number of deliveries (Objective B). This insight helped us develop other scenarios and models based on the objectives. We assume that the deliveries are sequential for Objective A (equivalently, assuming the transshipment node starts empty). This assumption therefore shows the time, if the replenishment is done sequentially. The results, therefore, reflect maximum time needed. Delivering in parallel will reduce this time. Objective A assumes “milk run” scenario as opposed to simultaneous or parallel deliveries (assuming, equivalently, that the transshipment node starts full, with a vessel available to deliver to the shore). Objective B finds the minimum number of deliveries needed to meet the demand. These are deliveries by specific vessels on compatible routes and not number of vessels. We call this model Model by Aggregation, and it is given in Appendix C.

In the process of developing these models, given that the fuel (F) is stored separately from ammunition and supplies (A-S), we separated the models for F and A-S. Fuel capacity is measured in barrels whereas ammunition and supplies are in pallets. In case of A-S, both potentially occupy the same square footage of the vessels. Therefore, we combined these two commodities (A-S) when we developed square footage constraints for the models. The models for both F and A-S are very similar except for the supply, demand, and capacities.

Scenario for Bounds on Number of Deliveries

Scenario

Based on our discussions with sponsors and subject matter experts, we developed another scenario that has more granularity than the scenario in Figure 4. In the scenario depicted in Figure 5, the supply from CLF (node 1) is assumed to be in the controlled zone. The remaining demand nodes are in contested zones. The demand nodes in this scenario are SAG (node 2), Transshipment (node 3), Anti-Surface Warfare (ASuW) (node 4), Forward Arming and Refueling Point (FARP) (node 5) and Maritime/Naval Logistics EAB (LOG) (node 6). The supply to ASuW (node 4), FARP (node 5), and LOG (node 6) originates in CLF but is transferred through Transshipment. We use the scenarios in Figure 5 for all the models developed. However, these models were executed with different parameters and inputs.

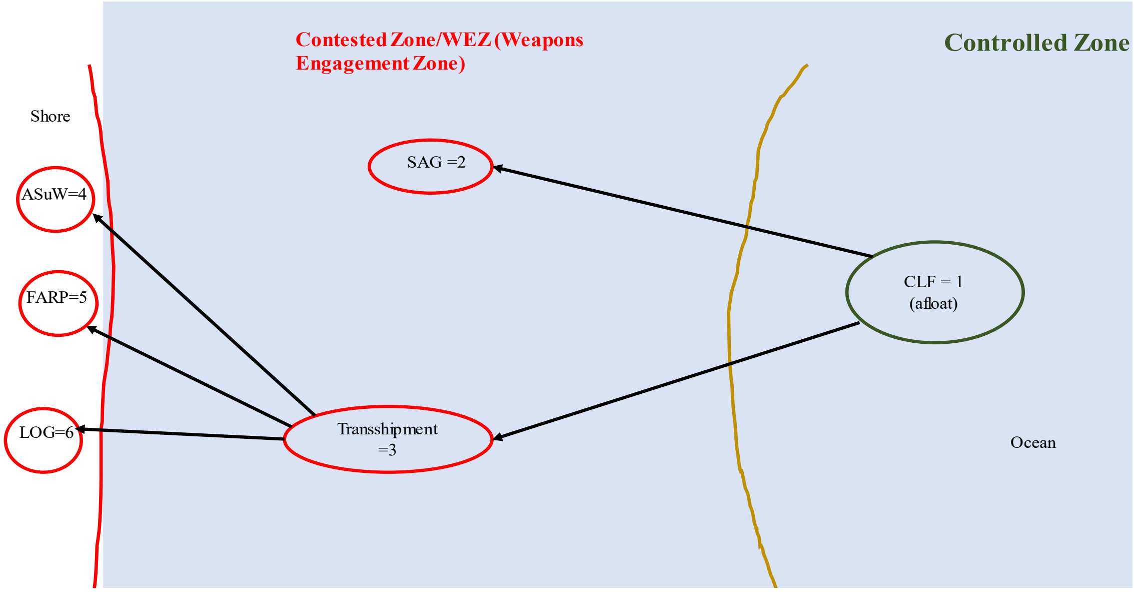

Figure 5. Scenario: Refuel, Rearm, and Resupply for Upper Bounds on Number of Deliveries

In this scenario (Figure 5), we wanted to find out what the upper bounds are on the number of deliveries by the three different vessels, if employed by themselves. The model below is developed for that purpose. The nodes represent various supplies and demands. The arcs represent transportation by SALP vessels, PSV, FSV, and LAW, one at a time. The model, Model-3.4-4, is given in Appendix D. In the actual execution we used *only* PSV, *only* FSV, and *only* LAW in the network for the deliveries. In other words, we assumed each route for transportation has only one kind of vessel, and we made separate model runs for a single type of vessel. The scenarios were executed for F and A-S separately.

We developed similar model for A-S with supply and demands for ammunition and supplies. The capacities, in pallets, for both these commodities were combined. Other than these distinctions, the structure of the models was identical. Replacing supplies, demands, and capacities for F with those of A-S created the A-S model.

Results

The supply and demand at the nodes and capacities of vessels are given in Table 3-1 for Fuel and Table 3-2 for Ammunition and Supplies. We would like to point out that we have made certain assumptions for the capacities of PSV. Given that PSV cannot engage SAG in the contested environment for more than 1 hour, thus delivering a maximum of 5500 BBLs of fuel in one trip, we model this as their storage capacity (per trip). Pallets of ammunition and supplies are delivered at the same time. Therefore, within that hour, only 60 pallets can be delivered by the PSV to SAG instead of 800 pallets, which is the real capacity of PSV. However, when delivering via the same ship to other demand nodes, since such a time restriction does not exist, the capacity of the PSV is assumed to be 800 pallets.

The results from this computational experiment are given in Tables 4-1 (Fuel) and 4-2 (Ammunition with Supplies) with the Objective B (minimizing number of deliveries). In order to find the bounds on the possible number of each type of vessels needed, we used the model (Model by Aggregation; see Figure 4). This model identifies number of deliveries in case only one type of vessel is used for transportation. We performed this computational experiment to find the bounds on each type of vessel irrespective of their capability to deliver for that route.

Table 3-1. Supply, Demand, and Capacities: Fuel

Fuel in BBL	Supply/Demand
Fuel Supply at CLF 1	100000
Fuel Supply at Trans 3	6500
Fuel Demand at SAG 2	22000
Fuel Demand at Trans 3	6500
Fuel Demand at ASuW 4	100
Fuel Demand at FARP 5	6300
Fuel Demand at LOG 6	100
Fuel in BBL	**Capacity**
PSV from CLF 1 to SAG 2	5500
PSV from CLF 1 to Trans 3	5500
PSV from Trans 3 to ASuW 4	5500
PSV from Trans 3 to FARP 5	5500
PSV from Trans 3 to LOG 6	5500
FSV from CLF 1 to SAG 2	1000
FSV from CLF 1 to Trans 3	1000
FSV from Trans 3 to ASuW 4	1000
FSV from Trans 3 to FARP 5	1000
FSV from Trans 3 to LOG 6	1000
LAW from CLF 1 to SAG 2	2200
LAW from CLF 1 to Trans 3	2200
LAW from Trans 3 to ASuW 4	2200
LAW from Trans 3 to FARP 5	2200
LAW from Trans 3 to LOG 6	2200

Table 3-2. Supply, Demand, and Capacities: Ammunition and Supplies

Ammunition and Supplies in Pallets	Supply/Demand
A-S Supply at CLF 1	100000
A-S Supply at Trans 3	750
A-S Demand at SAG 2	100
A-S Demand at Trans 3	750
A-S Demand at ASuW 4	50
A-S Demand at FARP 5	350
A-S Demand at LOG 6	350
Ammunition and Supplies in Pallets	**Capacity**
PSV from CLF 1 to SAG 2	60
PSV from CLF 1 to Trans 3	800
PSV from Trans 3 to ASuW 4	800
PSV from Trans 3 to FARP 5	800
PSV from Trans 3 to LOG 6	800
FSV from CLF 1 to SAG 2	60
FSV from CLF 1 to Trans 3	250
FSV from Trans 3 to ASuW 4	250
FSV from Trans 3 to FARP 5	250
FSV from Trans 3 to LOG 6	250
LAW from CLF 1 to SAG 2	60
LAW from CLF 1 to Trans 3	1000
LAW from Trans 3 to ASuW 4	1000
LAW from Trans 3 to FARP 5	1000
LAW from Trans 3 to LOG 6	1000

The results in Table 4-1 reveal that, to minimize the delivery time, the bounds on the number of vessel-trips on PSV is 10, FSV is 38, and LAW is 18. These results are obtained under the assumed values of the input of demand and supplies, and the parametric values of capacities of fuel for the vessels PSV, FSV, and LAW. It must be stated at this point that the value of 10 for PSV can be interpreted in many ways. If each PSV makes only one delivery, then there need to be 10 PSVs, whereas if each PSV makes two deliveries, then there need to be at least five PSVs. This logic can be expanded further based on the choice of the decision-makers for all vessels.

Table 4-1. Upper Bounds on Vessel-Trips to Minimize Number of Deliveries: Fuel

	PSV only Deliveries	FSV only Deliveries	LAW only Deliveries
PSV from CLF 1 to SAG 2	4		
PSV from CLF 1 to Trans 3	2		
PSV from Trans 3 to ASuW 4	1		
PSV from Trans 3 to FARP 5	2		
PSV from Trans 3 to LOG 6	1		
FSV from CLF 1 to SAG 2		22	
FSV from CLF 1 to Trans 3		7	
FSV from Trans 3 to ASuW 4		1	
FSV from Trans 3 to FARP 5		7	
FSV from Trans 3 to LOG 6		1	
LAW from CLF 1 to SAG 2			10
LAW from CLF 1 to Trans 3			3
LAW from Trans 3 to ASuW 4			1
LAW from Trans 3 to FARP 5			3
LAW from Trans 3 to LOG 6			1
Total	10	38	18

Table 4-2. Upper Bounds on Vessel-Trips to Minimize Number of Deliveries: Ammunition and Supplies

	PSV only Deliveries	FSV only Deliveries	LAW only Deliveries
PSV from CLF 1 to SAG 2	2		
PSV from CLF 1 to Trans 3	1		
PSV from Trans 3 to ASuW 4	1		
PSV from Trans 3 to FARP 5	1		
PSV from Trans 3 to LOG 6	1		
FSV from CLF 1 to SAG 2		2	
FSV from CLF 1 to Trans 3		3	
FSV from Trans 3 to ASuW 4		1	
FSV from Trans 3 to FARP 5		2	
FSV from Trans 3 to LOG 6		2	
LAW from CLF 1 to SAG 2			2
LAW from CLF 1 to Trans 3			1
LAW from Trans 3 to ASuW 4			1
LAW from Trans 3 to FARP 5			1
LAW from Trans 3 to LOG 6			1
Total	6	10	6

The results in Table 4-2 reveal that, to minimize the delivery time, the upper bound on PSV is 6, FSV is 10, and LAW is 6. These results are obtained under the assumed values of the input of demand and supplies and the capacities of ammunition and supplies for the vessels PSV, FSV, and LAW. Similar logic may be applied to offer a choice to decision-makers as before, namely, if each LAW makes only one delivery, then six LAWs are needed, but if they make three deliveries each, then only two LAWs are necessary.

Subject Matter Expert Feedback (Capability Restricted Transportation)

We now offer two scenarios and the corresponding models based on feedback from subject matter experts (SMEs). Vessels allowed on the respective routes are shown in Figure 6-1. This scenario first looks at the entire network (Figure 6-1). We offer a different perspective by splitting the transshipment network into two separate transportation networks (Figure 6-2). Here the model treats SAG (node 2) as one entity. The model, Model-3.4-5 is given in Appendix E.

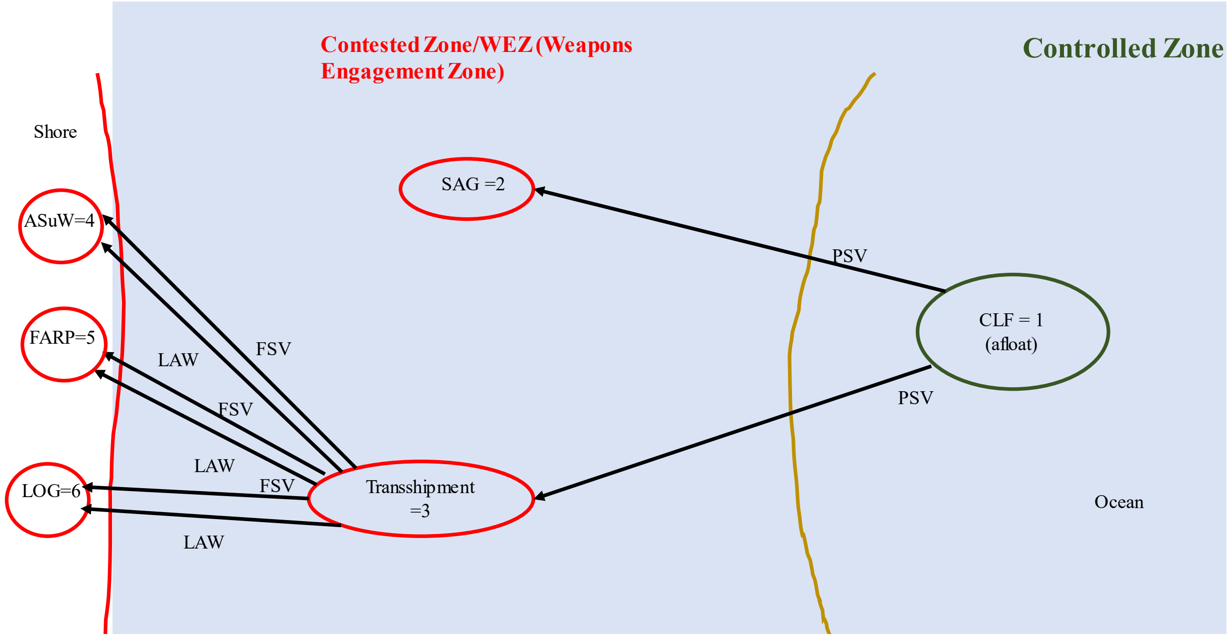

Figure 6-1. Scenario Based on Subject Matter Expert Feedback

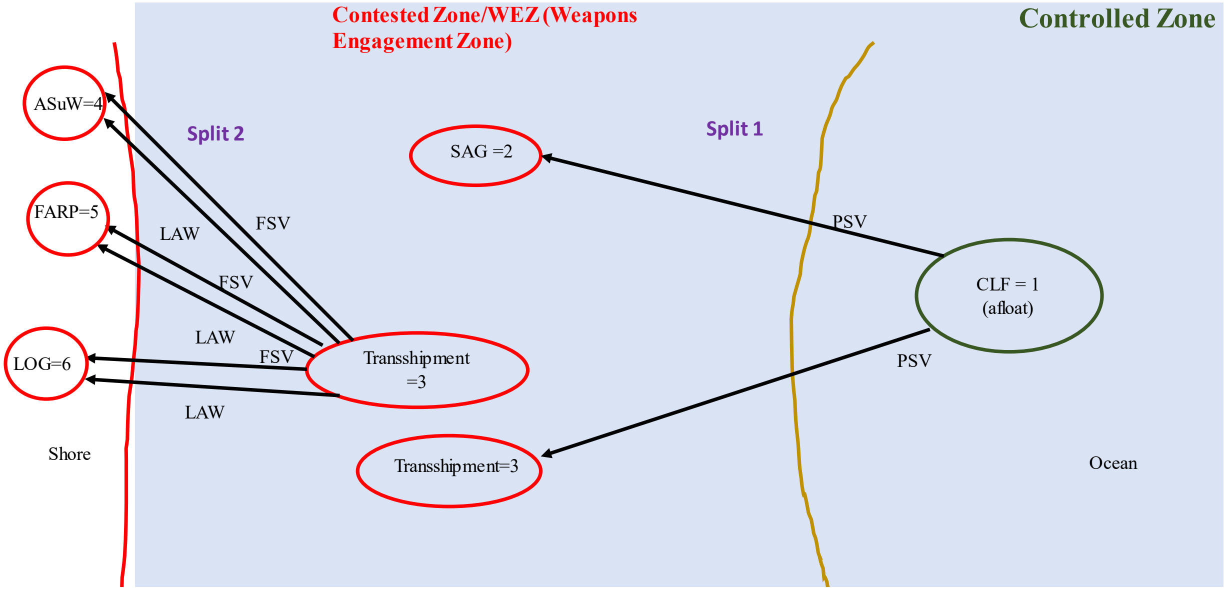

Figure 6-2. Scenario Based on Subject Matter Expert Feedback with Split 1 and Split 2

As shown in Figure 6-2, Split 1 transports commodities from CLF to SAG and Transshipment whereas Split 2 transports commodities from Transshipment to ASuW, FARP, and LOG. The advantage of splitting the entire/combined/transshipment network into two transportation networks is twofold. One, Split 1 focuses on the USN whereas Split 2 focuses on the USMC. This helps in maintaining the needs of Marines ashore and Navy forces afloat. Second, transshipment of the commodities is assumed to be done sequentially, and though the two transportation networks have the same assumption, they can be executed in parallel, thus reducing total time. The corresponding model, Model-3.3-6 is given in Appendix F. Similar models based on Figures 6-1 and 6-2 were developed and executed for A-S.

Results

We further evaluated number of deliveries by the vessels by incorporating the restrictions on the vessels due to their capabilities. Top-level requirements for NGLSs informed us of the inability of certain vessels for transportation between certain nodes. These were incorporated in the structure of the scenarios and corresponding models. The supply and demand at the nodes and capacities of vessels in these scenarios are given in Table 5-1 for Fuel and Table 5-2 for Ammunition and Supplies. In Table 5-2, the capacity of vessels for ammunition and supplies is constrained from CLF to SAG by length of time of 1 hour, the maximum time any ship in the SAG can be engaged for fueling. The assumption is that since the pallets are delivered at the rate of 60 pallets/hour, only 60 pallets can be delivered to SAG, though the capacity of PSV is 800 pallets.

Table 5-1. Supply, Demand, and Capacities: Fuel

Fuel in BBL	Supply/Demand
Fuel Supply at CLF 1	100000
Fuel Supply at Trans 3	6500
Fuel Demand at SAG 2	22000
Fuel Demand at Trans 3	6500
Fuel Demand at ASuW 4	100
Fuel Demand at FARP 5	6300
Fuel Demand at LOG 6	100
Fuel in BBL	**Capacity**
PSV from CLF 1 to SAG 2	5500
PSV from CLF 1 to Trans 3	5500
FSV from Trans 3 to ASuW 4	1000
FSV from Trans 3 to FARP 5	1000
FSV from Trans 3 to LOG 6	1000
LAW from Trans 3 to ASuW 4	2200
LAW from Trans 3 to FARP 5	2200
LAW from Trans 3 to LOG 6	2200

Table 5-2. Supply, Demand, and Capacities: Ammunition and Supplies

Ammunition and Supplies in Pallets	Supply/Demand
A-S Supply at CLF 1	100000
A-S Supply at Trans 3	750
A-S Demand at SAG 2	100
A-S Demand at Trans 3	750
A-S Demand at ASuW 4	50
A-S Demand at FARP 5	350
A-S Demand at LOG 6	350
Ammunition and Supplies in Pallets	**Capacity**
PSV from CLF 1 to SAG 2	60
PSV from CLF 1 to Trans 3	800
FSV from Trans 3 to ASuW 4	250
FSV from Trans 3 to FARP 5	250
FSV from Trans 3 to LOG 6	250
LAW from Trans 3 to ASuW 4	1000
LAW from Trans 3 to FARP 5	1000
LAW from Trans 3 to LOG 6	1000

Here too we implemented the model (Model for Capability Restricted Transportation based on Figures 6-1 and 6-2) using both the objectives. The scenarios are given in Figures 6-1 and 6-2, and the results are given in Tables 6-1 through 7-2, with both objectives, minimum time for deliveries and minimum number of deliveries by the vessels.

In Table 6-1 (fuel), results from Objective A (minimizing delivery time) for scenario in Figures 6-1 and 6-2 offer two interpretations of the objective. The column "Time (in days)" gives how long it will take to refuel for the supplies and demands with given capacities of the NGLS vessels, given the assumptions for distance (nm) within the network and vessel speed (nm/h). The results show that it is necessary to have total of 11 deliveries and the total time taken is almost 16 days. This is under the assumption that the deliveries are carried out sequentially (equivalently, that the transshipment node starts empty). Based on the urgency, level of conflict, and acquisition strategy, this may change.

Table 6-1. Minimum Time Needed for Transportation of Fuel

Scenarios	Combined		Split-1		Split-2	
Fuel in BBL		**Time (in days)**		**Time (in days)**		**Time (in days)**
PSV from CLF 1 to SAG 2	4	7	4	7		
PSV from CLF 1 to Trans 3	2	4.83	2	4.83		
FSV from Trans 3 to ASuW 4	1	0.54			1	0.54
FSV from Trans 3 to FARP 5	0	0			0	
FSV from Trans 3 to LOG 6	1	0.83			1	0.83
LAW from Trans 3 to ASuW 4	0	0			0	
LAW from Trans 3 to FARP 5	3	2.75			3	2.75
LAW from Trans 3 to LOG 6	0	0			0	
Total	11	15.95	6	11.83	5	4.12

In Table 6-2 (ammunition and supplies), results from Objective A (minimizing delivery time) for scenario in Figure 6-1 and 6-2 again offer two interpretations of the objective. The column "Time (in days)" shows how long it will take to rearm and resupply for the supplies and demands with given capacities. We have assumed distance (nm) within the network and speed (nm/h) for SALP vessels. It is necessary to have a total of six deliveries, and the total time taken is more than 8 days. This may seem confusing, since the NGLSs are supplying the SAG for an 8-day interval. But these 8.42 days represent the makespan of delivering Ammunition and Supplies, the total time required by all ships. The longest time on any one route is 3.5 days, required by the PSV to deliver to the SAG. While this time does not include the return trip, it is important to remember that two trips are required because of the reduced capacity necessitated by the 1-hour delivery window requirement. The PSV would not need to return to port to load more Ammunition and Supplies before returning for the second offload.

Table 6-2. Minimum Time Needed for Transportation of Ammunition and Supplies

Scenarios	Combined		Split-1		Split-2	
Ammunition and Supplies in Pallets		**Time (in days)**		**Time (in days)**		**Time (in days)**
PSV from CLF 1 to SAG 2	2	3.5	2	3.5		
PSV from CLF 1 to Trans 3	1	2.42	1	2.42		
FSV from Trans 3 to ASuW 4	1	0.54			1	0.54
FSV from Trans 3 to FARP 5	0	0			0	0
FSV from Trans 3 to LOG 6	0	0			0	0
LAW from Trans 3 to ASuW 4	0	0			0	0
LAW from Trans 3 to FARP 5	1	0.92			1	0.92
LAW from Trans 3 to LOG 6	1	1.04			1	1.04
Total	6	8.42	3	5.92	3	2.5

It should be noted that in the combined network, the deliveries are carried out sequentially (Tables 6-1 and 6-2). Splitting the transshipment network into two transportation networks, one from CLF to SAG and Transshipment node, and the other from Transshipment node to demand nodes on shore in the contested zone, allows the transportation for deliveries to be in parallel, thus taking less time. As mentioned earlier, Split 1 transports commodities from CLF to SAG and Transshipment whereas Split 2 transports commodities from Transshipment to ASuW, FARP, and LOG. For Objective A, minimizing the total time for transportation, combined network transporting the commodities is assumed to be done sequentially. However, the two split transportation networks can be executed in parallel, thus reducing total time. For the combined network, it takes about 16 days to deliver fuel (Table 6-1), whereas in the split networks it takes maximum of 11 days. In case of ammunition and supplies, the combined network delivers in about 8 days, whereas the split networks deliver in 6 days. Thus, as is evident, sequential deliveries take longer than parallel, and this separation enhances this issue.

In Table 7-1 (fuel), results from Objective B (minimizing number of deliveries) for scenario in Figure 6-1 and 6-2 show that it is necessary to have total of 11 deliveries. The results are same as those in Table 6-1 where we minimize the delivery time. It can be seen from Table 7-2 that the number of deliveries in the combined network and the total from Split networks are the same; however, the configuration has changed.

Table 7-1. Minimum Number of Deliveries for Transportation of Fuel

Scenarios	Combined	Split 1	Split 2
Fuel in BBL	**Deliveries**	**Deliveries**	**Deliveries**
PSV from CLF 1 to SAG 2	4	4	
PSV from CLF 1 to Trans 3	2	2	
FSV from Trans 3 to ASuW 4	1		0
FSV from Trans 3 to FARP 5	0		0
FSV from Trans 3 to LOG 6	1		1
LAW from Trans 3 to ASuW 4	0		1
LAW from Trans 3 to FARP 5	3		3
LAW from Trans 3 to LOG 6	0		0
Total	11	6	5

Table 7-2. Minimum Number of Deliveries for Transportation of Ammunition and Supplies

Scenarios	Combined	Split 1	Split 2
Ammunition and Supplies in Pallets	**Deliveries**	**Deliveries**	**Deliveries**
PSV from CLF 1 to SAG 2	2	2	
PSV from CLF 1 to Trans 3	1	1	
FSV from Trans 3 to ASuW 4	1		0
FSV from Trans 3 to FARP 5	0		0
FSV from Trans 3 to LOG 6	0		0
LAW from Trans 3 to ASuW 4	0		1
LAW from Trans 3 to FARP 5	1		1
LAW from Trans 3 to LOG 6	1		1
Total	6	3	3

Separated SAG: Three DDGs and One LCS or One FFG

Scenario

In order to offer another perspective, we further expanded the scenarios where we separated SAG 2 into three DDGs and one LCS (Figure 7-1) in one case and three DDGs and one FFG (Figure 7-2) in the other. It needs to be noted that splitting SAG in corresponding vessels offers better insight into the situation since it offers delivery numbers for each demand nodes. We believe this would further help decision-makers. The corresponding model, Model-3.4-7 is given in Appendix G.

In both scenarios, the demand node afloat is SAG, and demand nodes ashore are EABs, specifically ASuW EAB, FARP, and LOG. It should also be noted that we used a period of 8 days in this scenario, since it is the maximum period for a DDG between refueling events. This assumption forces LCS in the first case and FFG in the other to be refueled twice; therefore, we assumed the demand at LCS in the first case and FFG in the other to be twice as much. The increased demand for these vessels increases the deliveries to these ships and not DDGs. Given the capacities of the SALP vessels and the demand at LCS and FFG, the delivery numbers were different. In case of ammunition and supply replenishment, this scenario changes. DDGs can only be engaged for at most 1 hour for delivery of fuel. Therefore, we assumed that corresponding A-S delivery, since it is done by the same vessel, can also be done in parallel for only 1 hour at the rate of 60 pallets per hour. If we remove this restriction for A-S delivery, the capacities change. The idea here is that the refueling can be done for one DDG at a time independently or consecutively (like a milk run). Though we separated SAG into different demand nodes, we did not execute the model for minimizing delivery time since approximate distances from CLF to each node in SAG would be similar.

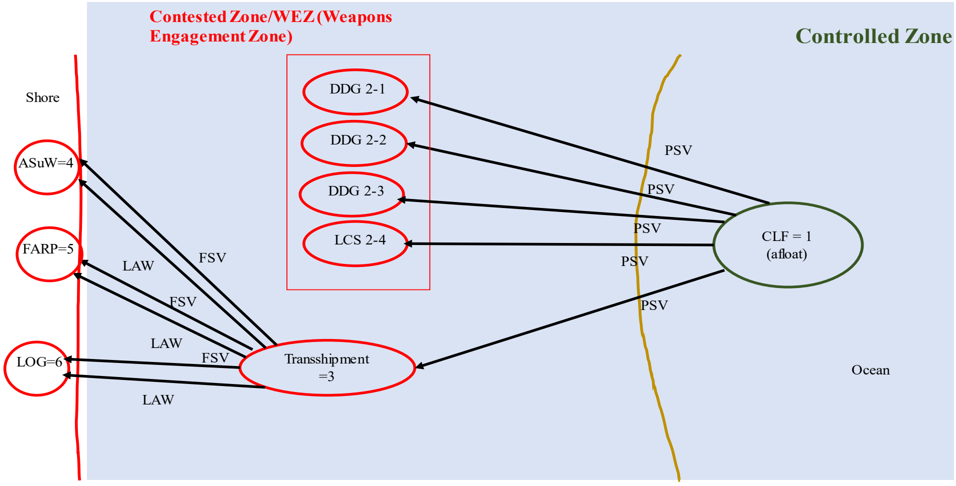

Figure 7-1. Scenario Based on Separated SAG: 3 DDGs and LCS

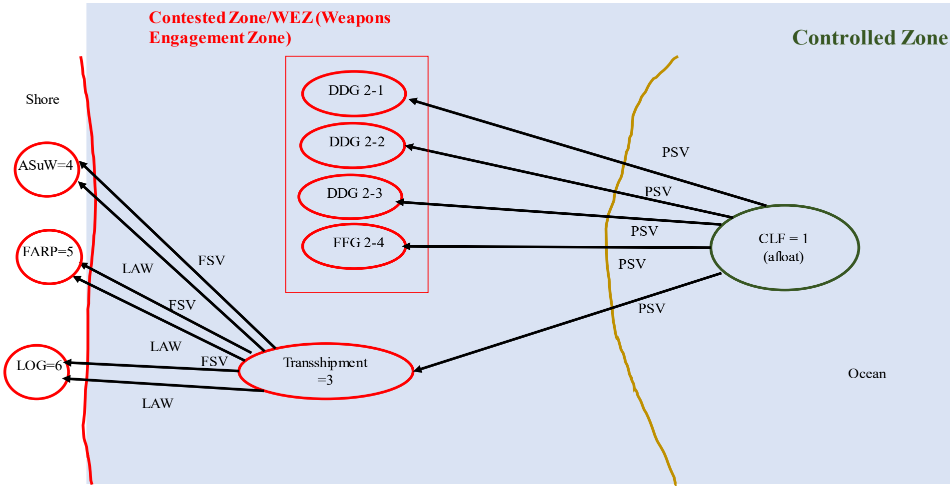

Figure 7-2. Scenario Based on Separated SAG: 3 DDGs and FFG

We developed and executed similar models for A-S based on the scenarios in Figure 7-1 and 7-2.

Results

Separating SAG into DDGs and LCS or FFG creates a unique difficulty in replenishment. We incorporated the replenishment for a scenario where the period was preset, and we created a scenario to incorporate this variation. Periodic replenishment over time was not considered due to uncertainty and stochasticity of the actual scenarios. However, we incorporated the maximum length of time among demand nodes (SAG, consisting of DDG, FFG and LCS, LAW, and EAB-S) to provide sustainment for rest of the nodes. The supply and demand at the nodes, and capacities of vessels, in these scenarios are given in Table 8-1 for Fuel and Table 8-2 for Ammunition and Supplies, in case of LCS.

Table 8-1. Supply, Demand, and Capacities with Sustainment, LCS: Fuel

Fuel in BBL	Supply/Demand
Fuel Supply at CLF 1	1000000
Fuel Supply at Trans 3	6500
Fuel Demand at DDG 2-1	5000
Fuel Demand at DDG 2-2	5000
Fuel Demand at DDG 2-3	5000
Fuel Demand at LCS 2-4	3000
Fuel Demand at Trans 3	6500
Fuel Demand at ASuW 4	100
Fuel Demand at FARP 5	6300
Fuel Demand at LOG 6	100
Fuel in BBL	**Capacity**
Capacity of PSV from CLF 1 to DDG 2-1	5500
Capacity of PSV from CLF 1 to DDG 2-2	5500
Capacity of PSV from CLF 1 to DDG 2-3	5500
Capacity of PSV from CLF 1 to DDG 2-4	5500
Capacity of PSV from CLF 1 to Trans 3	5500
Capacity of FSV from Trans 3 to ASuW 4	1000
Capacity of FSV from Trans 3 to FARP 5	1000
Capacity of FSV from Trans 3 to LOG 6	1000
Capacity of LAW from Trans 3 to ASuW 4	2200
Capacity of LAW from Trans 3 to FARP 5	2200
Capacity of LAW from Trans 3 to LOG 6	2200

Table 8-2. Supply, Demand, and Capacities with Sustainment, LCS: Ammunition and Supplies

Ammunition and Supplies in Pallets	Supply/Demand
A-S Supply at CLF 1	100000
A-S Supply at Trans 3	750
A-S Demand at DDG 2-1	25
A-S Demand at DDG 2-2	25
A-S Demand at DDG 2-3	25
A-S Demand at LCS 2-4	20
A-S Demand at Trans 3	750
A-S Demand at ASuW 4	50
A-S Demand at FARP 5	350
A-S Demand at LOG 6	350
Ammunition and Supplies in Pallets	**Capacity**
Capacity of PSV from CLF 1 to DDG 2-1	60
Capacity of PSV from CLF 1 to DDG 2-2	60
Capacity of PSV from CLF 1 to DDG 2-3	60
Capacity of PSV from CLF 1 to DDG 2-4	60
Capacity of PSV from CLF 1 to Trans 3	800
Capacity of FSV from Trans 3 to ASuW 4	250
Capacity of FSV from Trans 3 to FARP 5	250
Capacity of FSV from Trans 3 to LOG 6	250
Capacity of LAW from Trans 3 to ASuW 4	1000
Capacity of LAW from Trans 3 to FARP 5	1000
Capacity of LAW from Trans 3 to LOG 6	1000

In the case of FFG, results are given in Table 9-1 for Fuel and Table 9-2 for Ammunition and Supplies.

Table 9-1. Supply, Demand, and Capacities FFG: Fuel

Fuel in BBL	Supply/Demand
Fuel Supply at CLF 1	1000000
Fuel Supply at Trans 3	6500
Fuel Demand at DDG 2-1	5000
Fuel Demand at DDG 2-2	5000
Fuel Demand at DDG 2-3	5000
Fuel Demand at FFG 2-4	7000
Fuel Demand at Trans 3	6500
Fuel Demand at ASuW 4	100
Fuel Demand at FARP 5	6300
Fuel Demand at LOG 6	100
Fuel in BBL	Capacity
Capacity of PSV from CLF 1 to DDG 2-1	5500
Capacity of PSV from CLF 1 to DDG 2-2	5500
Capacity of PSV from CLF 1 to DDG 2-3	5500
Capacity of PSV from CLF 1 to DDG 2-4	5500
Capacity of PSV from CLF 1 to Trans 3	5500
Capacity of FSV from Trans 3 to ASuW 4	1000
Capacity of FSV from Trans 3 to FARP 5	1000
Capacity of FSV from Trans 3 to LOG 6	1000
Capacity of LAW from Trans 3 to ASuW 4	2200
Capacity of LAW from Trans 3 to FARP 5	2200
Capacity of LAW from Trans 3 to LOG 6	2200

Table 9-2. Supply, Demand, and Capacities FFG: Ammunition and Supplies

Ammunition and Supplies in Pallets	Supply/Demand
A-S Supply at CLF 1	100000
A-S Supply at Trans 3	750
A-S Demand at DDG 2-1	25
A-S Demand at DDG 2-2	25
A-S Demand at DDG 2-3	25
A-S Demand at FFG 2-4	25
A-S Demand at Trans 3	750
A-S Demand at ASuW 4	50
A-S Demand at FARP 5	350
A-S Demand at LOG 6	350
Ammunition and Supplies in Pallets	Capacity
Capacity of PSV from CLF 1 to DDG 2-1	60
Capacity of PSV from CLF 1 to DDG 2-2	60
Capacity of PSV from CLF 1 to DDG 2-3	60
Capacity of PSV from CLF 1 to DDG 2-4	60
Capacity of PSV from CLF 1 to Trans 3	800
Capacity of FSV from Trans 3 to ASuW 4	250
Capacity of FSV from Trans 3 to FARP 5	250
Capacity of FSV from Trans 3 to LOG 6	250
Capacity of LAW from Trans 3 to ASuW 4	1000
Capacity of LAW from Trans 3 to FARP 5	1000
Capacity of LAW from Trans 3 to LOG 6	1000

Assuming that DDG can sustain for 8 days without refueling, FFG must be refueled every 7 days and LCS every 4 days. We incorporated this by changing the corresponding demands in the models based on Figure 7-1 and 7-2. The results with

LCS are given in Tables 10-1 (fuel) and 10-2 (ammunition and supplies). Tables 11-1 (fuel) and 11-2 (ammunition and supplies) describe the results with FFG.

Table 10-1. Minimum Number of Deliveries for Transportation of Fuel: Three DDGs and One LCS

	Deliveries
PSV from CLF 1 to DDG 2-1	1
PSV from CLF 1 to DDG 2-2	1
PSV from CLF 1 to DDG 2-3	1
PSV from CLF 1 to LCS 2-4	1
PSV from CLF 1 to Trans 3	2
FSV from Trans 3 to ASuW 4	1
FSV from Trans 3 to FARP 5	0
FSV from Trans 3 to LOG 6	1
LAW from Trans 3 to ASuW 4	0
LAW from Trans 3 to FARP 5	3
LAW from Trans 3 to LOG 6	0
Total	11

Table 10-2. Minimum Number of Deliveries for Transportation of Ammunition and Supplies: Three DDGs and One LCS

	Deliveries
PSV from CLF 1 to DDG 2-1	1
PSV from CLF 1 to DDG 2-2	1
PSV from CLF 1 to DDG 2-3	1
PSV from CLF 1 to LCS 2-4	1
PSV from CLF 1 to Trans 3	1
FSV from Trans 3 to ASuW 4	1
FSV from Trans 3 to FARP 5	0
FSV from Trans 3 to LOG 6	0
LAW from Trans 3 to ASuW 4	0
LAW from Trans 3 to FARP 5	1
LAW from Trans 3 to LOG 6	1
Total	8

Table 11-1. Minimum Number of Deliveries for Transportation of Fuel: Three DDGs and One FFG

	Deliveries
PSV from CLF 1 to DDG 2-1	1
PSV from CLF 1 to DDG 2-2	1
PSV from CLF 1 to DDG 2-3	1
PSV from CLF 1 to FFG 2-4	2
PSV from CLF 1 to Trans 3	2
FSV from Trans 3 to ASuW 4	1
FSV from Trans 3 to FARP 5	0
FSV from Trans 3 to LOG 6	1
LAW from Trans 3 to ASuW 4	0
LAW from Trans 3 to FARP 5	3
LAW from Trans 3 to LOG 6	0
Total	12

Table 11-2. Minimum Number of Deliveries for Transportation of Ammunition and Supplies: Three DDGs and One FFG

	Deliveries
PSV from CLF 1 to DDG 2-1	1
PSV from CLF 1 to DDG 2-2	1
PSV from CLF 1 to DDG 2-3	1
PSV from CLF 1 to FFG 2-4	1
PSV from CLF 1 to Trans 3	1
FSV from Trans 3 to ASuW 4	0
FSV from Trans 3 to FARP 5	0
FSV from Trans 3 to LOG 6	0
LAW from Trans 3 to ASuW 4	1
LAW from Trans 3 to FARP 5	1
LAW from Trans 3 to LOG 6	1
Total	8

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Summary Analysis and Conclusion

Feedback from the SME helped us gain insight into the complexity of the problem and its vast scope. We used this input to refine our scenarios. We developed mathematical models based on these scenarios. We have listed those scenarios that will offer decision-makers with a choice based on their requirement. If the need is to find the least amount of time needed to make the deliveries, then results from models with Objective A can be considered. But if the choice is to consider minimum number of deliveries, then results from models with Objective B can be considered. In Objective A, we only considered time for transportation, but not the actual delivery (load/unload). The decision-makers can incorporate the delivery time and schedule the vessels based on that. However, they do now know the least time it takes for transportation in fulfilling the demand of all the nodes. We did constrain the capacity based on the maximum time a ship can be engaged in a supply event to reflect the delivery time.

The top-level requirements of the vessels under consideration, as we understood, incorporate capability of a vessel on certain route based on speed, platform, and capacity. The fuel storage tanks are separate from the storage for ammunition and supplies. Hence, we kept these two commodities separate. Fuel has its own issues, and so do ammunition and supplies. Note that the separate trips for these two commodities could be combined when trying to operationalize these results into a schedule, involving a particular number of ships.

The sponsor did not wish us to model an objective of minimizing costs (which were not available) or the number of ships required to deliver commodities within a certain deadline of under a certain schedule (because deadlines and schedules change based on operational priorities). Measuring the number of deliveries required allowed us to determine a mix of NGLS vessels without addressing cost, deadline, or scheduling restrictions.

We would like to point out that number of deliveries are the deliveries made by a specific vessel, from a supply node to a demand node, on a specific route for a specific commodity. Deliveries can be interpreted in many ways. For example, a LAW making

13 deliveries of fuel to FARP can be (a) 13 LAWs (making one delivery each), or (b) seven LAWs (six LAWs making two deliveries each and one LAW making one delivery), or six LAWs (making one delivery each, and one LAW making seven of the 13 deliveries). Thus, it is up to the decision-makers how they would like to interpret and implement the results. A conservative decision-maker may go for 13 LAWs if the cost is reasonable and the environment is highly contested. But if it is not, perhaps seven LAWs will be adequate. Again, the number of deliveries may be interpreted by the decision-makers based on their preference, and there could be many such interpretations. Similar statements can be made about PSVs or FSVs. For example, if there are five deliveries made by PSVs, it could mean that (a) there are five PSVs making one delivery each, or (b) two PSVs making two deliveries each and one PSV making one. One must note, however, that the deliveries will be constrained by overall capacity of the vessel. If one PSV tops out after four deliveries, then the interpretation would change. It would be entirely up to the decision-makers how they would want to interpret the solution.

In Tables 12-1 (Fuel) and 12-2 (Ammunition and Supplies), we summarize the results of the scenarios.

Table 12-1. Summary of Scenario Results for Fuel

	Objective A : Minimizing Delivery Time				Objective B: Minimizing Number of Deliveries			
Scenario	Number of Deliveries by PSV	Number of Deliveries by FSV	Number of Deliveries by LAW	Total Deliveries	Number of Deliveries by PSV	Number of Deliveries by FSV	Number of Deliveries by LAW	Total Deliveries
Scenario: Upper Bounds on Number of Deliveries (Figure 6)	NA				10	38	18	NA
Scenario Based on Subject Matter Expert Feedback (Figure 6-1 and 6-2)								
Combined	6	2	3	11	6	2	3	11
Split 1 and Split 2	6	2	3	11	6	1	4	11
Scenario Based on Separated SAG: 3 DDGs and LCS with Sustainment (Figure 7-1)	NA				6	2	3	11
Scenario Based on Separated SAG: 3 DDGs and FFG with Sustainment (Figure 7-2)	NA				7	2	3	12

Table 12-2. Summary of Scenario Results for Ammunition and Supplies

	Objective A : Minimizing Delivery Time				Objective B: Minimizing Number of Deliveries			
Scenario	Number of Deliveries by PSV	Number of Deliveries by FSV	Number of Deliveries by LAW	Total Deliveries	Number of Deliveries by PSV	Number of Deliveries by FSV	Number of Deliveries by LAW	Total Deliveries
Scenario: Upper Bounds on Number of Deliveries (Figure 6)	NA				6	10	6	NA
Scenario Based on Subject Matter Expert Feedback (Figure 6-1 and 6-2)								
Combined	3	1	2	6	3	1	2	6
Split 1 and Split 2	3	1	2	6	3	0	3	6
Scenario Based on Separated SAG: 3 DDGs and LCS with Sustainment (Figure 8-1)	NA				5	1	2	8
Scenario Based on Separated SAG: 3 DDGs and FFG with Sustainment (Figure 8-2)	NA				5	0	3	8

The scenarios can be expanded as per the requirement of number of demand nodes. For example, if there are three SAGs that must be supported, the demand of one SAG in our scenario can be multiplied by three. Of course, in that case, the number of deliveries will increase. Or there may be more than one ASuW Strike EAB, say two, or both these cases may exist. In that case, the demand for that demand node can be doubled. Such adjustments can be also be made to distances or when minimum time for deliveries needs to be known. The corresponding results are given in Table 13-1 for Fuel and Table 13-2 for Ammunition and Supplies.

Table 13-1. Minimum Deliveries with Increased Demand Nodes: Fuel

Scenarios	Three SAGS	Two ASuWs	Three SAGs and Two ASuWs
Fuel in BBL	Deliveries	Deliveries	Deliveries
PSV from CLF 1 to SAG 2	12	4	12
PSV from CLF 1 to Trans 3	2	2	2
FSV from Trans 3 to ASuW 4	0	0	0
FSV from Trans 3 to FARP 5	0	0	0
FSV from Trans 3 to LOG 6	0	1	0
LAW from Trans 3 to ASuW 4	1	1	1
LAW from Trans 3 to FARP 5	3	3	3
LAW from Trans 3 to LOG 6	1	0	1
Total	19	11	19

Table 13-2. Minimum Deliveries with Increased Demand Nodes: Ammunition and Supplies

Scenarios	Three SAGS	Two ASuWs	Three SAGs and Two ASuWs
Ammunition and Supplies in Pallets	Deliveries	Deliveries	Deliveries
PSV from CLF 1 to SAG 2	5	2	5
PSV from CLF 1 to Trans 3	1	1	1
FSV from Trans 3 to ASuW 4	0	0	0
FSV from Trans 3 to FARP 5	0	0	0
FSV from Trans 3 to LOG 6	0	0	0
LAW from Trans 3 to ASuW 4	1	1	1
LAW from Trans 3 to FARP 5	1	1	1
LAW from Trans 3 to LOG 6	1	1	1
Total	9	6	9

As stated earlier, we did not incorporate load and unload time. Incorporating time for load and unload time might increase the total time for deliveries. This may lead to acquisition of more vessels so the actual transportation and delivery can be done in parallel, to reduce the time. For example, in case four PSVs are needed to deliver required fuel to SAG (based on the assumptions about distance and speed of PSV), and that a warship can only be engaged for at most 1 hour for this delivery our model shows, it takes total of 7 days. However, given that DDGs can sustain for 8 days after one refueling event and there are three DDGs in a SAG, an acquisition strategy for acquiring four PSVs so each PSV takes less than 2 days to deliver may be a better solution than one PSV making four deliveries in 7 days. Again, this is a choice the decision-makers can make based on the flexibility of these models.

Based on our analysis, we recommend the following to negotiate battlespace constraints. We suggest that the time constraint for PSV engaging with SAG in WEZ should be investigated, since that is the binding constraint on capacity to transfer. The capacity of PSV for carrying fuels is much larger than that, and the same is true for transferring the pallets of ammunition and supplies. It will be necessary to increase the rate of transfer if the time spent in the WEZ cannot be altered. Our capacity assumptions were based on threshold as opposed to objective TLRs. Hence, objective TLRs may be the direction to go. This may need tweaking at the TLRs and some platform modification so that sustainment can be made much faster and with fewer deliveries.

We summarize number of deliveries made by FSV and LAW for each of the scenarios in Table 14.

Table 14. Deliveries by FSV and LAW

		Fuel		Ammunition and Supplies	
Number	**Scenario**	**Number of Deliveries by FSV**	**Number of Deliveries by LAW**	**Number of Deliveries by FSV**	**Number of Deliveries by LAW**
1	Scenario Based on Subject Matter Expert Feedback (Figure 6-1 and 6-2)				
1.1	Combined	1	3	1	2
1.2	Split 1 and Split 2	2	4	0	3
2	Scenario Based on Separated SAG: 3 DDGs and LCS with Sustainment (Figure 7-1)	2	3	1	2
3	Scenario Based on Separated SAG: 3 DDGs and FFG with Sustainment (Figure 7-2)	2	3	0	3
4	Scenario Based on Increased Demand Nodes				
4.1	Three SAGS	0	5	0	3
4.2	Two ASuWs	1	4	0	3
4.3	Three SAGs and Two ASuWs	0	5	0	3

Based on this summary, one can see that the most FSVs needed for each of these scenarios to transport fuel are *two,* whereas for the same scenarios *five* LAWs are needed. Similarly, the most FSVs needed for each of these scenarios to transport ammunition and supplies is *one*. However, *three* LAWs are needed for the same. These results and our analysis therefore suggest that acquisition of LAWs is preferred to FSVs, since it may be prohibitively expensive to maintain a separate maintenance support infrastructure for FSVs, when their range of usefulness is relatively narrow. Although the FSV does not look very useful in these scenarios, these scenarios did not require the TLRs in which that ship dominated the others.

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Appendix 1. USN Ships

Acronym	Ship
	USN
CVN	Aircraft Carrier
CVN	Aircraft Carrier
LHD	Amphibious Assault
LHA	Amphibious Assault
LCC	Amphibious Command
LPD	Amphibious Transport Dock
LPD	Amphibious Transport Dock
LSD	Dock Landing Ship
LSD	Dock Landing Ship
CG	Cruisers
DDG	Destroyers (FLT I & II)
DDG	Destroyers (FLT IIA)
FFG	Frigates
LCS	Littoral Combar Ship
LCS	Littoral Combar Ship
PC	Patrol Forces
MCM	Minesweepers / Minehunters

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Appendix 2. MSC Ships

	MSC
T-AOE	Fast Combat Support Ship
T-AO	Fleet replenishment Oiler
T-AE	Ammunition Ship
T-AKE	Dry Cargo / Ammunition
T-ARS	Rescue and Salvage
T-ATF	Fleet Ocean Tug
T-AH	Hospital Ship
LCC	Command Ship
AS	Submarine Tender
T-AGOS	Ocean Surveillance Ship
T-AGS	Oceanographic Survey Ship
T-AGS	Navigation Test Support Ship
T-AGM	Missile Range Instrumentation
T-ARC	Cable Laying / Repair
T-AK, T-AKR	Large Medium Speed RO/RO (LMSR)
Bobo (T-AK)	MPF Container and RO/RO (MPS)
T-AK	MPF Container
T-AOT	MPF Petroleum Tanker
T-AK	Air Force Container
T-AK	Army Container
T-AVB	Aviation Logistics Support
T-AG	Offshore Petroleum Distribution System (OPDS)
T-AK	Break-Bulk
HSV	High Speed Vessel (HSV)
T-AK	Large Medium Speed RO/RO (LMSR)
T-AOT	Petroleum Tanker (T-5)
	Common Use Tanker
T-AK	Dry Cargo
	Ready Reserve Forces (RRF)
	Fast Sealift Ship
	RO/RO ships
	Crane Ships
	Lighterage-aboard ships
	Offshore Petroleum Discharge Tankers
	Break-Bulk Ships
	Seabee Ships
	Aviation Logistics Support

Appendix 2 Continued

LCAC	Landing Craft, Air Cushioned
LCU	Landing Craft, Utility
LCM	Landing Craft, Mechanized
LCM	Landing Craft, Mechanized
Name	Aircraft
Seahawk	SH-60B
Seahawk	SH-60F
Seahawk	MH-60R
Seahawk	MH-60S
Seahawk	HH-60H
Sea Knight	CH-46E
Sea Stallion	CH-53D
Super Stallion	CH-53E
Sea Dragon	MH-53E
Super Cobra	AH-1W / AH-1Z
Twin Huey	HH-1N / UH-1N / UH-1Y
Osprey	MV-22 / CV-22

Appendix 3. Description of USN and MSC Ships

U.S. Navy	Nuclear Carrier	CVN (Nimitz)	An aircraft carrier is a warship with a full-length flight deck and facilities for carrying, arming, deploying, and recovering aircraft, that serves as a seagoing airbase. A nuclear carrier is powered by nuclear power.
		CVN (Enterprise)	
	Amphibious Ships	LHD	The Amphibious ships have the ability to move swiftly through water and over land. They operate year-round, handling power projection and beach assault, as well as assisting in crisis response, humanitarian operations and disaster relief.
		LHA	
		LCC	
		LPD (San Antonio)	
		LPD (Austin)	
		LSD (Harpers Ferry)	
		LSD (Whidbey Island)	
	CRUDES	CG	Navy cruisers, destroyers and frigates make certain no carrier, cargo/supply ship or oil tanker proceeds into an area where enemy action is possible. With lightning-quick communications, space-based radar systems, precision weapons and advanced engineering systems, these agile surface warfare ships provide anti-aircraft, anti-submarine and anti-ship protective measures.
		DDG (FLT I & II)	
		DDG (FLT IIA)	
		Frigates	
	Other	LCS (Freedom)	Littoral combat ships, patrol craft, and mine countermeasures ships.
		LCS (Independence)	
		PC	
		MCM	

Appendix 3 (Description of USN and MSC ships)

Military Sealift Command (MSC)	PM - 1	T-AOE	Naval Fleet Auxiliary Force (NFAF) are the supply lines to USN ships at sea. These ships provide virtually everything that navy ships need, including fuel, food, ordnance, spare parts, mail and other supplies.
		T-AO	
		T-AE	
		T-AKE	
		T-ARS	
		T-ATF	
		T-AH	
	PM - 2	LCC	Special Mission Program ships provide operating platforms and services for a wide variety of U.S. military and other U.S. Government missions. Most special mission ships are Government-owned and operated by civilian mariners who work for private companies under contract to MSC.
		AS	
		T-AGOS	
		T-AGS (Survey)	
		T-AGS (Nav)	
		T-AGM	
		T-ARC	
	PM - 3	LMSR	MSC's prepositioning ships are able to discharge cargo pierside or while anchored offshore by using shallow-draft barges, called lighterage, that are carried aboard. This allows cargo to be ferried to shore in areas where ports are to operate in both developed and undeveloped areas of the world.
		MPS	
		MPF Container	
		T-AOT	
		T-AK (USAF)	
		T-AK (USA)	
		T-AVB	
		OPDS	
		Break-Bulk	
		HSV	
	PM - 5	LMSR	MSC's Sealift ships provides high-quality, efficient and cost-effective ocean transportation for DOD and other federal agencies during peacetime and war.
		T-5	
		Common Use Tanker	
		Dry Cargo	
	Ready Reserve Force	Fast Sealift Ship	The Department of Transportation's Maritime Administration (MARAD) maintains cargo ships in the Ready Reserve Force (RRF) to provide prompt sealift support in the event they are needed for the rapid deployment of military forces. The RRF includes RO/RO cargo ships, breakbulk ships, barge carriers, Auxiliary Crane Ships (ACSs), tankers, and two troop ships for surge sealift requirement which are capable of handling bulky, oversized military equipment.
		RO/RO ships	
		Crane Ships	
		Lighterage-aboard ships	
		OPDT	
		Break-Bulk Ships	
		Avaition Logistics Support	
Landing Craft		LCAC	Landing craft are used by amphibious forces to transport equipment and troops to the shore. Landing craft are also used to support civilian humanitarian/maritime operations. Landing craft are capable of transporting cargo, tracked and/or wheeled vehicles and troops from amphibious assault ships to beachheads or piers.
		LCU	
		LCM	
		LCM	

Appendix A

Model-3.3-1: Resupply, rearm, and refuel with cost as objective:

I = set of vessels, for $i \in I$;

J = set of capabilities, for $j \in J$

$= \{j \mid j = \text{refuel } [f], \text{ rearm } [a], \text{ resupply } [s]\}$

D_j = demand level for capability, for $j \in J$

$\{\eta_{ij}\}_{IxJ}$ = capability of vessel $i \in I$ for capability $j \in J$

c_i = daily operating cost of vessel $i \in I$

Decision Variable:

Y_i = number of vessels $i \in I$

$$\text{minimize} \quad \sum_{i \in I} c_i Y_i \qquad (1)$$

$$\text{subject to} \quad \sum_{i \in I} \eta_{ij} Y_i \geq D_j \quad \forall j \in J \qquad (2)$$

$$Y_i \text{ integer} \quad \forall i \in I \qquad (3)$$

η_{if} = computed capability of vessel i to refuel f,

- f depends on fuel storage capacity, fuel consumption rate and max speed.
  - Fuel consumption depends on speed
    - Speed depends on state of sea, wind and service time

η_{ia} = computed capability of vessel i to rearm a

η_{is} = computed capability of vessel i to resupply s

- s depends on dry goods storage, refrigerated storage, fresh water, freshwater production and fuel storage.

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Appendix B

Model-3.3-2: Resupply, rearm, and refuel with ranks of the vessels based on capabilities as objective

I = set of vessels, for $i \in I$;

J = set of capabilities, for $j \in J$

= $\{j \,/\, j$ = refuel [f], rearm [a], resupply [s]$\}$

D_j = demand level for capability, for$j \in J$

The demand levels can be a distribution

$\{\eta_{ij}\}_{IxJ}$= capability of vessel $i \in I$ for capability $j \in J$

$\{\mu_{ij}\}_{IxJ}$= rank based on capability η_{ij} of vessel $i \in I$ for capability $j \in J$

Decision Variable:

Y_i = number of vessels $i \in I$

The Optimization Model 2-i (Integer)

$$\text{minimize} \quad \sum_{i \in I} \mu_{ij} Y_i \qquad \forall j \in J \qquad (1)$$

$$\text{subject to} \quad \sum_{i \in I} \eta_{ij} Y_i \geq D_j \quad \forall j \in J \qquad (2)$$

$$Y_i \text{ integer} \quad \forall i \in I \qquad (3)$$

η_{if} = computed capability of vessel i to refuel f,

- f depends on fuel storage capacity, fuel consumption rate, and max speed.
    - Fuel consumption depends on speed
        - Speed depends on state of sea, wind, and service time

η_{ia} = computed capability of vessel i to rearm a

η_{is} = computed capability of vessel i to resupply s

- s depends on dry goods storage, refrigerated storage, fresh water, freshwater production, and fuel storage.

Note: *The optimal solution Y* are the number of vessels of each type or number of trips needed to be done by each type of vessel.*

The Optimization Model 2-c (Continuous)

$$\text{minimize} \quad \sum_{i\in I} \mu_{ij} Y_i \qquad \forall j \in J \qquad (1)$$

$$\text{subject to} \quad \sum_{i\in I} \eta_{ij} Y_i \geq D_j \quad \forall j \in J \qquad (2)$$

$$Y_i \geq 0 \qquad \forall i \in I \qquad (3)$$

η_{if} = computed capability of vessel i to refuel f,

- f depends on fuel storage capacity, fuel consumption rate, and max speed.
    - Fuel consumption depends on speed
        - Speed depends on state of sea, wind, and service time

η_{ia} = computed capability of vessel i to rearm a

η_{is} = computed capability of vessel i to resupply s

- s depends on dry goods storage, refrigerated storage, fresh water, freshwater production, and fuel storage.

Note: *The optimal solution Y* are the percentage of each type of vessels*

Appendix C

Model-3.3-3

Model by Aggregation (Figure 4)

Modes of Transportation: *PSV*, $k = 1$; *FSV*, $k = 2$; *LAW*, $k = 3$

Speed of vessel $k = s_k$

Three types of commodities: F: fuel, A: Ammunition, S: class I, II, IV, and VIII supplies

Shared capacity on vessel k *enroute* $ij = c_{kij}$

cF_{kij} = *fuel capacity of ship k on route ij (bbls)*

cAS_{kij} = *shared ammo & supply capacity of ship k on route ij (sq. ft.)*

Distance vector:

	12	13	34
	d_{12}	d_{12}	d_{23}

Delivery-Time matrix: $t_{kij} = d_{ij} / s_k$

	d_{12}	d_{13}	d_{34}
m_1	t_{112}	t_{113}	t_{134}
m_2	t_{212}	t_{213}	t_{234}
m_3	t_{312}	t_{313}	t_{334}

Decision Variables:

X_{Fkij} = flow of **fuel** from source i to node j on vessel-type k, $i=1$, $j= 2, 3$, $k = 1, 2, 3$

X_{Akij} = flow of **ammunition** from source i to node j on vessel-type k, $i=1$, $j= 2, 3$, $k = 1, 2, 3$

X_{Skij} = flow of **supplies** from source i to node j on vessel-type k, $i=1$, $j= 2, 3$, $k = 1, 2, 3$

X_{Fkjl} = flow of **fuel** from transshipment node j to sink l on vessel-type k, $j=3$, $l= 4$, $k = 1, 2, 3$

X_{Akjl} = flow of **ammunition** from transshipment node j to sink l on vessel-type k, $j=3$, $l= 3, 4$, $k = 1, 2, 3$

X_{Skjl} = flow of **supplies** from transshipment node j to sink l on vessel-type k, $j=2$, $l=4$, $k=1, 2, 3$

Y_{kij} = *number of deliveries made by vessel-type* k; $k = 1, 2, 3$, *(i, j) shown in Figure 5.*

Objective Function A

Minimize Delivery Time

$$\min\left(\sum_{j=2}^{3}\sum_{i=1}^{1}\sum_{k=1}^{3}(t_{kij})y_{kij} + \sum_{l=4}^{4}\sum_{j=3}^{3}\sum_{k=1}^{3}(t_{kjl})y_{kjl}\right)$$

OR

Objective Function B

Minimize Number of Deliveries

$$\min\left(\sum_{j=2}^{3}\sum_{i=1}^{1}\sum_{k=1}^{3} y_{kij} + \sum_{l=4}^{4}\sum_{j=3}^{3}\sum_{k=1}^{3} y_{kjl}\right)$$

Constraints

Supply

$$\sum_{k=1}^{3}\sum_{j=2}^{3} X_{Fkij} \le F_i \qquad i = 1 \text{ \{only one supply point in these scenarios\}}$$

$$\sum_{k=1}^{3}\sum_{j=2}^{3} X_{Akij} \le A_i \qquad i = 1$$

$$\sum_{k=1}^{3}\sum_{j=2}^{3} X_{Skij} \le S_i \qquad i = 1$$

Transshipment

$$\sum_{j=3}^{3}\sum_{i=1}^{1} X_{Fkij} - \sum_{l=4}^{4}\sum_{j=3}^{3} X_{Fkjl} \ge 0 \qquad k = 1, 2, 3$$

Demand

$$\sum_{k=1}^{3}\sum_{i=1}^{1} X_{Fkij} \ge F_j \qquad j = 2, 3$$

$$\sum_{k=1}^{3}\sum_{i=1}^{1} X_{Akij} \geq A_j \qquad j = 2, 3$$

$$\sum_{k=1}^{3}\sum_{i=i}^{1} X_{Skij} \geq S_j \qquad j = 2, 3$$

$$\sum_{k=1}^{3}\sum_{i=3}^{3} X_{Fkij} \geq F_j \qquad j = 4$$

$$\sum_{k=1}^{3}\sum_{i=3}^{3} X_{Akij} \geq A_j \qquad j = 4$$

$$\sum_{k=1}^{3}\sum_{i=3}^{3} X_{Skij} \geq S_j \qquad j = 4$$

Capacity

Capacity Fuel Volume,

$$(cF_{k12})Y_{k12} - X_{F112} \geq 0 \qquad k = 1, 2, 3$$

$$(cF_{k13})Y_{k13} - X_{Fk13} \geq 0 \qquad k = 1, 2, 3$$

$$(cF_{k34})Y_{k34} - X_{Fk34} \geq 0 \qquad k = 1, 2, 3$$

Capacity Ammunition and Supplies Volume,

$$(cAS_{k12})Y_{k12} - (X_{Ak12} + X_{Sk12}) \geq 0 \qquad k = 1, 2, 3 \qquad (13)$$

$$(cAS_{k13})Y_{k13} - (X_{Ak13} + X_{Sk13}) \geq 0 \qquad k = 1, 2, 3 \qquad (14)$$

$$(cAS_{k34})Y_{k34} - (X_{Ak34} + X_{Sk34}) \geq 0 \qquad k = 1, 2, 3 \qquad (15)$$

Y_{kij}'s integer, X_{kij}'s ≥ 0 *(i, j) shown in Figure 4, $k = 1, 2, 3$* *(16)*

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Appendix D

Model-3.4-4

Model for Bounds on Deliveries for Fuel (Figure 5)

Modes of Transportation: *PSV, k =1; FSV, k = 2; LAW, k = 3*

Speed of $k = s_k$

Type of commodities: F: fuel

Total supply at node i for fuel = S_{Fi}

Total demand at node j for fuel = D_{Fj}

Shared volume capacity for fuel **on vessel** k enroute ij = cF_{kij}

Trip Time matrix: $t_{kij} = (d_{ij}/ s_k)$

Trip Time	12	13	34	35	36	12	13	34	35	36	12	13	34	35	36
Vessel 1	t_{112}	t_{113}	t_{134}	t_{135}	t_{136}										
Vessel 2						t_{212}	t_{213}	t_{234}	t_{235}	t_{236}					
Vessel 3											t_{312}	t_{313}	t_{334}	t_{335}	t_{336}

Decision Variables:

X_{Fkij} = flow of **fuel** from source i to node j on vessel k, $i=1, j= 2, 3, 4, 5, k = 1, 2, 3$

X_{Fkjl} = flow of **fuel** from transshipment node j to sink l on vessel k, $j=5, l= 6, k = 1, 2, 3$

Y_{kij} = *number of deliveries by vessels of type k ((=1 for PSV, 2 for FSV and 3 for LAW) from node i to j*

Objective Function A

Minimize Delivery Time

$$\min((t_{112})y_{112} + (t_{113})y_{113} + (t_{134})y_{134} + (t_{135})y_{135} + (t_{136})y_{136})$$

or

$$\min((t_{212})y_{212} + (t_{213})y_{213} + (t_{234})y_{234} + (t_{235})y_{235} + (t_{236})y_{236})$$

or

$$\min((t_{312})y_{312} + (t_{313})y_{313} + (t_{334})y_{334} + (t_{335})y_{335}) + (t_{336})y_{336})$$

OR

Objective Function B

Minimize Number of Deliveries

$$\min(y_{112} + y_{113} + y_{134} + y_{135} + y_{136})$$
or
$$\min(y_{212} + y_{213} + y_{234} + y_{235} + y_{236})$$
or
$$\min(y_{312} + y_{313} + y_{334} + y_{335} + y_{336})$$

Constraints

Supply

At CLF = 1

$$(x_{F112} + x_{F113}) \le SF_1$$
or
$$(x_{F212} + x_{F213}) \le SF_1$$
or
$$(x_{F312} + x_{F313}) \le SF_1$$

At Transshipment = 3

$$(x_{F134} + x_{F135} + x_{F136}) \le SF_3$$
or
$$(x_{F234} + x_{F235} + x_{F236}) \le SF_3$$
or
$$(x_{F334} + x_{F335} + x_{F336}) \le SF_3$$

Demand

At SAG = 2

$$x_{F112} \ge DF_2$$
or
$$x_{F212} \ge DF_2$$
or
$$x_{F312} \ge DF_2$$

At Transshipment = 3

$$x_{F113} \geq DF_3$$
or
$$x_{F213} \geq DF_3$$
or
$$x_{F313} \geq DF_3$$

At ASuW = 4

$$x_{F114} \geq DF_4$$
or
$$x_{F214} \geq DF_4$$
or
$$x_{F314} \geq DF_4$$

At FARP= 5

$$x_{F115} \geq DF_5$$
or
$$x_{F215} \geq DF_5$$
or
$$x_{F315} \geq DF_5$$

At LOG = 6

$$x_{F116} \geq DF_6$$
or
$$x_{F216} \geq DF_6$$
or
$$x_{F316} \geq DF_6$$

Capacity Fuel Volume

$$(cF_{112})Y_{112} - X_{F112} \geq 0$$
$$(cF_{113})Y_{113} - X_{F113} \geq 0$$
$$(cF_{114})Y_{114} - X_{F114} \geq 0$$
$$(cF_{115})Y_{115} - X_{F115} \geq 0$$
$$(cF_{156})Y_{156} - X_{F156} \geq 0$$

or

$$(cF_{212})Y_{212} - X_{F212} \geq 0$$
$$(cF_{213})Y_{213} - X_{F213} \geq 0$$
$$(cF_{214})Y_{214} - X_{F214} \geq 0$$
$$(cF_{215})Y_{215} - X_{F215} \geq 0$$
$$(cF_{256})Y_{256} - X_{F256} \geq 0$$

or

$$(cF_{312})Y_{312} - X_{F312} \geq 0$$
$$(cF_{313})Y_{313} - X_{F313} \geq 0$$
$$(cF_{314})Y_{314} - X_{F314} \geq 0$$
$$(cF_{315})Y_{315} - X_{F315} \geq 0$$
$$(cF_{356})Y_{356} - X_{F356} \geq 0$$

Y_{kij}*'s integer,* X_{kij}*'s* ≥ 0 *(i, j) shown in Figure 6,* $k = 1, 2, 3$

Appendix E

Model-3.4-5

Model for Capability Restricted Transportation based on Scenario in Figure 6-1 for Fuel

Modes of Transportation: *PSV, k =1; FSV, k = 2; LAW, k = 3*

Shared volume capacity for fuel **on vessel** *k* enroute *ij* = cF_{kij}

Decision Variables:

X_{Fkij} = flow of **fuel** from source *i* to node *j* on vessel *k, i=1, j= 2, 3, k = 1*

X_{Fkjl} = flow of **fuel** from transshipment node *j* to sink *l* on vessel *k, j=3, l=4, 5, 6, k = 2, 3*

Y_{kij} = *# of deliveries by vessels of type k from node i to j and j to l*

Objective Function A

$$\min((t_{112})y_{112} + (t_{113})y_{113} + (t_{234})y_{234} + (t_{235})y_{235} + (t_{236})y_{236} + (t_{334})y_{334} + (t_{335})y_{335}) + (t_{336})y_{336}))$$

OR

Objective Function B

Minimize Number of Deliveries

$$\min(y_{112} + y_{113} + y_{234} + y_{235} + y_{236} + y_{334} + y_{335} + y_{336})$$

Constraints

Supply

At CLF = 1

$$(x_{F112} + x_{F113}) \leq SF_1$$

At Transshipment = 3

$$x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336} \leq SF_3$$

Demand

At SAG = 2

$x_{F112} \geq DF_2$

At Transshipment = 3

$x_{F113} \geq DF_3$

At ASuW = 4

$x_{F234} + x_{F334} \geq DF_4$

At FARP = 5

$x_{F235} + x_{F335} \geq DF_5$

At LOG = 6

$x_{F236} + x_{F336} \geq DF_6$

Transshipment

$x_{F113} - (x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336}) \geq 0$

Capacity Fuel Volume

$(cF_{112})Y_{112} - X_{F112} \geq 0$
$(cF_{113})Y_{113} - X_{F113} \geq 0$
$(cF_{234})Y_{234} - X_{F234} \geq 0$
$(cF_{235})Y_{235} - X_{F235} \geq 0$
$(cF_{236})Y_{236} - X_{F236} \geq 0$
$(cF_{334})Y_{334} - X_{F334} \geq 0$
$(cF_{335})Y_{335} - X_{F335} \geq 0$
$(cF_{336})Y_{336} - X_{F336} \geq 0$

Y_{kij}*'s integer,* X_{kij}*'s* ≥ 0 *(i, j) shown in Figure 7-1, k = 1, 2, 3*

Appendix F

Model-3.4-6

Model (Split) for Capability Restricted Transportation based on Scenario in Figure 6-2 for Fuel

Modes of transportation: *PSV =1, FSV = 2, LAW = 3*

Split 1

Decision Variables:

X_{Fkij} = flow of **fuel** from source *i* to node *j* on vessel *k, i=1, j= 2, 3, k = 1*

Y_{kij} = *# of deliveries by vessels of type k from node i to j and l*

Objective Function A

Minimize Delivery Time

$$\min(t_{112})y_{112} + (t_{113})y_{113}$$

Objective Function B

Minimize Number of Deliveries

$$\min(y_{112} + y_{113})$$

Constraints

Supply

At CLF = 1

$$(x_{F112} + x_{F113}) \leq SF_1$$

Demand

At SAG = 2

$$x_{F112} \geq DF_2$$

At Transshipment = 3

$$x_{F113} \geq DF_3$$

Capacity Fuel Volume

$$(cF_{112})Y_{112} - X_{F112} \geq 0$$
$$(cF_{113})Y_{113} - X_{F113} \geq 0$$

Y_{kij}*'s integer*

X's $\geq$ *0*

Split 2

Decision Variables:

X_{Fkjl} = flow of **fuel** from transshipment node *j* to sink *l* on vessel *k, j=3, l=4, 5, 6, k = 2, 3*

Y_{kij} *= # of deliveries by vessels of type k from node i to j and l*

Objective Function A

Minimize Delivery Time

$$\min(t_{234})y_{234} + (t_{235})y_{235} + (t_{236})y_{236} + (t_{334})y_{334} + (t_{335})y_{335}) + (t_{336})y_{336})$$

Objective Function B

Minimize Number of Deliveries

$$\min(y_{234} + y_{235} + y_{236} + y_{334} + y_{335} + y_{336})$$

Constraints

Supply

At Transshipment = 3

$$x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336} \leq SF_3$$

Demand

At ASuW = 4

$$x_{F234} + x_{F334} \geq DF_4$$

At FARP = 5

$$x_{F235} + x_{F335} \geq DF_5$$

At LOG = 6

$$x_{F236} + x_{F336} \geq DF_6$$

Capacity Fuel Volume

$$(cF_{234})Y_{234} - X_{F234} \geq 0$$
$$(cF_{235})Y_{235} - X_{F235} \geq 0$$
$$(cF_{236})Y_{236} - X_{F236} \geq 0$$
$$(cF_{334})Y_{334} - X_{F334} \geq 0$$
$$(cF_{335})Y_{335} - X_{F335} \geq 0$$
$$(cF_{336})Y_{336} - X_{F336} \geq 0$$

Y_{kij}*'s integer,* X_{kij}*'s* ≥ 0 *(i, j) shown in Figure 7-2, k = 1, 2, 3*

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Appendix G

Model-3.4-7

Models based on scenarios in Figure 7-1 and 7-2 for Fuel

Modes of transportation: *PSV =1, FSV = 2, LAW = 3*

Decision Variables:

X_{Fkij} = flow of **fuel** from source *i* to node *j* on vessel *k, i=1, j= 2-1, 2-2, 2-3, 2-4, and 3, k = 1*

X_{Fkjl} = flow of **fuel** from transshipment node *j* to sink *l* on vessel *k, j=3, l=4, 5, and 6, k = 2, 3*

Y_{kij} *= # of deliveries by vessels of type k from node i to j and l*

Objective Function B

Minimize Number of Deliveries

$$\min(y_{112-1} + y_{112-2} + y_{112-3} + y_{112-4} + y_{113} + y_{234} + y_{235} + y_{236} + y_{334} + y_{335} + y_{336})$$

Constraints

Supply

At CLF = 1

$$(x_{F112-1} + x_{F112-2} + x_{F112-3} + x_{F112-4} + x_{F113}) \leq SF_1$$

At Transshipment = 3

$$x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336} \leq SF_3$$

Demand

At DDG = 2-1

$$x_{F112-1} \geq DF_{2-1}$$

At DDG = 2-2

$$x_{F112-2} \geq DF_{2-2}$$

At DDG = 2-3

$$x_{F112-3} \geq DF_{2-3}$$

At LCS or FFG = 2-4

$$x_{F112-4} \geq DF_{2-4}$$

At Transshipment = 3

$$x_{F113} \geq DF_{3}$$

At ASuW = 4

$$x_{F234} + x_{F334} \geq DF_{4}$$

At FARP = 5

$$x_{F235} + x_{F335} \geq DF_{5}$$

At LOG = 6

$$x_{F236} + x_{F336} \geq DF_{6}$$

Transshipment (Flow Balance)

$$x_{F113} - (x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336}) \geq 0$$

Capacity Fuel Volume

$$(cF_{112-1})Y_{112-1} - X_{F112-1} \geq 0$$
$$(cF_{112-2})Y_{112-2} - X_{F112-2} \geq 0$$
$$(cF_{112-3})Y_{112-3} - X_{F112-3} \geq 0$$
$$(cF_{112-4})Y_{112-4} - X_{F112-4} \geq 0$$
$$(cF_{113})Y_{113} - X_{F113} \geq 0$$
$$(cF_{234})Y_{234} - X_{F234} \geq 0$$
$$(cF_{235})Y_{235} - X_{F235} \geq 0$$
$$(cF_{236})Y_{236} - X_{F236} \geq 0$$
$$(cF_{334})Y_{334} - X_{F334} \geq 0$$
$$(cF_{335})Y_{335} - X_{F335} \geq 0$$
$$(cF_{336})Y_{336} - X_{F336} \geq 0$$

Y_{kij}'s integer, X_{kij}'s ≥ 0 *(i, j) shown in Figure 7-1, 7-2, k = 1, 2, 3*

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