SYM-AM-21-062

Excerpt from the Proceedings of the Eighteenth Annual Acquisition Research Symposium

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

May 11–13, 2021

Published: May 10, 2021

Prepared for the Naval Postgraduate School, Monterey, CA 93943.

The research presented in this report was supported by the Acquisition Research Program of the Graduate School of Defense Management at the Naval Postgraduate School.

Framework for Augmenting Current Fleet with Commercially Available Assets for Logistics Support in Contested Environment[1]

Dr. Aruna Apte—is a tenured Professor of Operations and Logistics Management in the Graduate School of Defense Management, Naval Postgraduate School (NPS), Monterey, CA. Apte received her PhD in operations research from Southern Methodist University (SMU) in Dallas. She joined NPS in 2005 as tenure-track Assistant Professor. [auapte@nps.edu]

Dr. Uday Apte—is Distinguished Professor and Associate Dean of Research and Development at the Graduate School of Business and Public Policy, Naval Postgraduate School, Monterey, CA. Before joining NPS, Dr. Apte taught at the Wharton School, University of Pennsylvania, Philadelphia, and at the Cox School of Business, Southern Methodist University, Dallas. He is experienced in teaching a range of operations management and management science courses in the Executive and Full-time MBA programs. Prior to his career in the academia, Dr. Apte worked for over 10 years in managing operations and information systems in the financial services and utility industries. Since then he has consulted with several major US corporations and international organizations. [umapte@nps.edu]

Dr. Ken Doerr—B.S. (Quantitative Business Analysis) Indiana University Bloomington, 1984; Ph.D. (Management Science) University of Washington Seattle, 1994. Appointed to the faculty at the Naval Postgraduate School in 2001. Other academic posts include faculty appointments with the University of Miami in Coral Gables and Santa Clara University, research fellowships at the University of Waterloo and the University of Cincinnati, and a sabbatical year with the Industrial Engineering faculty at Tel Aviv University. His research has focused on logistics risk, the cost-benefit analysis of technology investments, and behavioral operations management. His papers have appeared in several leading journals, including Management Science, The Academy of Management Review, IIE Transactions and The Journal of Applied Psychology. Prior to joining academia, Dr. Doerr was employed for several years as a Systems and Management Science professional with Shell Oil, Monsanto (now part of Bayer), and Peoplesoft (now part of Oracle). [khdoerr@nps.edu]

Abstract

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

The objective in this research is to study and analyze options for rearming, refueling, and resupplying in the contested and distributed environment. The framework created is flexible in terms of the scenarios.

Feedback from subject matter experts (SMEs) helped us gain insight into the complexity of the problem and its vast scope. We developed mathematical models based on the scenarios approved by the sponsor. The sponsor did not wish us to model an objective of minimizing costs or the number of ships required to deliver commodities within a certain deadline or under a certain schedule. Measuring the number of deliveries required in a scenario supplied by SMEs allowed us to determine a mix of NGLS vessels without cost or deadline data. We would like to point out that the number of deliveries needed by vessels of each type, as described in the report, can be interpreted in many ways, in terms of the number of ships required. The summary of our results and analysis suggests certain recommendations.

---

[1] Please note that this is an abridged version of the original technical report. The full report is available as NPS-LM-20-155 at ARP.

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 its claims in the South China Sea, is contrary to international law (Figure 1). 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 (Apte et al., 2020).

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 (Figure 2). 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 3).

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 allied combatant forces in the Pacific through Next Generation Logistics Ships (NGLSs).

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

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 resupply mission scenarios developed for this research are based on actual data supplied by subject matter experts (SMEs), 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 mentioned in question 2 are based on top-level requirements supplied to the authors by SMEs. The methodology considers the supply chain from controlled zone to contested zone, utilizing only those new vessels. We develop and use different scenarios and methodologies to arrive at answers based on different objectives. We 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 allied combatants in the contested and distributed environment.

Motivation for the New Vessels

To optimize its future fleet logistics platforms, the USN and United States Marine Corps (USMC) are exploring the concept of a common hull, multi-mission auxiliary ship design. The Commandant of the Marine Corps, General 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 USN and USMC 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 the Chief of Naval Operations (CNO) and Commandant of the USMC (O'Rourke, 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. (O'Rourke, 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" (O'Rourke, 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. (O'Rourke, 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: Next Generation Logistics Ships (NGLS)

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 a sustained speed of about 11–12 knots. The range of travel for the platform supply vessel (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 planned for the PSV is to deliver about 5,000 bbl of fuel in 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 the PSV but much faster, the sustained speed of a fast supply vessel (FSV) is 23 knots, and the range of travel is about 800–1000 nm. The fuel-storage 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 planned for the FSV is to replenish the PSV in littorals. It also needs to do water transfers with hose reel with roll-on/roll-off capabilities. On shore, the FSV needs to be able to refuel at a minimum of about 500 gallons/minute with a 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 (LAW) will serve as maneuver and sustainment vessels to confront the changing character of warfare. The LAW will have beachability and the 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 environments. 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, the LAW should deal with 1:40 to 1:100 beach gradients. The loaded LAW should have a speed of about 18 knots. Thus, its speed is between the speeds of the PSV and FSV. Its minimum operating range is to be about 5,000 nm. It is to be capable of transferring 500 gallons/minute of fuel at sea or to shore. The LAW is to be 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 will 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 a cargo area of about 10,000 sq ft and deck loading capacity of about 500 lb/sq ft.

Our methodology derives a mathematical model based on capabilities for resource optimization for humanitarian missions (Apte & Yoho, 2018). However, we bear in mind the distinction between a contested environment and an uncontested environment, since the PSV and the FSV cannot defend themselves, but the LAW can. Therefore, if the NGLS ships 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 model combat attrition in this study; we merely note that it is a factor which favors the LAW over the alternatives. In short, the humanitarian assistance and disaster relief (HADR) inference is relevant in the contested environment.

Methodology

We include the capacities of the vessels and offer an objective that minimizes the ***number*** of deliveries by the appropriate vessels on corresponding route. There exists a time constraint for total unload time to ships in the Weapon Engagement Zone (WEZ). To 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 or 5,000 BBL of fuel, we modified its cargo-capacity accordingly.

These transportation/transshipment models consider controlled and contested zones. An assumption of the scenarios we were given 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 supplies for the different Expeditionary Advance Bases (EABs) on the shore in the contested zone. We developed models and analyzed scenarios for the NGLS vessels. The modes of transportation in the models and scenarios are the 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.

We define a delivery as the carrying of commodities from a supply node to a demand node on the given route by a vessel designated to travel on that route. 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.

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 the 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: Capability Restricted Transportation

We offer two scenarios and the corresponding models based on feedback from SMEs. Vessels allowed on the respective routes are shown in Figure 4-1. This scenario first looks at the entire network (Figure 4-1). We offer a different perspective by splitting the transshipment network into two separate transportation networks (Figure 4-2). In these scenarios, the model treats SAG (node 2) as one entity.

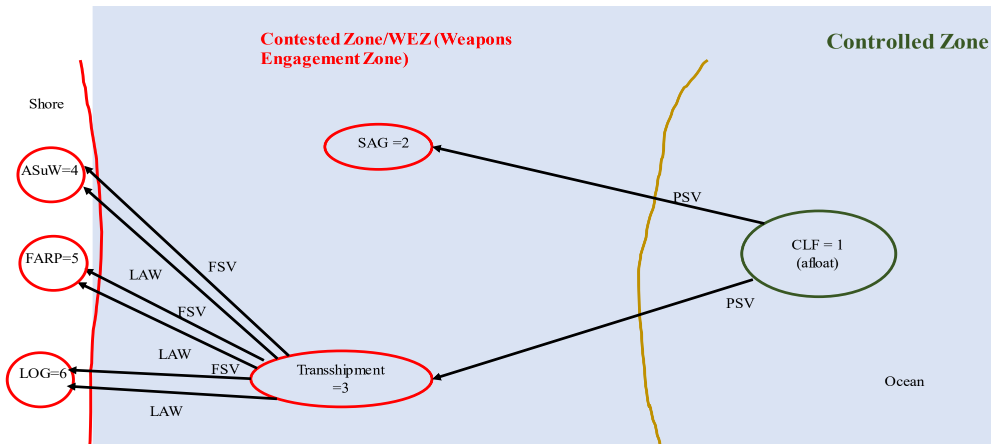

Figure 4-1. Scenario Based on Subject Matter Expert Feedback

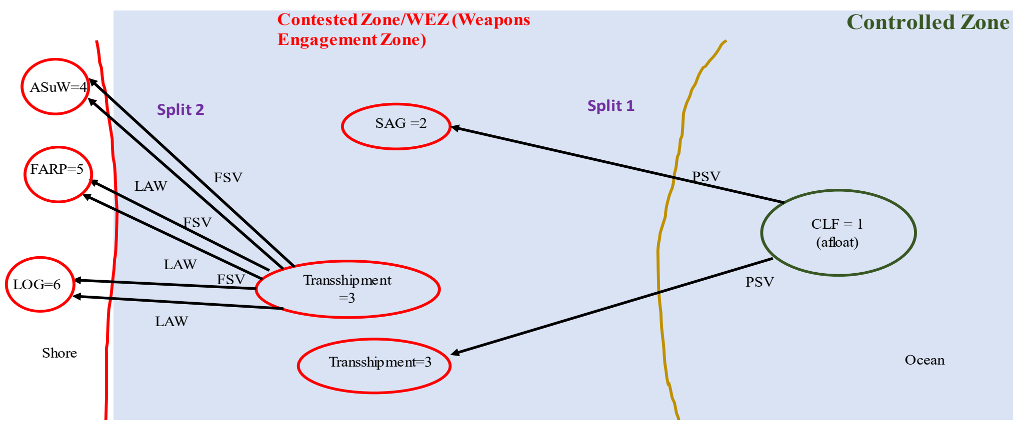

Figure 4-2. Scenario Based on SME Feedback With Split 1 and Split 2

As shown in Figure 4-2, 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. First, 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. In the split model, of course, the supply from the transshipment node is set equal to the demand to the transshipment node. The corresponding model is given next.

Model (Split) for Capability Restricted Transportation based on Scenarios in Figures 4.1 and 4.2 for 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 from node i to node j =* cF_{kij}

Modes of transportation, k*: 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: *Minimize Number of Deliveries*

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

Constraints:

Supply *at CLF = 1,* $(x_{F112} + x_{F113}) \le SF_1$

Demand *at SAG = 2,* $x_{F112} \ge DF_2$

at Transshipment = 3, $x_{F113} \ge DF_3$

Capacity Fuel Volume

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

Y_{kij}*'s integer and ≥ 0,* X_{kij}*'s ≥ 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_{kjl} *= # of deliveries by vessels of type k from node j to l*

Objective Function: *Minimize Number of Deliveries*

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

Constraints:

Supply *at Transshipment = 3,* $x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336} \le SF_3$

Demand *at ASuW = 4,* $x_{F234} + x_{F334} \ge DF_4$

at FARP = 5, $x_{F235} + x_{F335} \ge DF_5$

at LOG = 6, $x_{F236} + x_{F336} \ge DF_6$

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_{kjl}'s integer and ≥ 0, X_{kjl}'s ≥ 0

Results

We further evaluated the 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 1 for F and for Ammunition and Supplies. In Table 1, the capacity of vessels for ammunition and supplies is constrained from CLF to SAG by the 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 true capacity of the PSV is 800 pallets.

Table 1. Supply, Demand, and Capacities: Fuel in BBL and Ammunition and Supplies in Pallets

	Fuel in BBL	Ammunition and Supplies in Pallets
Nodes	Supply/Demand	Supply/Demand
Supply at CLF 1	100000	100000
Supply at Trans 3	6500	750
Demand at SAG 2	22000	100
Demand at Trans 3	6500	750
Demand at ASuW 4	100	50
Demand at FARP 5	6300	350
Demand at LOG 6	100	350
Routes	Capacity	Capacity
PSV from CLF 1 to SAG 2	5500	60
PSV from CLF 1 to Trans 3	5500	800
FSV from Trans 3 to ASuW 4	1000	250
FSV from Trans 3 to FARP 5	1000	250
FSV from Trans 3 to LOG 6	1000	250
LAW from Trans 3 to ASuW 4	2200	1000
LAW from Trans 3 to FARP 5	2200	1000
LAW from Trans 3 to LOG 6	2200	1000

In Table 2, results for the scenario in Figure 4-1 and 4-2 show that it is necessary to have a total of 11 deliveries for fuel and 6 for ammunition and supplies. It can be seen from

Table 2 that the number of deliveries in the combined network and the total from Split networks are the same, however.

Table 2. Minimum Number of Deliveries for Transportation of Fuel in BBL and Ammunition and Supplies in Pallets

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

In order to offer another perspective, we further expanded the scenarios where we separate SAG 2 into three DDGs and one LCS (Figure 5-1) in one case and three DDGs and one FFG (Figure 5-2) 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 node. We believe this will further help decision-makers.

In both scenarios, the demand node afloat is SAG, and demand nodes ashore are EABs, specifically ASuW, 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 an LCS in the first case and an 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 to DDGs. Given the capacities of the NGLS 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 a 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. The model for these is:

Models based on scenarios in Figure 5-1 and 5-2 for 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}

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: *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,* $(x_{F112-1} + x_{F112-2} + x_{F112-3} + x_{F112-4} + x_{F113}) \le SF_1$

at Transshipment = 3, $x_{F234} + x_{F235} + x_{F236} + x_{F334} + x_{F335} + x_{F336} \le SF_3$

Demand — *at DDG = 2-1,* $x_{F112-1} \ge DF_{2-1}$

at DDG = 2-2, $x_{F112-2} \ge DF_{2-2}$

at DDG = 2-3, $x_{F112-3} \ge DF_{2-3}$

at LCS or FFG = 2-4, $x_{F112-4} \ge DF_{2-4}$

at Transshipment = 3, $x_{F113} \ge DF_3$

at ASuW = 4, $x_{F234} + x_{F334} \ge DF_4$

at FARP = 5, $x_{F235} + x_{F335} \ge DF_5$

at LOG = 6, $x_{F236} + x_{F336} \ge DF_6$

Transshipment (Flow Balance)

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

Capacity Fuel Volume

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

Y_{kij}'s integer, X_{kij}'s ≥ 0

Scenario: Separated SAG: Three DDGs and One LCS or Three DDGs and One FFG

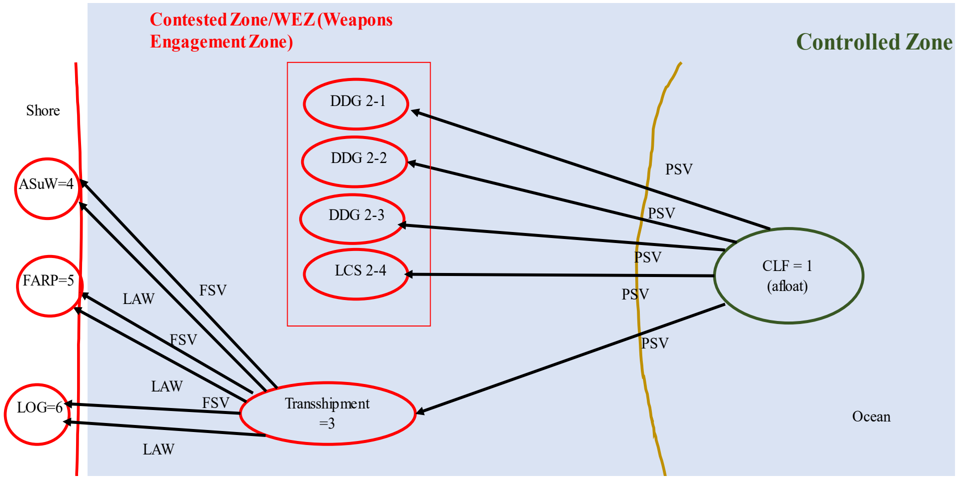

Figure 5-1. Scenario Based on Separated SAG: Three DDGs and One LCS

Separating SAG into DDGs and LCS or FFG creates a unique difficulty in replenishment. However, we adjusted ship capacity to accommodate the differences between resupply periods.

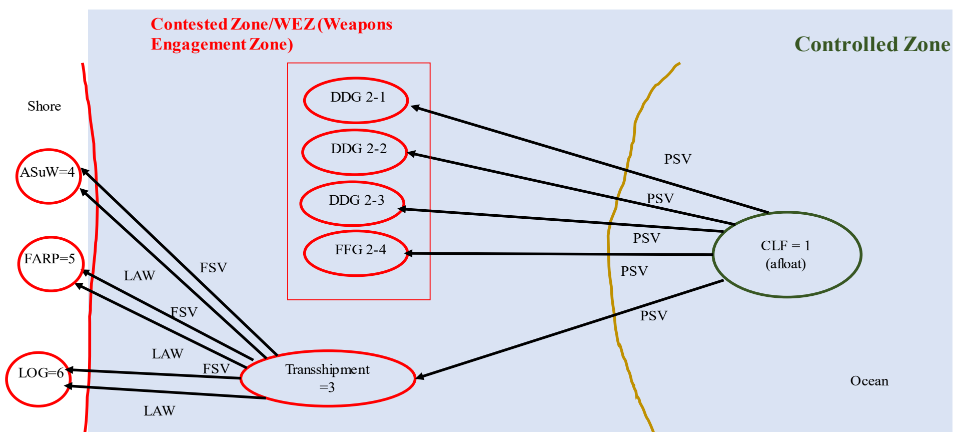

Figure 5-2. Scenario Based on Separated SAG: Three DDGs and One FFG

The supply and demand at the nodes, and capacities of vessels, in these scenarios are given in Table 3 in case of LCS and in Table 4 in case of FFG. Assuming that DDG can sustain for 8 days without refueling, FFG must be refueled every seven days and LCS every four days. We incorporated this by adjusting the demands for the given period in the models based on Figures 5-1 and 5-2.

Table 3. Supply, Demand, and Capacities: Three DDGs and One LCS

	Fuel in BBL	Ammunition and Supplies in Pallets
	Supply/Demand	Supply/Demand
Supply at CLF 1	1000000	100000
Supply at Trans 3	6500	750
Demand at DDG 2-1	5000	25
Demand at DDG 2-2	5000	25
Demand at DDG 2-3	5000	25
Demand at LCS 2-4	3000	20
Demand at Trans 3	6500	750
Demand at ASuW 4	100	50
Demand at FARP 5	6300	350
Demand at LOG 6	100	350
	Capacity	Capacity
PSV from CLF 1 to DDG 2-1	5500	60
PSV from CLF 1 to DDG 2-2	5500	60
PSV from CLF 1 to DDG 2-3	5500	60
PSV from CLF 1 to DDG 2-4	5500	60
PSV from CLF 1 to Trans 3	5500	800
FSV from Trans 3 to ASuW 4	1000	250
FSV from Trans 3 to FARP 5	1000	250
FSV from Trans 3 to LOG 6	1000	250
LAW from Trans 3 to ASuW 4	2200	1000
LAW from Trans 3 to FARP 5	2200	1000
LAW from Trans 3 to LOG 6	2200	1000

Table 4. Supply, Demand, and Capacities: Three DDGs and One FFG

	Fuel in BBL	Ammunition and Supplies in Pallets
	Supply/Demand	Supply/Demand
Supply at CLF 1	1000000	100000
Supply at Trans 3	6500	750
Demand at DDG 2-1	5000	25
Demand at DDG 2-2	5000	25
Demand at DDG 2-3	5000	25
Demand at FFG 2-4	7000	25
Demand at Trans 3	6500	750
Demand at ASuW 4	100	50
Demand at FARP 5	6300	350
Demand at LOG 6	100	350
	Capacity	Capacity
PSV from CLF 1 to DDG 2-1	5500	60
PSV from CLF 1 to DDG 2-2	5500	60
PSV from CLF 1 to DDG 2-3	5500	60
PSV from CLF 1 to DDG 2-4	5500	60
PSV from CLF 1 to Trans 3	5500	800
FSV from Trans 3 to ASuW 4	1000	250
FSV from Trans 3 to FARP 5	1000	250
FSV from Trans 3 to LOG 6	1000	250
LAW from Trans 3 to ASuW 4	2200	1000
LAW from Trans 3 to FARP 5	2200	1000
LAW from Trans 3 to LOG 6	2200	1000

Results

The results with LCS are given in Table 5. Table 6 describes the results with FFG.

Table 5. Minimum Number of Deliveries for Transportation of Fuel in BBL and Ammunition and Supplies in Pallets: Three DDGs and One LCS

	Fuel	Ammunition and Supplies
	Deliveries	Deliveries
PSV from CLF 1 to DDG 2-1	1	1
PSV from CLF 1 to DDG 2-2	1	1
PSV from CLF 1 to DDG 2-3	1	1
PSV from CLF 1 to LCS 2-4	1	1
PSV from CLF 1 to Trans 3	2	1
FSV from Trans 3 to ASuW 4	1	1
FSV from Trans 3 to FARP 5	0	0
FSV from Trans 3 to LOG 6	1	0
LAW from Trans 3 to ASuW 4	0	0
LAW from Trans 3 to FARP 5	3	1
LAW from Trans 3 to LOG 6	0	1
Total	11	8

Table 6. Minimum Number of Deliveries for Transportation of Fuel in BBL and Ammunition and Supplies in Pallets: Three DDGs and One FFG

	Fuel	Ammunition and Supplies
	Deliveries	Deliveries
PSV from CLF 1 to DDG 2-1	1	1
PSV from CLF 1 to DDG 2-2	1	1
PSV from CLF 1 to DDG 2-3	1	1
PSV from CLF 1 to LCS 2-4	2	1
PSV from CLF 1 to Trans 3	2	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	1	0
LAW from Trans 3 to ASuW 4	0	1
LAW from Trans 3 to FARP 5	3	1
LAW from Trans 3 to LOG 6	0	1
Total	12	8

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. We constrained 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 a 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 or 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.

In our model, *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. We would like to point out that 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 to determine how they would like to interpret and implement the results. A 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 available budget, 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 to decide how they would want to interpret the solution. In Table 7 we summarize the results of the scenarios.

Table 7. Summary of Scenario Results

	Fuel				Ammunition and Supplies			
Scenarios	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 Based on Figure 4-1 and 4-2								
Combined	6	2	3	11	3	1	2	6
Split 1 and Split 2	6	1	4	11	3	0	3	6
Scenario Based on Separated SAG: 3 DDGs and LCS (Figure 5-1)	6	2	3	11	5	1	2	8
Scenario Based on Separated SAG: 3 DDGs and FFG (Figure 5-2)	7	2	3	12	5	0	3	8

The models we have developed are scalable. 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 of 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 8.

Table 8. Minimum Deliveries With Increased Demand Nodes: Fuel in BBL and Ammunition and Supplies in Pallets

Scenarios	Three SAGs		Two ASuWs		Three SAGs, Two ASuWs	
	Deliveries		Deliveries		Deliveries	
	Fuel	Ammunition and Supplies	Fuel	Ammunition and Supplies	Fuel	Ammunition and Supplies
PSV from CLF 1 to SAG 2	12	5	4	2	12	5
PSV from CLF 1 to Trans 3	2	1	2	1	2	1
FSV from Trans 3 to ASuW 4	0	0	0	0	0	0
FSV from Trans 3 to FARP 5	0	0	0	0	0	0
FSV from Trans 3 to LOG 6	0	0	1	0	0	0
LAW from Trans 3 to ASuW 4	1	1	1	1	1	1
LAW from Trans 3 to FARP 5	3	1	3	1	3	1
LAW from Trans 3 to LOG 6	1	1	0	1	1	1
Total	19	9	11	6	19	9

As stated earlier, we did not incorporate load and unload time. Incorporating 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 the PSV), and that a warship can only be engaged for at most 1 hour for this delivery, our model shows it takes a 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 a PSV engaging with SAG in WEZ should be investigated, since that is the binding constraint on capacity to transfer. The capacity of the 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 the number of deliveries made by FSV and LAW for each of the scenarios in Table 9.

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 also needed. Similarly, the most FSVs needed for each of these scenarios to transport ammunition and supplies is *one*. However, *three* LAWs are also needed for those scenarios. 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. A closer examination of those instances in which the model recommended FSVs on a route reveals that, in every case, a LAW could have accomplished the resupply mission in an equal number of trips. That is, the model recommendation to acquire an FSV, in every case, is merely an alternate optima. Although the

FSV does not look very useful in these scenarios, these scenarios did not require the TLRs (especially speed, since deadlines were not given) in which that ship dominated the others.

Table 9. Deliveries by FSV and LAW

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

References

Abott, R. (2020, February 2). FY 2021 request starts work on future amphibs and logistics ships. *Defense Daily*. https://www.defensedaily.com/navy-starts-work-future-amphibious-logistics-ships/navy-usmc/

Apte, A., Doerr, K., & Apte, U. (2020). *Framework for augmenting current fleet with commercially available assets for logistics support in contested environment* (NPS-LM-20-155). Naval Postgraduate School, Acquisition Research Program.

Apte, A., & Yoho, K. (2018). Resource selection in support of humanitarian operations: A case of the United States Navy. *Journal of Humanitarian Logistics and Supply Chain Management*, *8*(2), 184–198.

Dougherty, S. R., Garcia, R. J., Lemenager, K. D., Nye, B. S., Rego, J., Sandridge, B. E., & Shofner, M. G. (2020). *Logistics in contested environment* [Capstone report, Naval Postgraduate School].

Eckstein, M. (2020, February 20). *Navy researching new class of medium amphibious ship, new logistics ships*. USNI News. https://news.usni.org/2020/02/20/navy-researching-new-class-of-medium-amphibious-ship-new-logistics-ships

Katz. (2020, May). Navy announces “Next Generation Logistics Ship” program with June 25 industry day. *Inside Defense*. https://insidedefense.com/insider/navy-announces-next-generation-logistics-ship-program-%C2%A0june-25%C2%A0industry-day

Liu, Z. (2016, July 11). Here’s what’s behind the “nine-dash line” that sparked the South China Sea conflict. *South China Morning Post*. https://www.businessinsider.com/the-nine-dash-line-at-the-heart-of-the-south-china-sea-conflict-2016-7

O’Rourke, R. (2020, September 8). *Navy force structure and shipbuilding plans: Background and issues for Congress* (CRS Report No. RL32665). Congressional Research Service. https://fas.org/sgp/crs/weapons/RL32665.pdf

Acquisition Research Program
Graduate School of Defense Management
Naval Postgraduate School
555 Dyer Road, Ingersoll Hall
Monterey, CA 93943

www.acquisitionresearch.net