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MULTI-COMMODITY LOGISTIC MODEL FOR DISTRIBUTED LETHALITY

by

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MULTI-COMMODITY LOGISTIC MODEL FOR DISTRIBUTED LETHALITY

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ABSTRACT

Evolving anti-ship ballistic missiles are enhancing the effectiveness of anti-access (A2) strategies, which seek to keep opposing forces out of an operating area. This may reduce the effectiveness of legacy U.S. Navy operational principles, which rely on large, multi-ship carrier strike groups. In response, the Navy created an offensive principle known as distributed lethality (DL) that would allow warships to project power within an A2 environment. DL calls for smaller, agile, and lethal combinations of ships, called adaptive force packages (AFPs), which operate in a distributed manner over a large area. This concept brings about the logistical challenge of satisfying distributed demand across many locations. Moreover, the A2 environment poses a threat to the Navy's standard resupply source, the Combat Logistics Force (CLF) ship. CLF ships can no longer afford to travel close to forward deployed units. These developments require modifications in the Navy's combat logistics chain. This thesis modifies the Navy combat logistics chain to support small- and medium-size warships operating as AFPs within a DL and A2 environment and analyzes requirements for the development of mini-CLF ships as the main AFP resupply source.

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LIST OF ACRONYMS AND ABBREVIATIONS

A2	Anti-access
AFP	Adaptive force package
ARL	Aft replenishment-at-sea lane
ASBM	Anti-ship ballistic missile
bbl	Barrel
CG	Guided-missile cruiser
CLF	Combat Logistics Force
CONSOL	Consolidation operations
DDG	Guided-missile destroyer
DFM	Distillate fuel marine
DL	Distributed lethality
FFG	Guided-missile frigate
FOS	Forward operating stations
FRL	Forward replenishment-at-sea lane
GS	Gas station
INREP	Inport replenishment
JP-5	Jet propellant-5
LCS	Littoral combat ship
MOE	Measure of effectiveness
NM	Nautical miles
PNV	Port not vulnerable to attack

PV	Port vulnerable to attack
RAS	Replenishment-at-sea
SAG	Surface action group
Simio	Simulation Modeling framework based on Intelligent Objects
SSC	Small surface combatant
ston	Short ton
T-AKE	Dry cargo and ammunition ship
T-AO	Fleet replenishment oiler
T-AOE	Fast combat support ship
UNREP	Underway replenishment
VLS	Vertical launching system

EXECUTIVE SUMMARY

Anti-access (A2) strategies, which seek to keep opposing forces out of an operating area, have been enhanced by improvements in anti-ship ballistic missile (ASBM) technology. The risk to large ships or even groups of ships may reduce the effectiveness of U.S. Navy legacy principles, which rely on large, multi-ship carrier strike groups. Responding to this challenge, the Navy developed a more offensively oriented principle known as distributed lethality (DL) that would allow warships to project power within an A2 environment (Rowden, Gumataotao, & Fanta, 2015). DL calls for smaller, agile, and lethal ship combinations, called adaptive force packages (AFPs), which operate in a distributed manner over a large area. This concept brings about a logistical challenge: how to satisfy customer demands that are potentially distributed across many locations and dispersed over a large, possibly contested, area. Moreover, ASBM presence poses a significant threat to the Navy's standard resupply source, the Combat Logistics Force (CLF) ship. CLF ships can no longer afford to travel with, or even operate close to, forward deployed units. These developments in the operational posture require modifications in the Navy's combat logistics chain.

In this thesis, we modify the Navy combat logistics chain to support small- and medium-size warships operating as AFPs within a DL and A2 environment and analyze the requirements to develop mini-CLF ships as the main source of resupply for AFPs. Our model focuses on logistical flexibility, which concentrates resources at a centralized location outside of the immediate operating area to redistribute resources. This enables the logistics chain to satisfy fluctuating demands over a wide area (Kress, 2016). Mini-CLF ships operate outside the combat zone at the aft replenishment-at-sea lane but inside the A2 threat area. AFPs prioritize traveling from their forward operating stations to an aft replenishment-at-sea lane for replenishment. CLF ships operate outside of the A2 threat area and can provide replenishment support to mini-CLF ships and AFPs. AFPs, mini-CLF ships, and CLF ships each have their own priorities for commodity replenishment, depending on the commodity and the availability of ports, mini-CLF ships, or CLF ships for replenishment.

Our model accounts for multiple commodities, such as distillate fuel marine, jet propellant-5, stores, and ordnance, which compete for storage and transportation capacities. We also assess the survivability of the logistics chain by introducing port and mini-CLF ship attrition while inside the A2 environment. To accomplish this, we develop a stochastic simulation model that emulates the performance of the resupply network under varying scenario and mini-CLF ship configurations. Attrition is defined as the probability of non-survival of a vulnerable port or mini-CLF ship by the end of 60 days. We assume each day, each mini-CLF ship or port still in operation is destroyed with a certain probability, and we assume destruction is independent across each day, mini-CLF ship, and port. Our first measure of effectiveness (MOE) is the fraction of time an AFP is on station and operating above its commodity safety levels. When an AFP crosses a commodity safety level, it seeks replenishment of its commodities. The second MOE is how often AFPs cross commodity extremis levels. An AFP risks running out of commodities when it crosses an extremis level.

Operating scenarios are divided between peacetime, with a 180-day time horizon, and wartime, with a 60-day time horizon. They are further divided by ASBM ranges of 1,000 and 2,000 nautical miles. Although our model is not based on a real world operating area, we vary notional geographic characteristics, such as the distance between operating stations, ports, and replenishment-at-sea lanes, to assess their impact on our MOEs.

Our preliminary analysis shows that mini-CLF ships are a feasible option to support AFPs operating in a DL and A2 environment. We determined that the number of mini-CLF ships operating provides a greater impact to AFPs, in terms of our MOEs, than the mini-CLF ship cargo capacity. As a result, we recommend operating with a one-to-one ratio of mini-CLF ships to AFPs during peacetime scenarios. A quantity of mini-CLF ships equal to one plus the number of AFPs is recommended for wartime scenarios when the level of attrition is less than or equal to 50%.

When mini-CLF ships are operating within our recommended force ratios, AFP performance in terms of our MOEs is almost equal across the range of mini-CLF ship commodity storage capacities. As a result, we choose the configuration that occupies the smallest physical footprint. Its cargo capacity is equal to the amount required to replenish the largest AFP after it reaches 10% below all of its commodity safety levels. This configuration has storage requirements that are only 28% of a Fast Combat Support CLF ship for liquid fuel and 13% for stores and ordnance.

At our recommended commodity configuration and force size for mini-CLF ships, we find that CLF ships are rarely used in peacetime scenarios when ports vulnerable to attack (PVs) are available for AFP and mini-CLF ship inport replenishment. CLF ship usage for replenishment increases in wartime scenarios due to the increased usage of ordnance by AFPs. In scenarios where PVs are removed from the network, CLF ship usage increases significantly for both peacetime and wartime by mini-CLF ships.

We find that as the range of ASBMs increases, AFP performance in terms of our MOEs decreases. This is because mini-CLF ship availability at the forward replenishment-at-sea lane for AFP replenishment reduces due to an increase in the replenishment distance between the mini-CLF ship and the CLF ship. In wartime, guided-missile destroyers and guided-missile cruisers must transit farther to ports outside the threat area for vertical launch system weapon replenishment. If there are no ports close to the operating area, the littoral combat ships will also have to travel to far away ports for inport maintenance.

Our analysis indicates that a port and mini-CLF ship level of attrition that is as high as 50% has a significant impact on AFP performance, in terms of our MOEs. However, some of the performance loss can be mitigated by the introduction of additional CLF and mini-CLF ships. Finally, we find that an AFP with a littoral combat ship (LCS) has a utilization rate that is up to 20% lower than an AFP without an LCS due to LCS inport maintenance requirements.

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I. INTRODUCTION

Some adversaries of the U.S. Navy and its allies have become increasingly capable with rapidly evolving sea denial technologies, such as improved ranges on anti-ship ballistic missiles (ASBMs), which are enhancing the effectiveness of anti-access (A2) strategies that seek to keep opposing forces out of an operating area. This may reduce the effectiveness of legacy operational principles, which rely on relatively large, multi-ship carrier strike groups. Responding to this challenge, the Navy developed a more offensively oriented principle known as distributed lethality (DL) that would allow warships to project power within an A2 environment (Rowden, Gumataotao, & Fanta, 2015). DL calls for smaller, agile, and lethal combinations of ships, called adaptive force packages (AFPs), which operate in a distributed manner over a large area. This concept brings about a logistical challenge: how to satisfy customer demands that are potentially distributed across many locations and dispersed over a large, possibly contested, area. Moreover, the presence of ASBMs pose a significant threat to the Navy's standard resupply source, the Combat Logistics Force (CLF) ship. CLF ships can no longer afford to travel with, or even operate close to, forward deployed units. These developments in the operational posture require modifications in the Navy's combat logistics chain.

This thesis examines modifications to the Navy combat logistics chain to support small- and medium-sized warships operating as AFPs within a DL and A2 environment and analyzes requirements for the development of mini-CLF ships as the main source of resupply for AFPs.

A. BACKGROUND

The Navy operates globally to defend the American way of life, to maintain freedom of the seas, which allows for the safe passage of personnel and goods in support of a global economy, and to promote liberty and peace for all of humanity (United States Navy, 2018b). It consists of 280 deployable battle force ships and submarines, more than 3,700 operational aircraft, and nearly 420,000 active duty and reserve Sailors (United

States Navy, 2018c). Sustainment of this large and global fleet of ships and personnel poses a logistical challenge.

In order to sustain Navy warships at sea, Military Sealift Command uses Combat Logistics Force (CLF) ships to conduct at-sea replenishment of commodities such as fuel, stores, and ordnance. This alleviates the need for Navy warships to replenish in port and allows Navy warships to remain on station longer. The actual method used for at-sea replenishment depends on the tactical situation. The stationing of a CLF ship can be with, near, or away from the warships the CLF supports. Furthermore, either warships can transit off station to meet a CLF ship or the CLF ship can transit to meet the warship on station. However, the ability for on-station replenishments is limited because CLF ships, in their current form, are not equipped to defend themselves.

The range of land-based ASBMs that can effectively target large ships and ports define the anti-access (A2) threat environment. Within this threat environment, it is risky to operate aircraft carriers and CLF ships. As the range and accuracy of ASBMs continue to increase, CLF ships cannot safely operate near the ships they support, significantly degrading the combat effectiveness of Navy warships by taking them farther off station to replenish commodities. Furthermore, there is a significant risk to concentrating Navy warships around an aircraft carrier within a carrier strike group. The concept of DL allows the Navy to continue to project force within the A2 environment. Surface Action Group AFPs, comprised of medium- and small-sized warships, operate in a lethal and distributed manner, dispersing the demand for at-sea replenishment geographically.

This study proposes the use of mini-CLF ships as the main resupply source for AFPs operating in an A2 environment. Mini-CLF ships, smaller, faster, and more agile than traditional CLF ships, can operate with reduced risk from ASBMs. Without the need to support a deployed aircraft carrier, mini-CLF ships can carry significantly smaller amounts of commodity cargo while still providing sufficient support to AFPs. As a result, mini-CLF ships may be less costly than traditional CLF ships to acquire and operate, allowing the use of multiple mini-CLF ships. Using multiple mini-CLF ships may allow the combat logistics chain to better support AFPs distributed geographically, while mitigating the impact on AFP sustainment when a mini-CLF ship is destroyed.

B. ANTI-ACCESS ENVIRONMENT

The strategy of A2 tries to restrict access to an area for an opposing force, usually by long-range capabilities or actions (Chairman of the Joint Chiefs of Staff, 2017). Our study focuses on the area within range of land based ASBMs, with the capability to destroy large targets such as aircraft carriers, CLF ships, and ports. The examples used for this study come from China. The Dong-Feng-21D ASBM can target Navy warships with a range that exceeds 1,500 km. The Dong-Feng-26 intermediate-range ballistic missile, fielded in 2016, can target U.S. ground and naval assets with a maximum range of 4,000 km (Office of the Secretary of Defense, 2017). The Navy will try to avoid placing large ships within the A2 environment. Our study accounts for the A2 environment by not allowing CLF ships to operate within range of enemy land based ASBMs. Instead, mini-CLF ships conduct at-sea replenishment within the A2 environment.

C. DISTRIBUTED LETHALITY

As the enemies of the U.S. become more capable, A2 environments will become more common. The concept of DL tries to address this issue by utilizing the surface force that we currently have and changing how we equip and employ it to create a more lethal force that can project power in a wider range of environments. The offensive capabilities of individual ships increase. Ships are employed in dispersed combinations known as SAG AFPs, consisting of destroyers, cruisers, small surface combatants, logistics ships and amphibious ships (Rowden, Gumataotao, & Fanta, 2015). The resulting ship formations are smaller, more agile, more lethal, and distributed over a large area. This makes Navy warships more lethal and harder to target. With smaller ships and distributed formations, AFPs can operate with significantly reduced risk in an ASBM A2 environment. Our study accounts for the use of DL by employing only surface action group AFPs within the A2 environment.

D. DISTRIBUTED LETHALITY LOGISTICS

In this section, we review guidance on naval logistics innovation and the concept of inventory pooling. We also review two previous research works addressing a "gas station" method of resupply (described in Subsection 3) and an optimization model for the use of mini-CLF ships to augment CLF ships (in Subsection 4).

1. Naval Logistics Innovation

Innovation in the Navy's logistics capabilities will allow it to retain a warfighting advantage over its enemies while maintaining its ability to maneuver freely across the maritime domain. The Secretary of the Navy produced a report to guide innovation in naval logistics (2016). In the report, lines of execution were discussed to help guide the effort. Logistics agility, persistence, mobility, and assurance represent a sample of the lines of execution.

According to *Innovation in Naval Logistics*, agility counters the enemy's ability to create uncertainty. We need to shift our reliance from immobile logistics sites and focus on making them forward deployed, mobile, and seabased. Persistence allows the Navy to sustain its forces by enabling them to stay on station longer. To do this, seabased logistics needs to provide logistics beyond the range of A2 capabilities while providing the flexibility to overcome asymmetric environments. Mobility reduces kinetic risk through increased maneuverability and will allow the Navy to remain on station longer. To improve this, we need to develop innovative ways to employ CLF ships. Assurance tries to reduce the vulnerability of huge stockpiles of commodities and long lines of communication through mobile seabased resupply sources that can make it difficult for the enemy to predict routes and locations (Secretary of the Navy, 2016).

Our study leverages the benefits of logistics agility, persistence, mobility, and assurance through mini-CLF ships operating as mobile seabases for AFP replenishment within an A2 environment.

2. Inventory Pooling

The process of inventory pooling combines the inventory from multiple locations into fewer locations that carry a larger amount of inventory (Ferrer, 2017). Figure 1 shows an example of how to pool inventory. The system on top has a dedicated distributor for each customer. The system on the bottom pools the inventory into a single distributor that services all three customers.

Ferrer stated multiple advantages to inventory pooling. By merging the demand, the overall demand uncertainty may be reduced. This allows the distributor to store less inventory due to a reduction in safety stock. Safety stock is the inventory kept on hand to minimize the risk of running out when there is uncertain demand. Fewer and larger replenishment orders can also be placed by the distributor due to economies of scale.

Our study treats a port or CLF ship as the manufacturer, the mini-CLF ship as the distributor, and the AFP as the customer. We concentrate resources outside of the combat area, with one or more mini-CLF ships who can each service multiple customers depending on the demand.

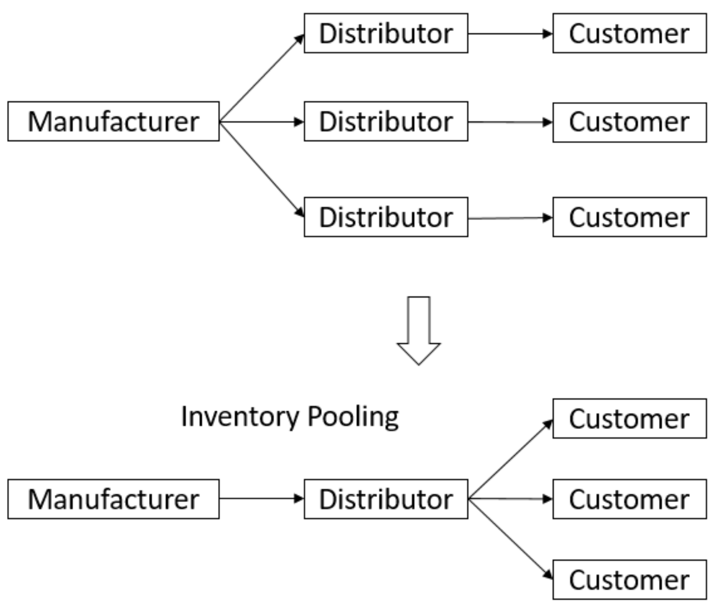


Figure 1. Inventory pooling example

3. Gas Station Resupply Method

When sufficient resources are concentrated within individual groups of ships, logistic attainability is achieved. This allows resources to be immediately available, but makes it difficult to redistribute resources to other groups of ships when the need arises. When resources are concentrated at a different centralized location such as a CLF ship located outside of the operating area, it is easier to redistribute resources at the cost of time. This is known as logistical flexibility and it enables the logistics chain to satisfy fluctuating demand over a wide area (Kress, 2016). The gas station resupply method focuses on logistical flexibility to meet the needs of AFPs operating within DL scenarios while gaining some of the efficiencies of inventory pooling.

The single commodity situation (notionally fuel) was studied in an earlier Naval Research Program study (Atkinson, Kress, & Szechtman, 2016) for the case of "pull" logistics, manifested in a "gas station" (GS)-type supply chain. In the GS approach, one CLF ship is the resupply source operating outside of the combat area. AFPs transit away from their operating stations to meet up with the GS outside the combat zone and "pull" resources at a resupply point. Since the GS is operating outside of the combat zone, the logistics tail of AFPs is minimized. This enhances AFP tactical agility and the survivability of supplies. Two modes of resupplying the GS were analyzed. The first mode consists of a mobile GS that transits from the resupply point to port to replenish resources. The second mode places a stationary GS at the resupply point and utilizes a shuttle that travels between the GS and port to replenish resources.

In this study, the authors developed a conceptual stochastic model for a GS setting and analyzed questions such as these: Where should the GS be located? How does the capacity of the GS affect the combat readiness of the AFP? What is the impact on an AFP's time off station as the number of AFPs serviced by the GS changes? Shall a separate shuttle resupply the GS or should the GS travel to port to replenish?

Our study builds upon the GS approach by utilizing the mini-CLF ship as a mobile GS with four commodities. The mini-CLF ship will resupply itself either by port or a CLF ship operating outside of the A2 environment. Our mini-CLF ship can also travel to different resupply points to support a greater range of AFPs operating in a large area.

4. Mini Combat Logistics Force Ship

The use of mini-CLF ships as shuttles between CLF ships and Navy warships was first studied in a Naval Postgraduate School thesis written by Colburn (2015). He developed the Dual Lane Replenishment At-Sea Model, which is a network-based linear program that prescribes the optimal at-sea replenishment schedule for Navy warships, mini-CLF ships, and CLF ships operating within an ASBM A2 environment. Mini-CLF ships are smaller and therefore considered safer from being destroyed by the Dong-Feng-21D ASBM. In the network, warships operate at forward operating stations and travel to forward replenishment-at-sea (RAS) lanes to meet mini-CLF ships. Mini-CLF ships travel between forward RAS lanes, ports for inport replenishment, and aft RAS lanes for replenishment with CLF ships. CLF ships travel between aft RAS lanes and ports for replenishment. Forward operating stations, forward RAS lanes, and some ports were within the ASBM threat area. In his thesis, the author assesses the optimal speed and liquid fuel capacity of mini-CLF ships as well as the optimal number of mini-CLF ships to employ to support one deployed carrier task force and one cruiser-destroyer SAG in both peacetime and wartime scenarios (Colburn, 2015).

Although our study uses a simulation instead of an optimization model, we utilize the same at-sea replenishment network and the mini-CLF ship concept. We also use a generic operating area instead of focusing on U.S. Seventh Fleet. Our model further differs from Colburn's model by

- Accounting for multiple commodities, such as stores and ordnance, instead of just liquid fuel.
- Allowing for (randomized) attrition of mini-CLF ships and ports during wartime scenarios.
- Randomizing the consumption rate of AFP commodities based on the mission of the AFP.
- Analyzing SAG AFPs only. No carrier strike groups are considered.

E. OBJECTIVES

This thesis expands the GS resupply method with the introduction of mini-CLF ships. The objective is to assess the feasibility of using mini-CLF ships as the main resupply source for AFPs operating in a DL and A2 environment. To accomplish this, we develop a simulation model that emulates the performance of the resupply network under varying scenario and mini-CLF ship configurations. Our first measure of effectiveness is the fraction of time an AFP is on station and operating above its commodity safety levels. When an AFP crosses a commodity safety level, it seeks replenishment of its commodities. The second measure of effectiveness is how often AFPs cross commodity extremis levels. AFPs are at risk of running out of commodities when it crosses an extremis level. We focus on the following aspects that were not considered in previous analyses in this area:

- Multi-commodity: move from a single supply type to multiple types that compete for storage and transportation capacities.

- Survivability of the logistics chain: assess the impact to our measures of effectiveness from port and mini-CLF ship attrition within the ASBM threat area.

- New customer requirements: recommend mini-CLF ship commodity cargo capacity and force size while supporting only surface action groups in a DL and A2 environment.

F. LIMITATIONS

Our model is not based on a real-world operating area. We vary notional geographic characteristics, such as the distance between operating stations, ports, and replenishment-at-sea lanes, to assess their impact on our measures of effectiveness. We also do not consider possible external demands on CLF ships.

II. SCENARIO, MODEL CONSTRUCTION, AND ASSUMPTIONS

This chapter describes the ingredients of our analysis: scenario, basic features of the model, and the assumptions used for modeling and analysis. A gas station (GS) approach is used, where mini-CLF ships are the main resupply GS source operating outside of the combat area but within the anti-ship ballistic missile (ASBM) range. AFPs transit from their operating stations in the combat area to meet up with the GS and "pull" resources at resupply points. Mini-CLF ships transit to port or to a CLF ship to replenish resources. The goal is to assess the impact to the time an AFP is on station while operating above its commodity safety levels and the number of times an AFP crosses an extremis level. When an AFP crosses a commodity safety level, it seeks replenishment. When an AFP crosses an extremis level, it is at risk for running out of commodities. The following are the motivating questions for this model:

1. What should be the cargo capacity of a mini-CLF ship and how should this cargo be distributed among four types of supply: distillate fuel marine (DFM), naval aviation fuel (JP-5), ordnance, and palletized stores?

2. How many mini-CLF and CLF ships are required to meet specified force readiness levels given that AFPs will periodically have to be off station to resupply?

3. How do questions one and two differ under wartime scenarios, peacetime scenarios, and differing ASBM ranges?

A. SCENARIO

U.S. Navy warships operate as AFP Surface Action Groups (SAGs) in an effort to distribute lethality. ASBMs, with the ability to target large ships, create an anti-access (A2), environment for CLF ships. Mini-CLF ships, smaller and more agile than CLF ships, are less vulnerable to ASBMs within the A2 area. As a result, Mini-CLF ships can provide commodities to AFPs within the threat area through the GS resupply method, more effectively and securely. Having mini-CLF ships stationed just outside of the combat area minimizes the time an AFP is off station to replenish commodities. CLF ships operate outside the threat area to provide commodities to replenish mini-CLF ships. Instead of defining a specific geographic operating area, we describe a general maritime scenario where the distances among entities vary in order to represent a wider range of potential operating areas. This general maritime scenario is visualized in Figure 2.

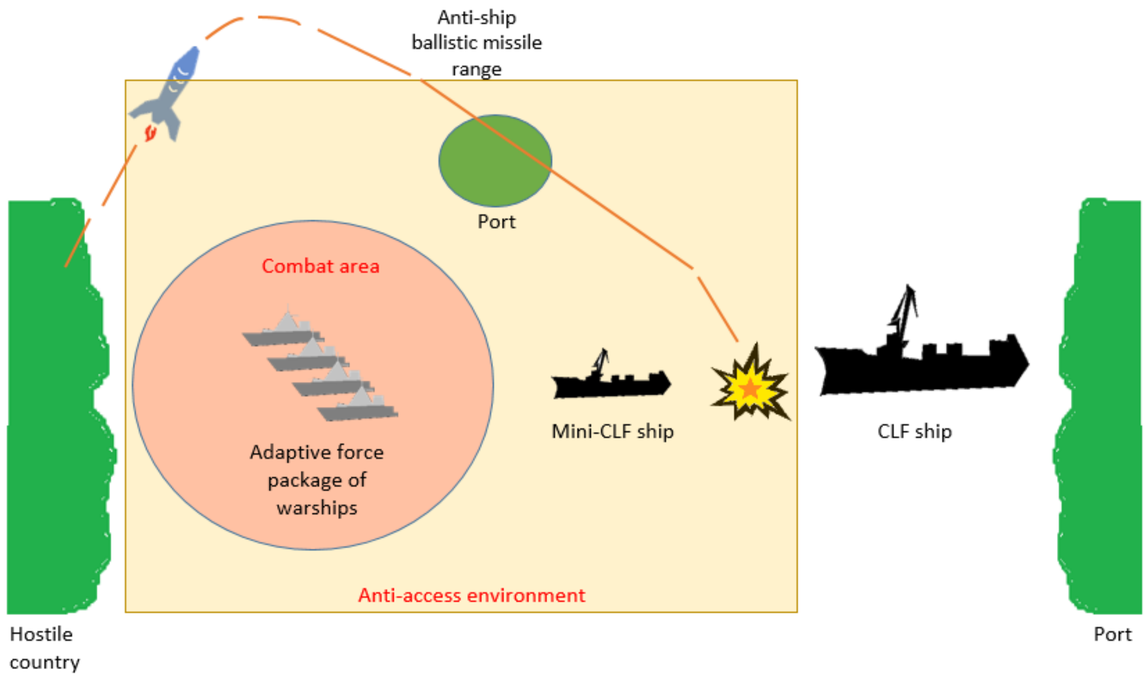


Figure 2. General maritime scenario for logistics in an anti-access environment

B. MODEL CONSTRUCTION

The model utilizes a process-flow method to represent the flow of AFPs, mini-CLF ships, and CLF ships through a logistics network. The nodes of the network consist of:

- Forward operating stations (FOSs)
- Ports vulnerable to attack (PVs)
- Ports not vulnerable to attack (PNVs)
- Forward RAS lanes (FRLs)

- Aft RAS lanes (ARLs)

AFPs operate at FOSs and consume their resources, Mini-CLF ships operate at FRLs as GSs resupplying AFPs. CLF ships operate at ARLs as GSs resupply mini-CLF ships and possibly AFPs. PVs and PNVs are stationary resupply nodes. Arcs in the network represent the travel routes (distances) between nodes. Figure 3 shows a simplified representation of the network. It specifies the ASBM threat area, the combat area, and stipulates which arcs and nodes AFPs, mini-CLF ships, and CLF ships can traverse. The figure is simplified because the actual network may have additional nodes such as FOSs, FRLs, and PVs. Further details on commodities, nodes, arcs, entities, states, and processes are described next.

1. Commodities

Resources that ships consume to operate are called commodities. Mini-CLF ships and CLF ships also store commodities as cargo for transfer to other ships. Commodities include DFM, JP-5, ordnance, and stores.

a. DFM

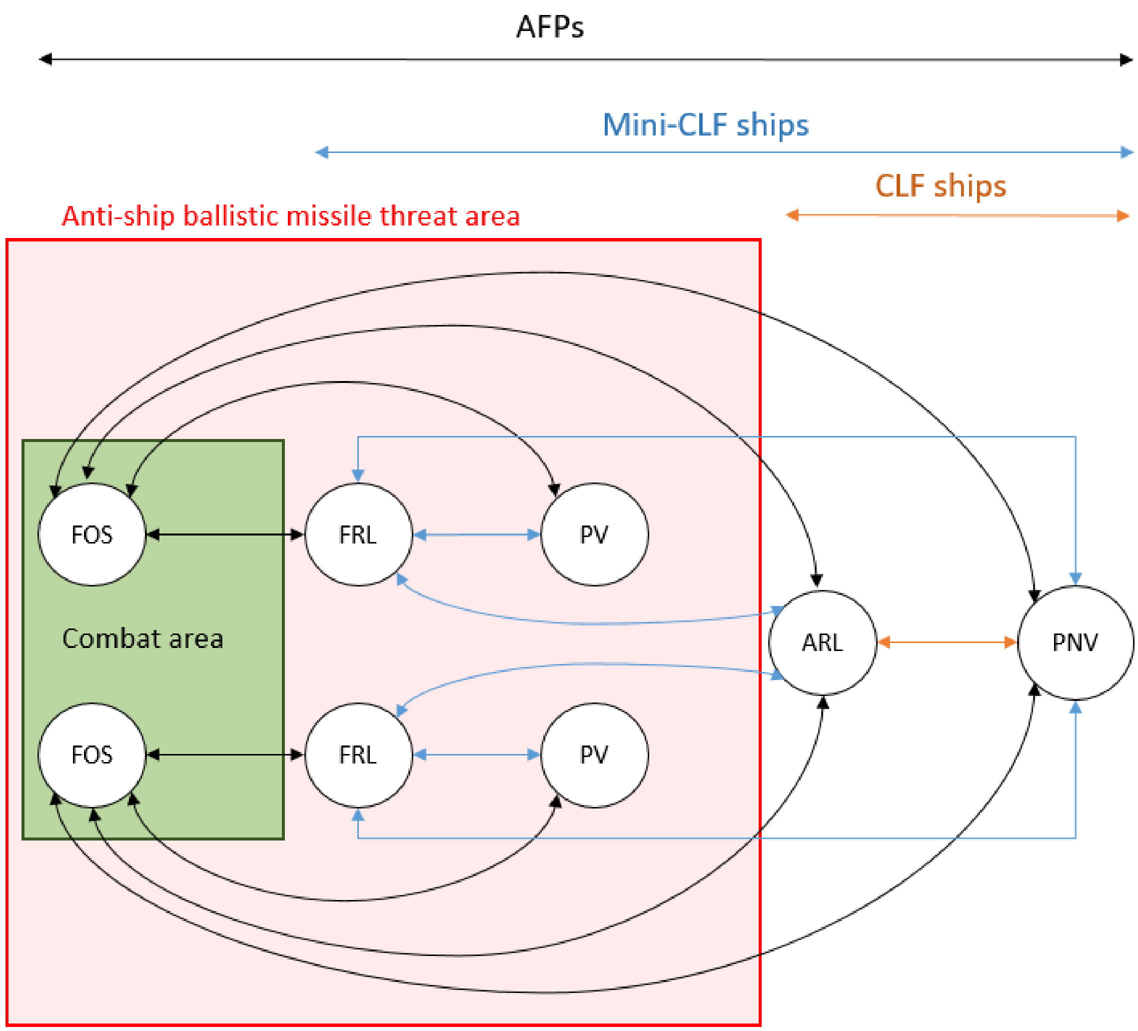
Fuel needed for the ship's propulsion systems.

b. JP-5

Aviation fuel needed for aircraft onboard ships in an AFP.

c. Ordnance

Munitions such as gun rounds, missiles, bombs, and torpedoes that can be fired from the ship or from an aircraft launched from the ship. DDGs and CGs also have Vertical Launch System (VLS) missiles that are included as ordnance. VLS missiles are not currently replenished at sea.



CLF ships stay out of the ASBM threat area and only visit PNVs and ARLs (via orange arcs). Mini-CLF ships can visit FRLs, PVs, ARLs, and PNVs (via blue arcs). AFPs can visit any node (via black arcs).

Figure 3. Simplified representation of the nodes, arcs, and threat area modeled

d. Stores

Food and dry stores that are consumed by the crew on ships.

2. Nodes and Arcs

Nodes and arcs are physical locations where entities can change states and processes can occur. The nodes are FOSs, FRLs, ARLs, PVs, and PNVs, and the arcs are sea lanes that connect the nodes.

a. FOS

A node within the network where an AFP is assigned to operate.

b. FRL

A node where a mini-CLF ship is assigned to operate. At this node, mini-CLF ships transfer commodities to replenish AFPs via underway replenishment (UNREP). An UNREP is where commodities are transferred ship to ship while at sea.

c. ARL

A node where a CLF ship is assigned to operate. At this node, CLF ships transfer commodities to replenish mini-CLF ships via consolidation operations (CONSOL). A CONSOL is where commodities are transferred between two CLF ships at sea.

d. PV

This node is a port, which is vulnerable to enemy attack, where AFPs and mini-CLF ships can replenish commodities such as DFM, JP-5, and stores via inport replenishment (INREP). It cannot replenish ordnance. An INREP is where ships pull into a port and receive commodities for replenishment from that port. PVs can be attacked and are subject to attrition. If a PV is destroyed, its node is removed from the network.

e. PNV

A node within the network where AFPs, mini-CLF ships, and CLF ships can replenish commodities such as DFM, JP-5, stores, and ordnance via INREP.

f. SEA LANE

An arc that connects nodes. Each arc has a value representing the length of the corresponding sea lane in nautical miles.

3. Entities

An entity is a ship, or a group of ships that move between nodes using sea lanes at specified transit speeds. The state of an entity, which can change depending on the action it is taking, comprises characteristics such as commodity consumption rates, transit speeds, and commodity transfer rates. Fixed characteristics of an entity include commodity capacities and the required time in port for INREP. Dynamic characteristics include inventory levels and the number of days since the last inport maintenance was completed. Entities are AFPs, CLF ships, and mini-CLF ships.

a. AFP

An AFP comprises one or more warships operating as a SAG at a FOS. Navy warships within the SAG can be guided-missile destroyers (DDGs), guided-missile cruisers (CGs), guided-missile frigates (FFGs), and/or littoral combat ships (LCSs). Commodities that are tracked and consumed for each warship within the AFP are DFM, JP-5, stores, and ordnance.

b. CLF Ship

A CLF ship is a major mobile supplier of commodities in the theater of operations. It acts as a mobile gas station to replenish commodities for mini-CLF ships. If necessary, it can also replenish commodities for AFPs. The commodities that are tracked in this ship include DFM for its own use as well as DFM, JP-5, stores, and ordnance as cargo available for transfer to mini-CLF ships and AFPs. Three types of CLF ships can be used: T-AO, T-AKE, and/or T-AOE. A T-AO is a fleet replenishment oiler that carries large quantities of DFM and JP-5 with a limited amount of stores. The T-AKE is an dry cargo and ammunition ship that carries large quantities of ordnance and stores with a limited amount of DFM and JP-5. The T-AOE is a fast combat support ship that carries moderate quantities of DFM, JP-5, stores, and ordnance.

c. Mini-CLF Ship

A mini-CLF ship is a mobile gas station for commodity replenishment to AFPs. Commodities that are tracked include DFM for its own use as well as DFM, JP-5, stores, and ordnance as cargo available for transfer to AFPs.

4. States

Entities are always in a certain state, which describes what the entity is currently doing. States include operating on station, transit, and replenishment. The consumption rate of commodities depends on the state of the entity.

a. Operating On Station

An AFP, mini-CLF ship, or CLF ship operating at their default assigned node are considered to be on station. AFPs are assigned an FOS, mini-CLF ships are assigned an FRL, and CLF ships are assigned an ARL. AFP consumption rates while on station also depend on its current mission such as assault, pre-assault, training, or on station.

b. Transit

Entities transit between nodes, using sea-lanes, at their assigned speed. A transit state occurs according to replenishment decision rules associated with an entity, discussed in section 6.

c. Replenishment

When an AFP, mini-CLF ship, or CLF ship refills commodities for its own use or as cargo, it is in a replenishment state. Replenishment can occur at the following nodes: FRL, ARL, PV, and PNV.

(1) FRL Replenishment

Each FOS is assigned an FRL for an AFP to replenish its commodities from a mini-CLF ship. When an AFP and a mini-CLF ship are present at the FRL node at the same time, an UNREP occurs. During the UNREP, each ship in the AFP takes turns replenishing its commodities with the mini-CLF ship. The time to replenish each AFP ship depends on the commodity transfer rates. Once the replenishment process is complete, the AFP transits back to its assigned FOS.

(2) ARL Replenishment

Mini-CLF ships initiate most ARL replenishments. AFPs can also initiate ARL replenishments. When a mini-CLF ship and the appropriate CLF ship are present at the ARL node at the same time, consolidation operations (CONSOL) occur to replenish the mini-CLF ship. When an AFP and the appropriate CLF ship are present at the ARL node at the same time, an UNREP occurs to replenish the AFP. The time to replenish each ship depends on the commodity transfer rates. Once the replenishment process is complete, the mini-CLF ship transits back to its assigned FRL or the AFP will transit back to its assigned FOS.

(3) PV Replenishment

In some situations, replenishments may occur at PVs. DFM, JP-5, and stores are replenished for an AFP or mini-CLF ship when it is present at a PV node via INREP. The replenishment is completed after a specified number of hours. If necessary, AFPs can also complete contractor inport maintenance, where civilian workers conduct maintenance on LCS equipment. After the completion of the replenishment, AFPs transit back to their assigned FOS and mini-CLF ships transit back to their assigned FRL.

(4) PNV Replenishment

All commodities are replenished for AFPs, mini-CLF ships and CLF ships when they are at a PNV node via INREP. The replenishment is completed after a specified number of hours. If necessary, AFPs can also complete contractor inport maintenance and replenish VLS weapons. After the completion of the replenishment, AFPs transit back to their assigned FOS, mini-CLF ships transit back their assigned FRL, and CLF ships will transit back to their ARL.

5. Processes

Processes occur at all times for all states. Processes include commodity consumption and attrition.

a. Commodity Consumption

Each entity has a defined set of commodity consumption rates based on the state and mission of the entity. Examples of states that can change consumption rates include transit, replenishment, and on station.

b. Attrition

Mini-CLF ships transiting within the threat area can be randomly destroyed based on assigned attrition rates. If a mini-CLF ship is destroyed, it will be removed from the network.

6. Replenishment Decision Rules

The type and time of a state transition of an entity is dictated by a set of decision rules. Each entity has assigned safety and extremis levels for the percentage of each commodity remaining. An entity establishes its need for a replenishment when a commodity crosses a safety level, though it may continue operating past the safety level if a desirable source of replenishment is not available. If the entity continues operating past the safety level without a replenishment, it will eventually cross an extremis level where it is at risk of running out of a commodity. An entity will always attempt to replenish its commodities when it crosses an extremis level. LCS ships within an AFP also have a maintenance level, requiring inport maintenance after a certain number of days have elapsed. For all entities, the source for replenishment is prioritized based on the type of commodity needing replenishment and minimizing the entire replenishment cycle time for each entity. The replenishment cycle time is the sum of the transit time and the time it takes to replenish commodities at the replenishment node.

While at the ARL, a mini-CLF ship or AFP gives priority to replenishment with a T-AOE because it carries suitable amounts of all four commodities. If a T-AOE is not available, it will replenish with a "T-AOE Alternative" consisting of a T-AO and a T-AKE.

a. AFP Replenishment

The need for replenishment occurs when the first warship within an AFP crosses a safety level for any commodity. Depending on the commodity that needs to be replenished, AFPs will transit to their preferred source of replenishment in the following order: UNREP at FRL, INREP at PV, UNREP at ARL, or INREP at PNV. Ordnance can only be replenished at FRLs, ARLs, and PNVs. Inport maintenance can be conducted at PVs or PNVs. VLS weapon replenishment can only be conducted at PNVs. As a result, the only time when an AFP would not replenish at an FRL is when a mini-CLF ship is off station for its own replenishment, the AFP requires inport maintenance, or the AFP requires VLS weapon replenishment.

b. Mini-CLF Ship Replenishment

The need for replenishment occurs when a mini-CLF ship crosses a safety or extremis level for personal use or cargo commodities. Since a mini-CLF ship can dip into its cargo DFM for ownship's use, the ownship's use DFM extremis level is the same as its DFM cargo extremis level. Depending on the commodity that needs to be replenished, mini-CLF ships will transit to their preferred source of replenishment in the following order: INREP at PV, CONSOL at ARL, or INREP at PNV. Ordnance can only be replenished at ARLs and PNV.

c. CLF Ship Replenishment

The need for replenishment occurs when a CLF ship crosses a safety level for a cargo commodity. A CLF ship can dip into cargo DFM for ownship's use when its ownship's use DFM storage is depleted. CLF ships only transit to PNVs for INREP. Since the PNV is always available, there is no extremis level for CLF ships.

7. Input

Logistics planning factors are used to define the values of the parameters in the model such as ship transit velocities, ship commodity consumption rates, commodity transfer rates, etc. The input variables that we focus on during our analysis in Chapter IV are the following:

- The number of mini-CLF ships operating. This is a key decision variable in our analysis.
- The commodity capacities for the mini-CLF ship. This is a key decision variable in our analysis.
- The number of AFPs and CLF ships operating.
- The ASBM range.
- The scenario being either peacetime or wartime.
- The probability of non-survival for port and mini-CLF ships at the end of 60 days for wartime scenarios.

8. Output

The model output is the utilization rate of AFPs, which is defined as the overall percentage of time an AFP, is on station and operating above its safety levels for all commodities and the number of times an AFP crosses an extremis level. Both outputs act as the measure of effectiveness (MOE) that may be used to assess the impact of changing the input variables. Larger values of the utilization rate and lower values of the number of times an AFP crosses an extremis level are preferred.

C. ASSUMPTIONS

In the simulation model, we make the following assumptions and define them as operational rules:

- All ships within an AFP stay together. If an LCS needs maintenance or if a DDG or CG needs VLS weapon reloading, then the entire AFP travels together.
- One warship can replenish with a mini-CLF ship or CLF ship at a time. Only one mini-CLF ship can replenish with a CLF ship at a time.
- All states can occur at any time of the day.
- All ports have unlimited berth capacity and can replenish all ships within the prescribed amount of time.
- All ports have an unlimited amount of commodity supplies. PVs only carry DFM, JP-5, and stores. PNVs carry all four commodities.
- All warships within an AFP do not suffer attrition. This is to ensure that the demand for AFP commodity replenishment does not decrease and thus, logistically, we consider the “worse-case” scenario.

III. IMPLEMENTATION

We use a simulation approach to analyze our model. This chapter describes the planning factors used as parameters within the model, the logic used to translate the model into a simulation, and the software used to conduct the simulation.

A. PLANNING FACTORS

We use logistics planning factors as parameters for our model. We obtained transit speeds, commodity capacities, commodity consumption rates, commodity transfer rates, and the required time to replenish in port from planning factors used in *Navy Warfare Publication 4–01.2* (CNO, 2007), the CLF Planner (Brown & Carlyle, 2008), and a study by CNA Corporation (Trickey, 2014). Fleet composition, safety levels, and mini-CLF ship characteristics are notional, as these inputs will vary depending on real-world application.

1. Assumptions

We make the following assumptions in order to implement logistics planning factors into our model:

- CGs and DDGs are considered to have depleted VLS weapons once 80% of ordnance has been consumed.
- VLS weapon inport replenishment time is set conservatively at five days. This process depends greatly on weather, equipment, and personnel.
- Ships do not leave station due to emergency maintenance.
- Legacy FFG consumption data is used because the new FFG design is not yet final.
- Mini-CLF ship characteristics are notional.

2. Fleet Composition

We evaluate three AFP compositions; each one is a SAG consisting of four ships. Table 1 shows the detailed breakdown of each AFP. The "Planned" column represents a few possible SAG compositions. The difference between the "Planned" and "Implemented" columns is the designation of small surface combatants (SSCs). FFGs and LCSs are used to fulfill the role of SSCs. The ship types that make up each AFP play a significant role in our MOE results. For example, LCS ships spend additional time off station due to an additional inport maintenance requirement.

Table 1. Composition of AFPs

AFP	Planned	Implemented
1	2x CG, 2x DDG	2x CG, 2x DDG
2	1x CG, 1x DDG, 2x SSC	1x CG, 1x DDG, 1x LCS, 1x FFG
3	1x DDG, 1x SSC, 2x LCS	1x DDG, 1x FFG, 2x LCS

3. AFP Consumption

Table 2 summarizes consumption rates for each warships, as obtained from the CLF Planner's planning factors. The four types of commodities that each ship can consume are DFM, JP-5, stores, and ordnance. The consumption rates are in barrels per day (bbls/day) for DFM and JP-5 and in short tons per day (stons/day) for stores and ordnance.

4. CLF Consumption

Table 3 summarizes consumption rates and cargo capacities for CLF ships. CLF ships have a DFM capacity for ownship's use and a separate capacity for cargo.

5. RAS Transfer Rates

Table 4 shows the transfer rates of each commodity from the CLF ship to consumers. Mini-CLF ship transfer rates are described in Section 9.

Table 2. Daily ship consumption rates in bbls for fuel and stons for stores and ordnance. Adapted from Brown and Carlyle (2008).

Ship	Commodity	Capacity	InTransit	On-Station	Training	PreAssault	Assault	Sustain
CG	DFM	15,032.00	757.00	605.60	757.00	1,429.00	757.00	757.00
CG	JP-5	475.00	8.50	17.00	25.50	17.00	39.00	25.50
CG	Stores	68.00	2.00	2.00	2.00	2.00	2.00	2.00
CG	Ordnance	94.00	0.08	0.15	0.60	0.60	5.00	3.00
DDG	DFM	10,518.00	646.00	516.80	646.00	1,200.00	646.00	646.00
DDG	JP-5	475.00	8.50	17.00	25.50	17.00	34.00	25.50
DDG	Stores	55.00	2.00	2.00	2.00	2.00	2.00	2.00
DDG	Ordnance	48.00	0.05	0.10	0.40	0.40	3.00	2.00
FFG	DFM	4,286.00	304.00	243.20	304.00	600.00	304.00	304.00
FFG	JP-5	475.00	8.50	17.00	25.50	17.00	34.00	25.50
FFG	Stores	35.00	1.00	1.00	1.00	1.00	1.00	1.00
FFG	Ordnance	16.00	0.02	0.04	0.15	0.15	1.00	0.75
LCS	DFM	2,663.00	180.00	288.00	180.00	360.00	180.00	180.00
LCS	JP-5	579.00	0.00	19.00	19.00	0.00	1.00	0.50
LCS	Stores	5.00	0.25	0.25	0.25	0.25	0.25	0.25
LCS	Ordnance	20.00	0.03	0.05	0.20	0.20	2.00	1.00

Table 3. CLF ship planning factors. Adapted from Trickey (2014).

Ship	Use DFM capacity (bbls)	DFM consumption (bbls/day)	DFM capacity (bbls)	JP-5 capacity (bbls)	Stores capacity (stons)	Ordnance capacity (stons)
T-AO	14,453	505	90,000	90,000	220	0
T-AOE	31,750	914	62,400	93,600	952	2,016
T-AKE	31,494	593	17,000	7,000	1,300	4,900

6. Transit

Table 5 summarizes the transit speeds for each ship type. Warship transit speeds based on the consumption DFM planning factors were obtained from the CLF Planner (Brown & Carlyle, 2008). CLF ship maximum transit speeds were obtained from a study by CNA Corporation (Trickey, 2014) and reduced by 25% to represent realistic transit speeds.

Table 4. RAS commodity transfer rates. Adapted from CNO (2007).

From CLF ship	To surface combatant: DFM or JP-5 (bbls per hour)	To surface combatant: stores or ordnance (stons per hour)	To LCS: DFM or JP-5 (bbls per hour)	To LCS: stores or ordnance (stons per hour)
T-AOE	8,571	55	4,286	35
T-AKE	4,286	55	4,286	35
T-AO	8,571	20	4,286	20

Table 5. Transit speeds

Ship	Transit speed
DDG	15
CG	15
FFG	15
LCS	15
T-AO	13
T-AOE	19
T-AKE	13

7. Ports

The time a ship spends in port depends on the reason why it entered port:

- If a warship, a mini-CLF ship, or a CLF ship enters port to replenish commodities, then it will remain in port for two days. This is based on the minimum duration in port from the CLF Planner (Brown & Carlyle, 2008).

- If an LCS requires inport maintenance, then it remains in port for five days. Fly-away teams enable maintenance to be conducted at PVs or PNVs. A fly-away team can consist of U.S. contractors that support deployed ships by traveling to overseas ports to accomplish inport maintenance. LCSs are required to conduct inport maintenance after operating for 25 days (United States Navy, 2018a).

- If a CG or a DDG requires the replenishment of VLS weapons, then it remains in port for five days.

8. Safety Levels

Safety and extremis commodity levels are shown in Table 6. Since actual safety levels depend on what numbered fleet a ship is operating in, estimates were used. Safety levels for T-AOEs, T-AOs, and T-AKEs represent cargo commodities. Safety levels for DDGs, CGs, FFGs, and LCSs represent commodities for ownship's use. The VLS safety level is crossed when a DDG or a CG consumes 80% of its ordnance capacity. The LCS maintenance level is crossed when an LCS has operated for 25 days since the last inport maintenance was completed.

Table 6. Safety levels

Ship	DFM	JP-5	Stores	Ord	Extremis DFM	Extremis JP-5	Extremis stores	Extremis ord
DDG	0.70	0.50	0.50	N/A	0.55	0.25	0.40	0.15
CG	0.70	0.50	0.50	N/A	0.55	0.25	0.40	0.15
FFG	0.70	0.50	0.50	0.40	0.55	0.25	0.40	0.20
LCS	0.70	0.50	0.50	0.40	0.55	0.25	0.40	0.20
T-AOE	0.25	0.25	0.50	0.25	N/A	N/A	N/A	N/A
T-AO	0.25	0.25	N/A	N/A	N/A	N/A	N/A	N/A
T-AKE	N/A	N/A	0.25	0.25	N/A	N/A	N/A	N/A

9. Mini-CLF Ship

Since there is not an official design for the mini-CLF ship, all of the design characteristics in this study are notional and subject to tradeoff analysis. The mini-CLF ship in this study is designed to be able to sprint during transit when it is low on cargo so that it can minimize the time in the threat area. The commodity transfer rates are adopted from the T-AOE. The ownship's use DFM capacity and consumption rate are adopted from the CG. Because a mini-CLF ship can dip into its cargo DFM for its own use, the ownship's

DFM extremis level is the same as its DFM cargo extremis level. Table 7 summarizes these characteristics.

The mini-CLF ship cargo capacity for DFM, JP-5, stores, and ordnance varies based on five unique configurations as summarized in Table 8. Each cargo capacity configuration describes how many times a mini-CLF ship can refill the largest capacity AFP configuration that needs to replenish up to its safety level, plus an additional 10% to account for transit time. For example, an AFP consists of four DDGs with a DFM capacity of 10,518 bbls each and a safety level of 70%. Since we account for an additional 10% for transit, our safety level for our calculation is 60%. We first subtract 60% from 100% to determine how much fuel is needed, which is equal to 40%. Next, we take 40% of 10,518 to represent how much DFM is needed by an individual DDG. Finally, we multiply the result by four to represent all four DDGs. We end up with 16,828 bbls of DFM to replenish the entire AFP.

To provide a rough estimate of the possible size of the mini-CLF ship, the last two columns of Table 8 show the relative cargo storage size of the mini-CLF ship configuration compared to the T-AOE. The actual percentage is shown in terms of total bbls of liquid fuel and total stons of stores and ordnance. For example, mini-CLF ship "Configuration 2" holds 32,558 bbls of liquid fuel as cargo while Table 3 shows that a T-AOE holds 156,000 bbls. This mini-CLF ship configuration only requires 14% of the T-AOE storage area for liquid fuel and results in a smaller ship.

Table 7. Notional mini-CLF ship operating characteristics

Category	Value
Transit speed (knots)	19
Reduced cargo transit speed (knots)	26
Ownship DFM consumption (bbls//day)	757
Ownship DFM capacity (bbls)	15,032
To surface combatant DFM/JP-5 transfer rate (bbls/hour)	8,571
To surface combatant stores/ordnance transfer rate (stons/hour)	55
To LCS DFM/JP-5 transfer rate (bbls/hour)	4,286
To LCS stores/ordnance transfer rate (stons/hour)	35
Days in port for INREP	2
Safety level for cargo DFM	0.50
Safety level for cargo JP-5	0.50
Safety level for cargo stores	0.50
Safety level for cargo ordnance	0.50
Extremis level for cargo DFM	0.25
Extremis level for cargo JP-5	0.25
Extremis level for cargo stores	0.25
Extremis level for cargo ordnance	0.25

Table 8. Mini-CLF ship cargo capacity configurations

Config	DFM (bbls)	JP-5 (bbls)	Stores (stons)	Ordnance (stons)	Minimum number of refills available for an AFP 10% below its safety threshold	% of T-AOE (bbls)	% of T-AOE (stons)
1	20,440	1,265	148	199	1.0	0.14	0.12
2	30,660	1,898	222	299	1.5	0.21	0.18
3	40,880	2,530	296	398	2.0	0.28	0.23
4	51,100	3,162	369	497	2.5	0.35	0.29
5	61,320	3,795	443	597	3.0	0.42	0.35

B. LOGIC

In order to implement the model construction as a mathematical model, we translate states and decisions rules into process flowcharts.

1. Replenishment States

When an AFP, a mini-CLF ship, or a CLF ship refills its ownship's or cargo commodities, it is in a replenishment state. Replenishment can occur at the following nodes: FRL, ARL, PV, and PNV.

a. FRL Replenishment

When an AFP and a mini-CLF ship are present at the FRL at the same time, an UNREP occurs as described in Figure 4. After a time delay for setup, one ship from the AFP begins commodity transfer with the mini-CLF ship. The order for ship replenishment is CG, DDG, FFG, and LCS. Ships that are waiting consume commodities at the on station rate. Once the ship is either fully replenished for each commodity or the mini-CLF ship runs out of a commodity to transfer, a time delay occurs to detach the ship. This process continues until all of the ships in the AFP are replenished or the mini-CLF runs out of all commodities. Once the replenishment process is complete, the AFP will transit back to its assigned FOS.

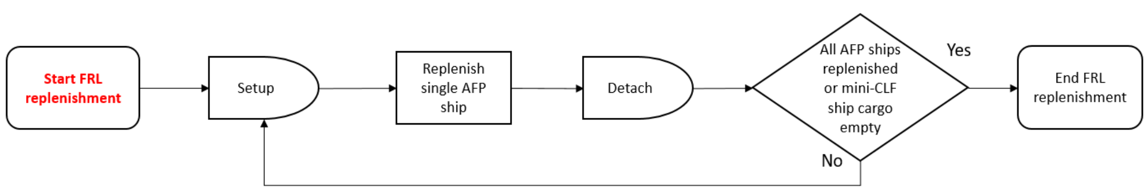


Figure 4. AFP replenishment process at the FRL

b. ARL Replenishment

When a mini-CLF ship arrives at the ARL, it will first check to see if a T-AOE is available. If so, it will start replenishment with the T-AOE; otherwise, it will start replenishment with a T-AO. If a mini-CLF ship has started replenishment with a T-AO for

DFM and JP-5, it will start replenishment with a T-AKE for stores and ordnance once it is complete. There are time delays to setup and detach from the CLF ship. This process is summarized in Figure 5. Once the replenishment process is complete, the mini-CLF ship will transit back to its assigned FRL.

When an AFP arrives at the ARL, it will first check to see if a T-AOE is available. If so, it will start replenishment with the T-AOE. After a time delay for setup, one ship from the AFP begins commodity transfer with the T-AOE. Ships that are waiting consume commodities at the on station rate. Once the AFP ship is either fully replenished with each commodity or the T-AOE runs out of a commodity to transfer, a time delay occurs to detach the ship. This process continues until all of the ships in the AFP are replenished or the T-AOE runs out of each commodity. If a T-AOE is not available, one ship from the AFP begins commodity transfer with a T-AO for DFM and JP-5. Once the AFP ship is either fully replenished with DFM and JP-5 or the T-AO runs out of a commodity to transfer, a time delay occurs to detach the ship. This process continues until all of the ships in the AFP are fully replenished with DFM and JP-5 or the T-AO runs out of each commodity. When the T-AKE is ready, one ship from the AFP will begin commodity transfer for stores and ordnance. Once the AFP ship is either fully replenished with stores and ordnance or the T-AKE runs out of a commodity to transfer, a time delay occurs to detach the ship. This process continues until all of the ships in the AFP are fully replenished of stores and ordnance or the T-AKE runs out of each commodity. Once the replenishment process is complete, the AFP will transit back to its assigned FOS. This process is summarized in Figure 6.

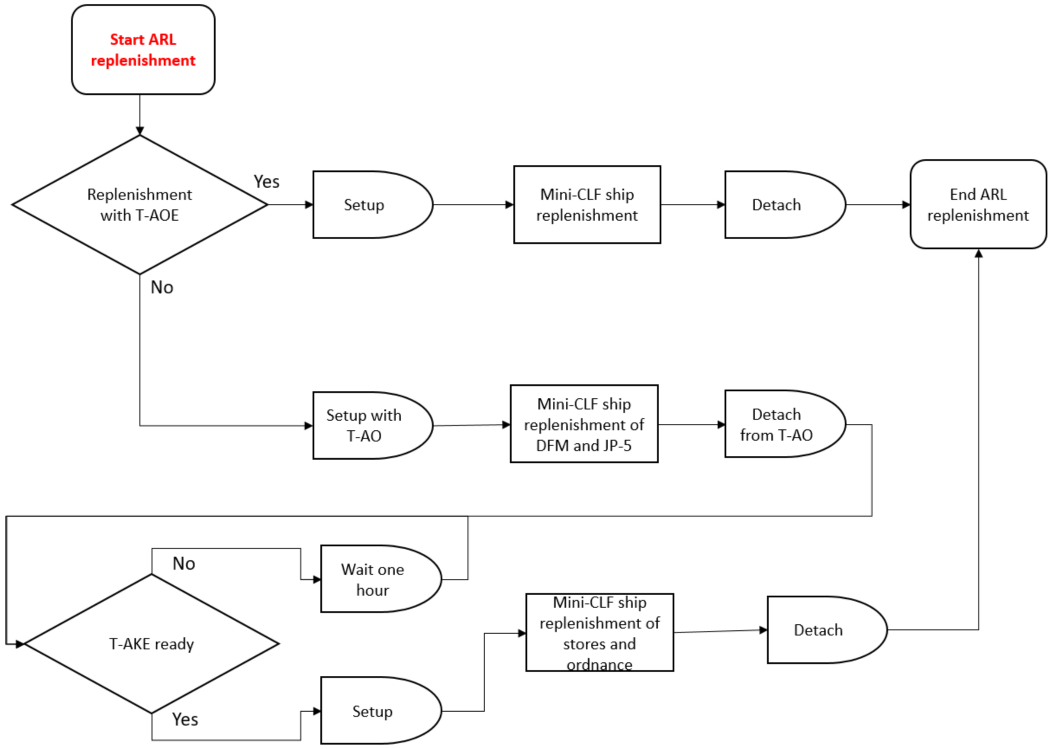


Figure 5. Mini-CLF ship replenishment process at the ARL

c. PV Replenishment

While at a PV, commodity consumption temporarily stops for AFPs and mini-CLF ships. After an assigned number of hours, DFM, JP-5, and stores are completely replenished for AFPs and mini-CLF ships. If required, AFPs can conduct LCS inport maintenance and the days since the last LCS inport maintenance counter can be reset. AFPs will transit back to their assigned FOS and mini-CLF ships will transit back to their assigned FRL.

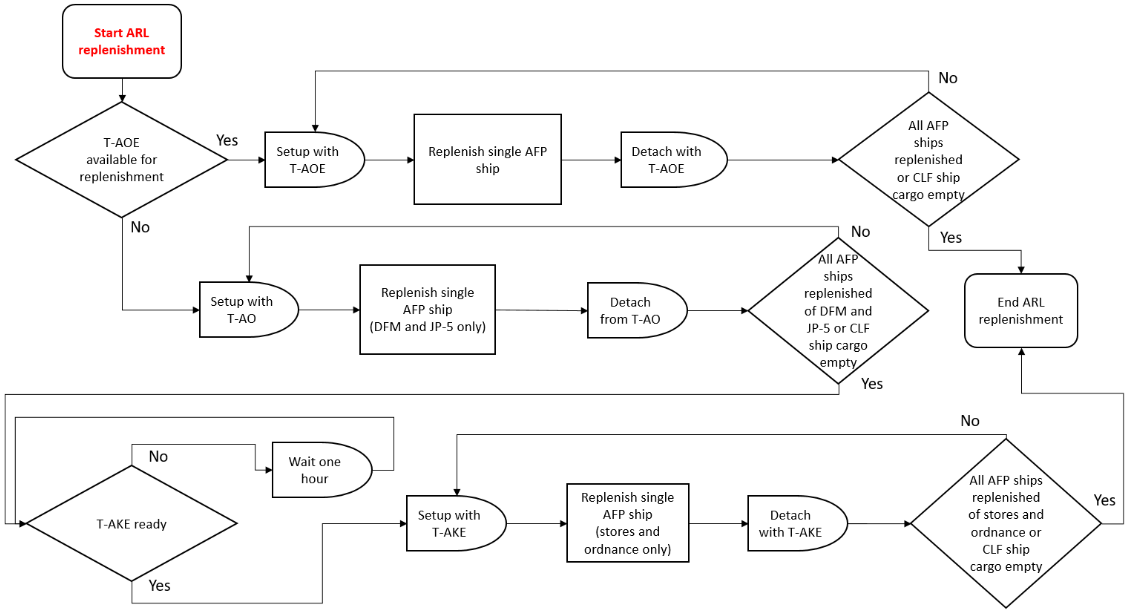


Figure 6. AFP replenishment process at the ARL

d. PNV Replenishment

While at a PNV, commodity consumption temporarily stops for AFPs, mini-CLF ships, and CLF ships. After an assigned number of hours, commodities are completely replenished for AFPs, mini-CLF ships, and CLF ships. AFPs also complete inport maintenance and VLS weapons replenishment after a specified number of days. After completion of inport maintenance, the number of days since the last inport maintenance counter is reset for LCSs. After the completion of the replenishment, AFPs will transit back to their assigned FOS, mini-CLF ships will transit back their assigned FRL, and CLF ships will transit back to the ARL.

2. Attrition

In this study, attrition is defined as the independent probability of non-survival of PVs and mini-CLF ships after 60 days. Based on the assigned level of attrition, a check is completed every 24 hours to determine if a PV or mini-CLF ship has been randomly destroyed. A PV is not removed from the network until berthed ships have completed INREP. If a mini-CLF ship is currently undergoing UNREP or INREP, it is not removed from the network until its current actions are completed.

3. Replenishment Decision Rules

We implement the replenishment decision portion of the model construction into a mathematical model with process flowcharts.

a. AFP Replenishment Decision

The decision rule logic for an AFP to replenish commodities is summarized in Figure 7. An AFP starts at its assigned FOS with a consumption rate based on its assigned mission. Every hour, the system checks to see if a level has been crossed and makes a decision in the following sequence:

- If a DDG or a CG crosses a VLS level, then the AFP will transit to a PNV for INREP.
- If an LCS crosses a maintenance level and a commodity has crossed a safety or extremis level, then the AFP will transit to a PV for INREP. If a PV is not available, then the LCS will transit to a PNV for INREP.
- If any ship within the AFP crosses a commodity safety level and a mini-CLF ship is available, then the AFP will transit to its assigned FRL for UNREP.
- If any ship within the AFP crosses a DFM, JP-5, or stores extremis level and a mini-CLF ship is available, then the AFP will transit to its assigned FRL for UNREP.
- If any ship within the AFP crosses a DFM, JP-5, or stores extremis level, a mini-CLF ship is not available, and a PV is available, then the AFP will transit to the PV for INREP.
- If any ship within the AFP crosses a DFM, JP-5, or stores extremis level, a mini-CLF ship is not available, a PV is not available, and a CLF ship is available, then the AFP will transit to an ARL for UNREP.

- If any ship within the AFP crosses a DFM, JP-5, or stores extremis level, a mini-CLF ship is not available, a PV is not available, and a CLF ship is not available, then the AFP will transit to a PNV for INREP.
- If a ship within the AFP crosses an ordnance extremis level and a mini-CLF ship is available, then the AFP will transit to its assigned FRL for UNREP.
- If a ship within the AFP crosses an ordnance extremis level, a mini-CLF ship is not available, and a CLF ship is available, then the AFP will transit to an ARL for UNREP.
- If a ship within the AFP crosses an ordnance extremis level, a mini-CLF ship is not available, and a CLF ship is not available, then the AFP will transit to a PNV for INREP.

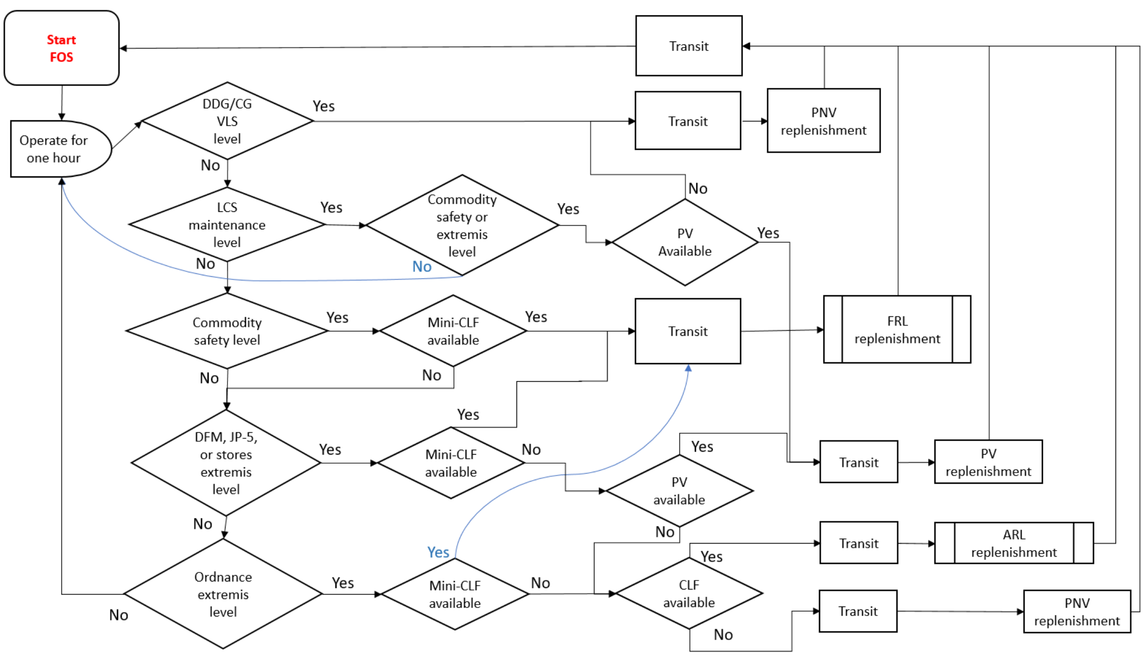


Figure 7. Replenishment decision rule for an AFP

b. Mini-CLF Ship Replenishment Decision

The decision rule logic for a mini-CLF ship to replenish commodities is summarized in Figure 8. Every hour the system first checks to see if an AFP needs an UNREP. If not, it then checks to see if the mini-CLF ship has crossed a safety or extremis level requiring replenishment. The decision sequence is as follows:

- If an AFP is present at the FRL for UNREP, then the mini-CLF ship will conduct an FRL replenishment as described in Section B, Part 1a.

- If an AFP is not present at the FRL, an AFP is at or transiting to an alternate FRL, no other mini-CLF ship is present at the alternate FRL, and no other mini-CLF ships are transiting to the alternate FRL, then the mini-CLF ship will transit to the alternate FRL to conduct an FRL replenishment. The mini-CLF ship will return to its assigned FRL upon completion.

- If the mini-CLF ship crosses a cargo ordnance safety or extremis level and a CLF ship is available, then it will transit to the ARL for CONSOL.

- If the mini-CLF ship crosses a cargo ordnance extremis level and a CLF ship is not available, then it will transit to the PNV for INREP.

- If the mini-CLF ship crosses a cargo DFM, cargo JP-5, or cargo stores safety level and a PV is available, then it will transit to the PV for INREP.

- If the mini-CLF ships crosses a cargo DFM, cargo JP-5, or cargo stores extremis level and a PV is available, then it will transit to the PV for INREP.

- If the mini-CLF ships crosses a cargo DFM, cargo JP-5, or cargo stores extremis level, a PV is not available, and a CLF ship is available, then it will travel to the ARL for CONSOL.

- If the mini-CLF ships crosses a cargo DFM, cargo JP-5, or cargo stores extremis level, a PV is not available, and a CLF ship is not available, then it will travel to the PNV for INREP.

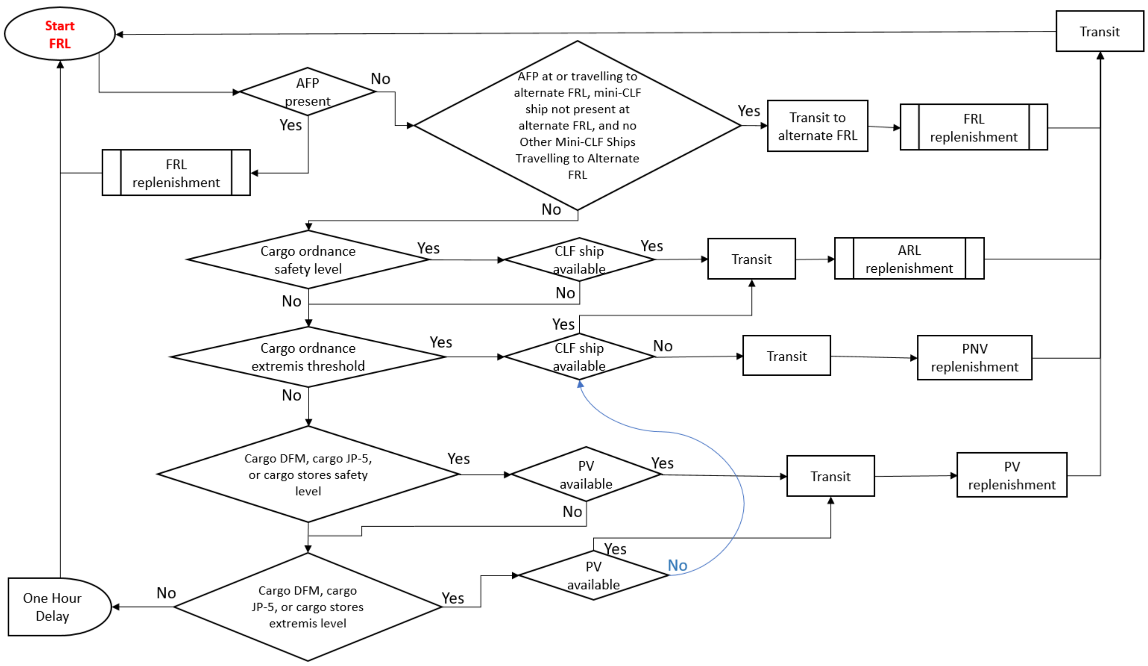


Figure 8. Replenishment decision rule for a mini-CLF ship

c. *CLF Ship Replenishment Decision*

The logic for the decision rules of a T-AOE, a T-AO, and a T-AKE are shown in Figures 9, 10, and 11, respectively. Every hour, a CLF ship will check to see if it needs to replenish a mini-CLF ship or an AFP. A T-AOE has priority to conduct ARL replenishment and a T-AKE will only replenish a mini-CLF ship or an AFP after a T-AO has completed ARL replenishment of a mini-CLF ship or an AFP. The ARL replenishment process is described in Section B, Part 1b. If there are no mini-CLF ships or AFPs needing replenishment at the ARL, then the system checks to see if a commodity safety level has been crossed for a CLF ship. If so, the CLF ship will transit to a PNV for INREP and transit back to the ARL once complete. Unlike an AFP, which consists of several warships traveling together as a group, CLF ships are independent from other CLF ships.

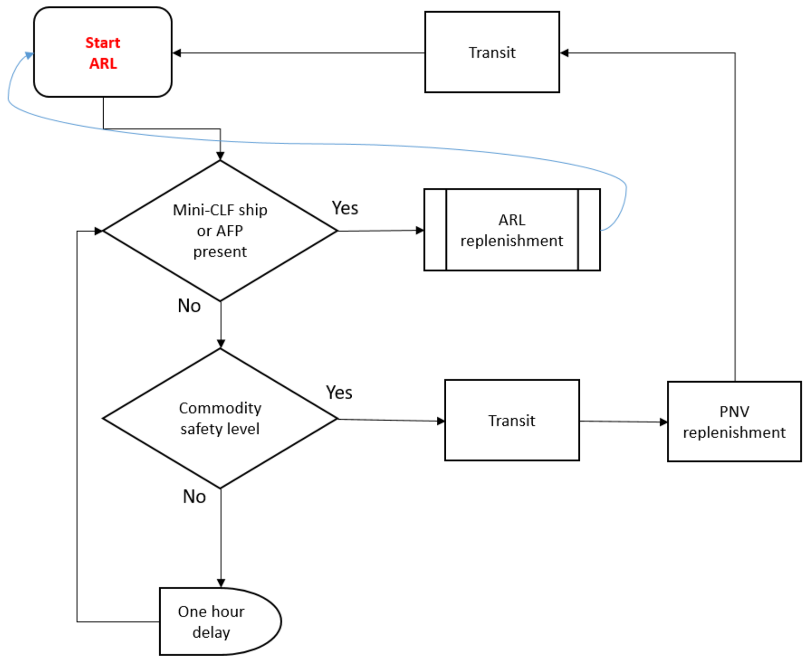


Figure 9. Replenishment decision rule for a T-AOE

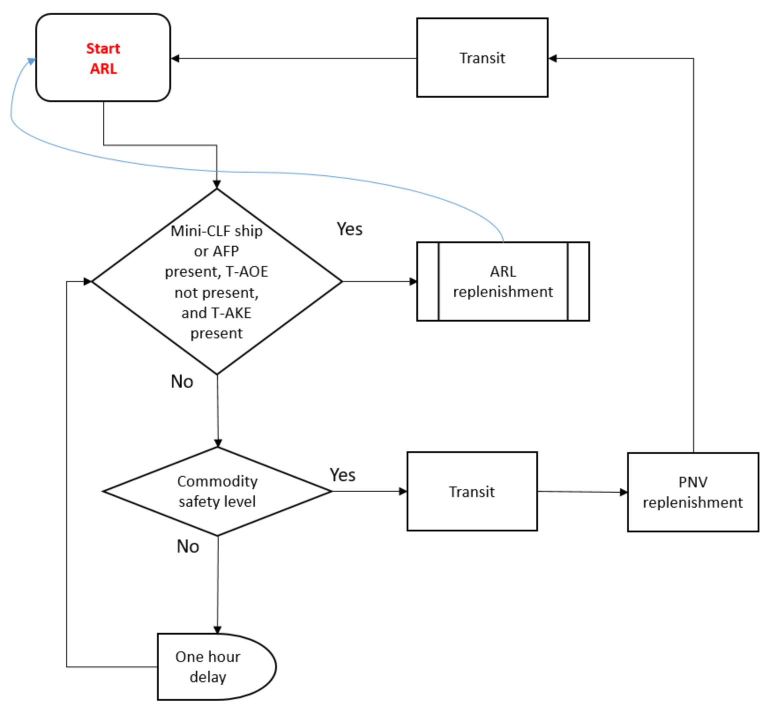


Figure 10. Replenishment decision rule for a T-AO

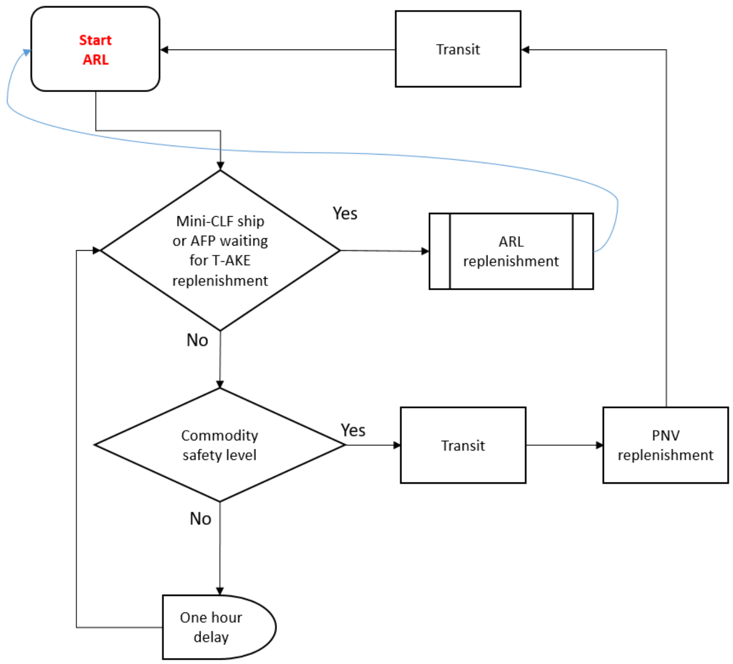


Figure 11. Replenishment decision rule for a T-AKE

4. Input

Logistics planning factors are used as parameters within the model. CLF ships are fixed at one T-AOE, one T-AO, and one T-AKE. Table 9 contains a summary of the input variables with a range of values. Input variables are as follows:

- Number of AFPs
- Number of mini-CLF ships
- Distance between the FOS and PNV
- Distance between the FOS and ARL based on the ASBM range
- Mini-CLF ship cargo DFM capacity
- Mini-CLF ship cargo JP-5 capacity
- Mini-CLF ship cargo stores capacity
- Mini-CLF ship ordnance capacity

- Port and mini-CLF ship attrition rate
- Length of scenario
- Wartime or peacetime

5. Output

The overall percentage of time an AFP is on station and operating above its safety levels for all commodities is defined as the utilization rate. Since multiple AFPs can be operating during a given scenario, the average utilization rate will be used. The number of times a single AFP crosses an extremis level, over 60 days for wartime and 180 days for peacetime, is also counted to represent the risk that AFPs are operating with low quantities of commodities remaining.

Table 9. Model input variables

Input Variable	Value
Number of AFP1s	0 - 5
Number of AFP2s	0 - 5
Number of AFP3s	0 - 1
Number of mini-CLF ships	0 - 9
Distance between PNV and FOS (NMs)	1,000 - 2,500
Distance between the FOS and ARL based on the ASBM range (NMs)	1,000 or 2,000
Mini-CLF cargo DFM capacity (bbls)	20,440 - 61,320
Mini-CLF cargo JP-5 capacity (bbls)	1,265 - 3,795
Mini-CLF cargo stores capacity (stons)	148 - 443
Mini-CLF cargo ordnance capacity (stons)	199 - 597
Port and mini-CLF ship probability of non-survival after 60 days	0% - 50%
Length of scenario (days)	60 or 180
Wartime or peacetime (0 = wartime, 1 = peacetime)	0 or 1

C. OPERATIONAL SETTING

The operational setting is broken up into peacetime and wartime. All FOSs are located 300 NM from their supporting FRLs in order to keep the FRL outside of the combat area. Each FOS has access to a single PV that is 500 NM away. Each FRL has access to the same PV its supported FOS has access to and this PV is located 500 NM from the FRL. The distance the FOS is from the ARL is equal to the ASBM range.

1. Peacetime

In peacetime, the consumption rate of AFPs is randomized based on the AFP's mission state. Every time an AFP enters the FOS, there is an equal chance that it will enter either a training or on-station mission. Mission commodity consumption rates were previously summarized in Table 2. There is no attrition of ports or mini-CLF ships.

2. Wartime

In wartime, the scenario has a global mission state that starts at pre-assault and transitions to assault and sustain as time goes on. The time the scenario is in each global mission state is randomized. AFP consumption rates depend on the global mission. Every time an AFP enters the FOS, it checks what the global mission is and it assumes that mission. Mini-CLF ships and ports are affected by attrition.

D. SIMIO

The software selected to accomplish this study is Simulation Modeling framework based on Intelligent Objects (Simio). Simio is a modeling tool that allows events, processes, objects, and agents to operate within a single framework and is designed to allow simple and rapid modeling (Kelton, Smith, & Sturrock, 2014). Our model logic was converted into the Simio modeling system.

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IV. ANALYSIS

In this chapter, we implement the multi-commodity logistics simulation described in Chapter III to study the impact different mini-CLF ship configurations have on the performance of AFPs. The AFP utilization rate, which is the percentage of time an AFP is on station and operating above its commodity safety levels, and the number of times an AFP crosses a commodity extremis level are outputs of the model that are evaluated against the mini-CLF ship cargo configuration size and the number of mini-CLF ships operating. Based on the results of this chapter, we offer recommendations about a mini-CLF ship force structure.

This analysis uses the parameters described in Chapter III with baseline input parameters of three AFPs, a distance between the FOS and PNV of 1,500 NM when we assume a 1,000 NM ASBM range and a distance between the FOS and PNV of 2,500 NMs when we assume a 2,000 NM ASBM range. Section A describes a peacetime scenario with a 180-day time horizon. Section B describes a wartime scenario, with a 60-day time horizon, which introduces attrition of ports and mini-CLF ships. After the selection of the recommended mini-CLF ship configuration for peacetime or wartime scenarios, a sensitivity analysis assesses the impact on the performance of AFPs based on varying the number of supported AFPs and removing access to PVs.

A stochastic model describes each scenario due to the randomness of AFP consumption and port and mini-CLF ship attrition. The analysis utilizes the average results from 100 replications of each scenario. Throughout this chapter, we plot our key measures of interest, such as the AFP utilization rate. We do not show error bars on these plots because the standard error of the estimate is small and plotting confidence intervals would only serve to clutter the figures, without providing any insight. For the AFP utilization rate, which is a percentage, the standard error was lower than 0.85 percentage points for all scenarios. The standard error was lower than 0.52 for the counting metrics: the number of times an AFP crosses a commodity extremis level, the number of times an AFP utilizes a CLF ship for replenishment, and the number of times a mini-CLF ship utilizes a CLF ship for replenishment.

The main takeaways from this analysis are as follows:

- A one-to-one ratio of mini-CLF ships to AFPs, with at least a commodity capacity that can refill the largest operating AFP one time when the AFP reaches 10% below all of its commodity safety levels, is sufficient to sustain the distributed force in peacetime scenarios where PVs are always accessible.

- A quantity of mini-CLF ships equal to one plus the number of AFPs during wartime scenarios with access to PVs and levels of port and mini-CLF attrition of up to 50% at the end of 60 days. Some mini-CLF ship resiliency against attrition is provided by operating in this fashion.

- A mini-CLF ship configuration with a commodity capacity that can refill the largest operating AFP one time when the AFP reaches 10% below all of its commodity safety levels is recommended because it balances AFP performance with mini-CLF ship physical size.

- The removal of CLF ships from peacetime scenarios with access to PVs and sufficient mini-CLF ships operating is recommended due to minimal usage of CLF ships by mini-CLF ships and no usage by AFPs for replenishment. However, CLF ships are important in wartime because mini-CLF ships start to use them for replenishment.

- An increase in the range of the ASBM reduces AFP performance. This is because the limited availability of mini-CLF ships at the FRL for AFP replenishment decreases due to an increase in the replenishment distance between the mini-CLF ship and the CLF ship. In wartime, DDGs and CGs must transit farther to a PNV for VLS replenishment.

- A removal of PVs from peacetime and wartime scenarios significantly increases CLF ship usage by mini-CLF ships and AFPs for replenishment. It also reduces AFP performance due to LCSs having to transit farther to a PNV for inport maintenance.

- A port and mini-CLF ship level of attrition that is as high as 50% at the end of 60 days has a significant impact on AFP performance. However, some of the performance loss can be mitigated by the introduction of additional CLF and mini-CLF ships.

- An AFP with an LCS has a utilization rate that is up to 20% lower than an AFP without an LCS due to LCS inport maintenance requirements.

A. PEACETIME OPERATIONS

We begin with the evaluation of the 1,000 NM and 2,000 NM ASBM missiles ranges for the case of three AFPs operating over the course of 180-days. Although this is a peacetime scenario, CLF ships do not operate within the ASBM range. After the selection of the recommended mini-CLF ship configuration for peacetime, a sensitivity analysis assesses it further.

1. Scenario Anti-Ship Ballistic Missile Threat Range of 1,000 Nautical Miles

Figure 12 comprises four graphs showing mini-CLF ship configuration performance by the type of AFP supported. The figure in the upper left-hand panel is the average performance of all three AFPs. The y-axis represents the AFP utilization rate, which is the percentage of time an AFP is operating on station and has not crossed a commodity safety level. The x-axis represents the number of mini-CLF ships present in the scenario. Each colored line represents a different mini-CLF ship cargo configuration in terms of how many times it can refill the largest AFP that has consumed 10% more than its safety level of commodities. The upper bound represents the highest possible value of the utilization rate assuming mini-CLF ships carry unlimited cargo and AFPs operate above their safety level in missions that allow for the maximum time on station due to having the lowest commodity consumption rates. The standard error of the mean was below 0.116 percentage points for all observations.

We observe that AFP1's utilization rate is as much as 20 percentage points higher than AFP2 and AFP3 in some situations. This is because AFP2 and AFP3 have LCSs that trigger an inport maintenance requirement every 25 days that require transit to a PV. Ships consume a limited amount of ordnance during peacetime while conducting training or performing missions while on station. As a result, CGs and DDGs do not consume enough ordnance to trigger a VLS replenishment resulting in AFP1 never having to transit to a PNV. Furthermore, because AFPs and mini-CLF ships prefer to replenish at PVs when ordnance is still above safety levels, CLF ships were not utilized by AFPs at the ARL when there was at least one mini-CLF ship operating. The number of mini-CLF ships operating had a greater impact on the utilization rate than the mini-CLF ship cargo configuration. The utilization rate shows minimal improvement for anything more than three mini-CLF ships operating. At this level, all five configurations provide similar performance.

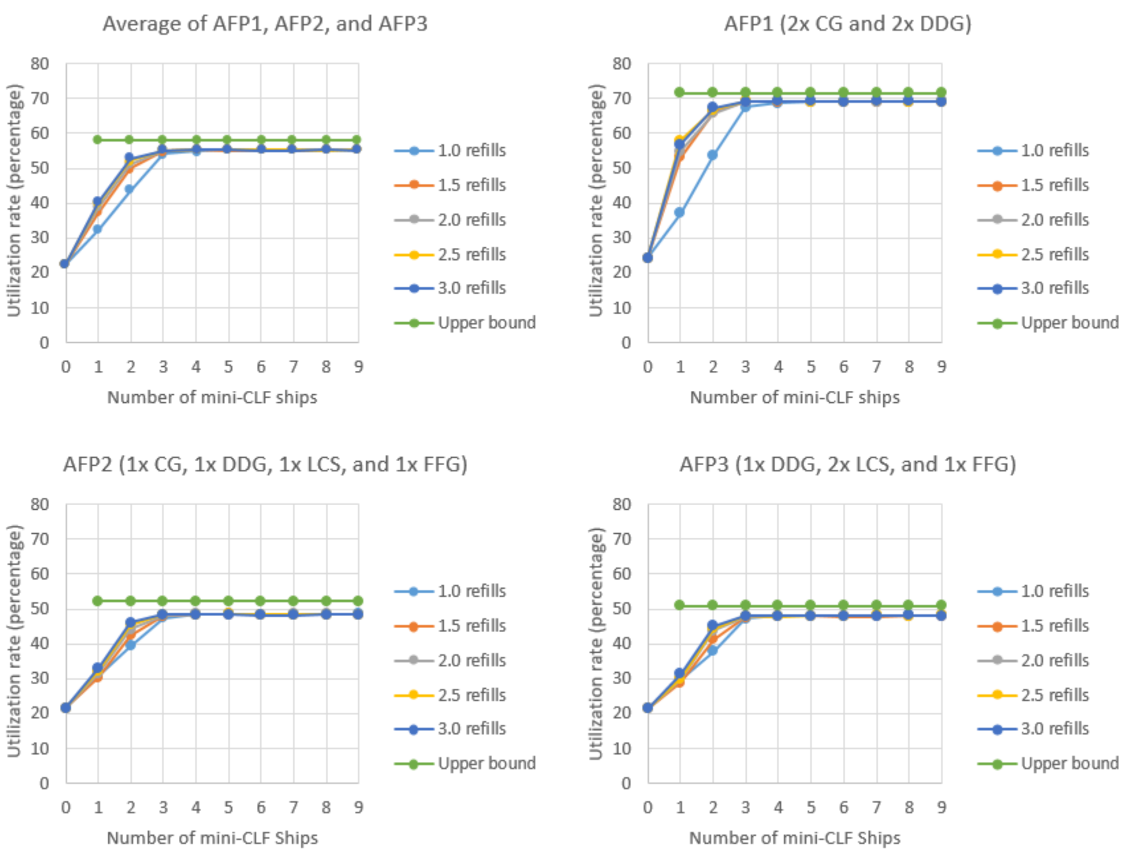

Figure 12. Average utilization rate for peacetime operations and a 1,000 NM ASBM range

Figure 13 shows the average number of times an individual AFP crosses a commodity extremis level in 180 days by mini-CLF ship configuration and the number of mini-CLF ships operating. Crossing a commodity extremis level puts a ship at a greater risk of running out of a commodity because it has less time available to resupply before it runs out. If a ship must transit a far distance for replenishment, it may run out of DFM and be dead in the water. As a result, we want this number to be as low as possible. When three or more mini-CLF ships are operating, no AFPs cross an extremis level during the 180-day period.

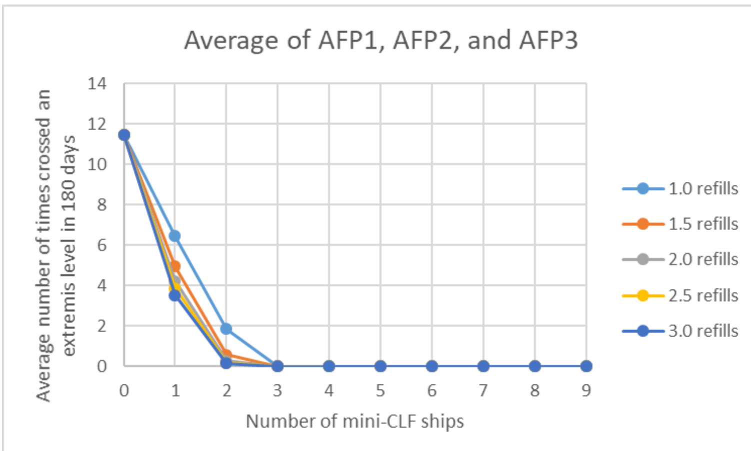

Figure 13. Average number of times one AFP crosses an extremis level in 180 days for peacetime operations and a 1,000 NM ASBM range

The total time on station for an AFP is comprised of two parts: the time it is operating above its commodity safety levels and the time it is operating below its safety levels while waiting for a mini-CLF ship to become available. Figure 14 shows the total on station time as an average of all three AFPs. It may seem surprising that the figure is flat. However, this is because when there is no mini-CLF ship available, AFPs wait on station longer for replenishment. As long as the mini-CLF ship becomes available prior to the AFP hitting an extremis level, it benefits from an increased total on station time. The total on station time can be misleading because it includes the time an AFP is operating below its safety levels. Operating while below a safety level presents an increased risk that the AFP may run out of commodities due to transit time and/or replenishment availability. Figure 15 shows the time AFPs are on station while operating below safety levels. This number peaks when zero mini-CLF ships are operating and reduces to zero once three mini-CLF ships are available. If the AFP hits an extremis level, its total on station time is reduced due to the longer cycle time of replenishing at a PV, ARL, or PNV. This observation implies that the total AFP on station time can be increased if an AFP chooses to delay replenishment with a mini-CLF ship, by reducing its safety levels, when it is known that a mini-CLF ship will be available before the AFP hits an extremis level.

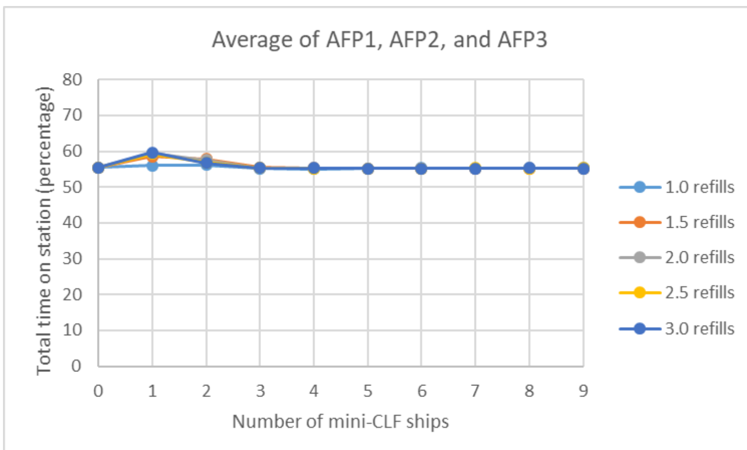

Figure 14. Average total time AFPs are on station for peacetime operations and a 1,000 NM ASBM range

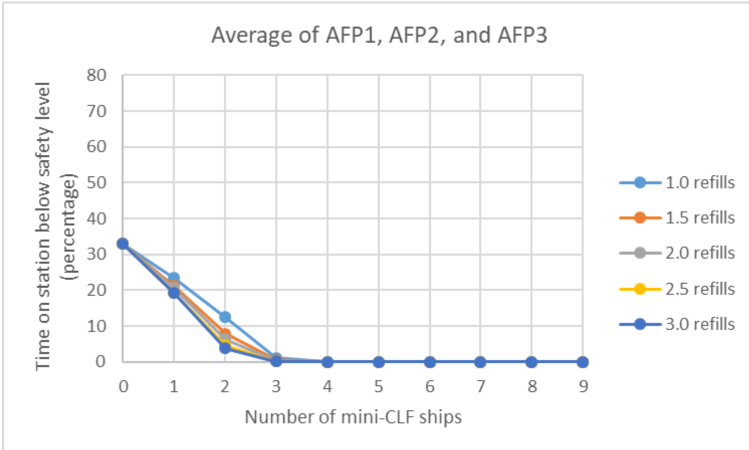

Figure 15. Average time AFPs are on station while operating below safety levels for peacetime operations and a 1,000 NM ASBM range

Based on the analysis, we recommend operating with three mini-CLF ships configured with 1.0 refill during peacetime operations with a 1,000 NM ASBM threat range and three AFPs. This is because at three mini-CLF ships, AFP performance for all five configurations are nearly the same and we prefer the configuration with the smallest physical footprint. Under this recommendation, we can consider removing CLF ships from the network as they are only utilized for replenishment an average of 1.3 times per 180 days by mini-CLF ships and zero times by AFPs.

2. Scenario Anti-Ship Ballistic Missile Threat Range of 2,000 Nautical Miles

In this scenario, we keep all of the parameters the same except the ASBM missile range is 2,000 NM, the PNV is 2,500 NM from the FOS, and the ARL is 2,000 NM from the FOS. Results are not shown because the decrease in AFP performance was minimal when compared to the 1,000 NM peacetime scenario. This is because AFPs and mini-CLF ships may require only a small number of replenishments at an ARL or PNV for ordnance due to low ordnance consumption in peacetime. The availability of PVs allow AFPs and mini-CLF ships to use PVs to replenish DFM, JP-5, and stores. As a result, the increase in transit distance only has a small effect on overall AFP performance. This scenario does not change our mini-CLF ship configuration recommendation.

3. Sensitivity Analysis

Since we recommended a mini-CLF ship configuration with at least 1.0 refill in the 1,000 NM and 2,000 NM ASBM peacetime scenarios, we use the 1.0 refill configuration as the basis for our sensitivity analysis. We begin by removing access to PVs and end with varying the number of AFPs operating.

a. Removing Access to Vulnerable Ports

We test the impact of removing all PVs from the network. For a 1,000 NM ASBM scenario, the FOS is 300 NM, 500 NM, 1,000 NM, and 1,500 NM from the FRL, PV, ARL, and PNV respectively. For a 2,000 NM ASBM scenario, the FOS is 300 NM, 500 NM, 2,000 NM, and 2,500 NM from the FRL, PV, ARL, and PNV respectively. Without the presence of PVs, AFPs and mini-CLF ships must transit farther for replenishment. AFP utilization decreases as the ASBM range and distance from the FOS to the PNV increases as shown in Figure 16. When operating with three mini-CLF ships, average AFP utilization is reduced by 4.7 percentage points under the 1,000 NM ASBM scenario and 22.9 percentage points under the 2,000 NM ASBM scenario. Without PVs, mini-CLF ships must transit farther to CLF ships at ARLs or a PNV for replenishment. This reduces mini-CLF ship availability at the FRL for AFP replenishment. When a mini-CLF ship is not available and AFPs cross an extremis level, AFPs must transit farther to CLF ships at ARLs or to a PNV for replenishment. Also, LCSs are forced to conduct inport maintenance at the PNV, which is three to five times farther than the PV.

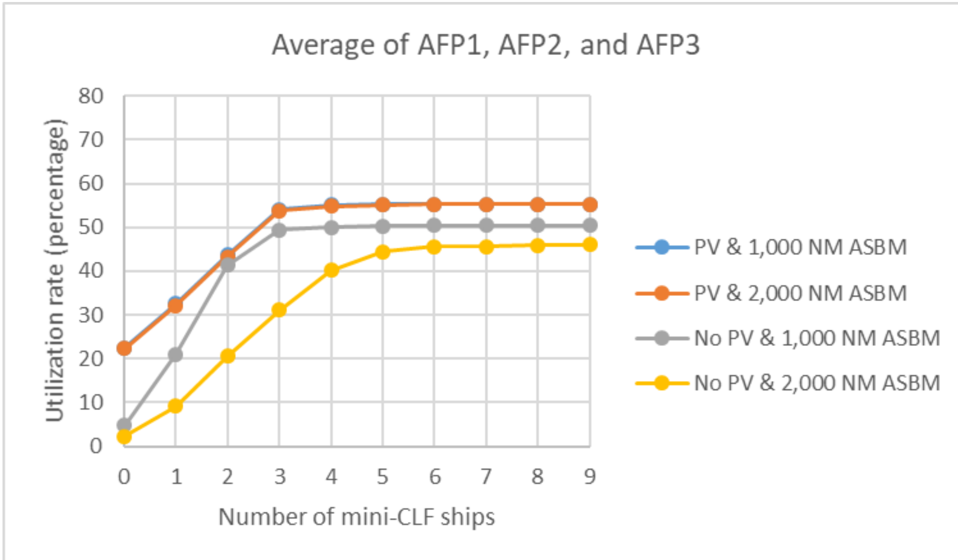

Figure 16. Average utilization rate for peacetime operations, a 1.0 refill mini-CLF ship configuration, varying ASBM ranges, and varying availability of vulnerable ports

Figure 17 shows the total number of times AFPs replenish with a CLF ship at an ARL by the number of mini-CLF ships and is further broken up by the presence of PVs and the ASBM range. Figure 18 is the same as Figure 17 except it shows the total number of mini-CLF replenishments with a CLF ship at an ARL. We observe that mini-CLF ships replenish more often with CLF ships at the ARL under 1,000 NM ASBM scenarios without PVs than 2,000 NM ASBM scenarios without PVs. This is because mini-CLF ships are spending less time transiting between the FRL and ARL, leaving more time to replenish AFPs. This leads to increased mini-CLF ship cargo consumption that requires additional replenishments with a CLF ship. We also observe that CLF ship usage by AFPs and mini-CLF ships increases significantly when no PVs are available. This observation suggests that CLF ships are a vital part of the peacetime replenishment network when PVs are not available.

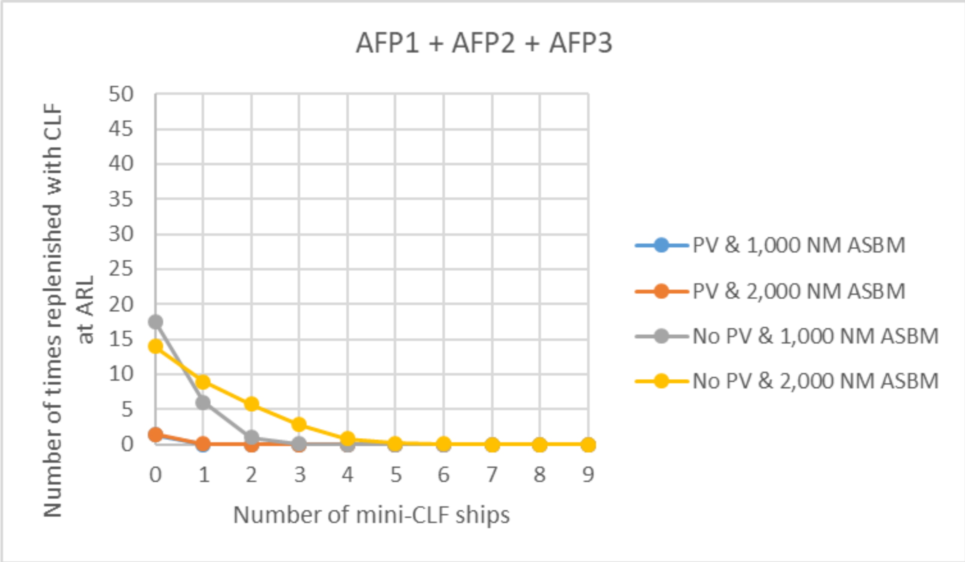

Figure 17. Average number of times all AFPs replenish with a CLF ship at an ARL in 180 days for peacetime operations, a 1.0 refill mini-CLF ship configuration, varying ASBM ranges, and varying availability of vulnerable ports

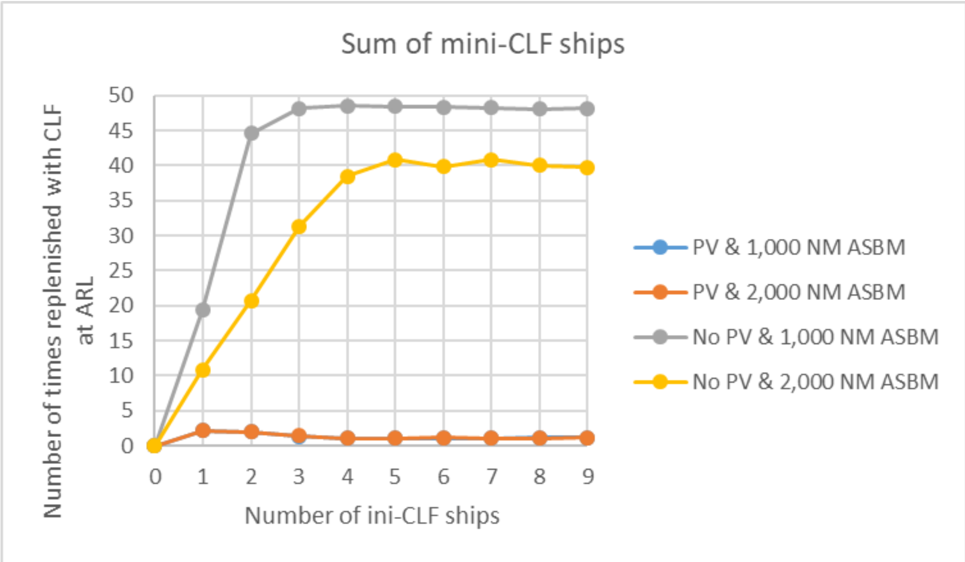

Figure 18. Average number of times all mini-CLF ships replenish with a CLF ship at an ARL in 180 days for peacetime operations, a 1.0 refill mini-CLF ship configuration, varying ASBM ranges, and varying availability of vulnerable ports

b. *Varying the Number of AFPs*

We test the impact of varying the number of AFPs between one and five with AFP compositions of either entirely AFP1 or AFP2. Figure 19 shows the average AFP utilization rate, and Figure 20 shows the average number of times one AFP crosses an extremis level in 180 days. We observe that the utilization rate increases with the addition of mini-CLF ships until a one-to-one ratio of AFPs to mini-CLF ships is present. For AFP1, the degree of improvement to the utilization rate with each additional mini-CLF ship increases. This suggests that AFP1s utilization rate is highly dependent on the number of mini-CLF ships operating. For AFP2, the improvement to the utilization rate is much more constant as mini-CLF ships are added. This is because the LCS inport maintenance requirement reduces AFP2's dependency on mini-CLF ships for the utilization rate. We also observe that a one-to-one ratio of mini-CLF ships to the number of AFPs keeps the number of times an AFP crosses an extremis level in 180 days to zero. At this ratio, AFPs are not competing with each other for mini-CLF ships and each AFP has a mini-CLF ship stationed at the FRL closest to it. As a result, we recommend operating with a one-to-one ratio of mini-CLF ships to the number of AFPs for peacetime operations.

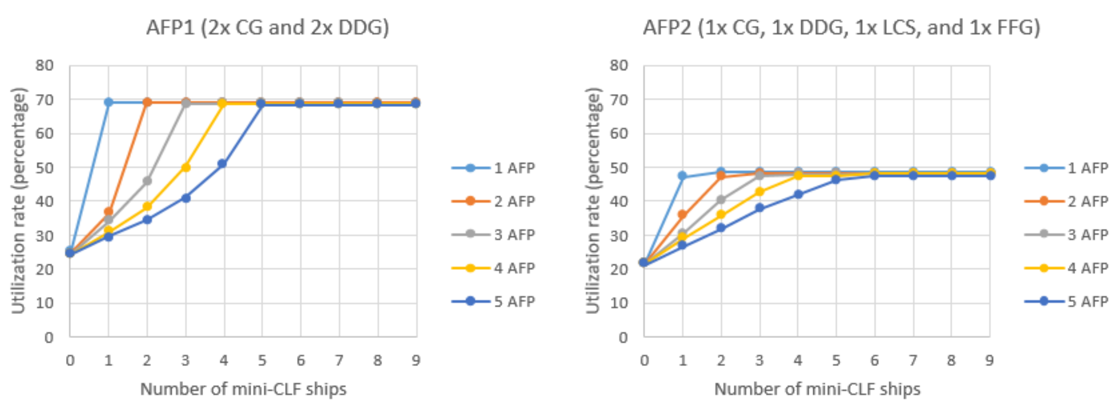

Figure 19. Average utilization rate for peacetime operations, a 1,000 NM ASBM range, a 1.0 refill mini-CLF ship configuration, and varying numbers of AFPs in the system

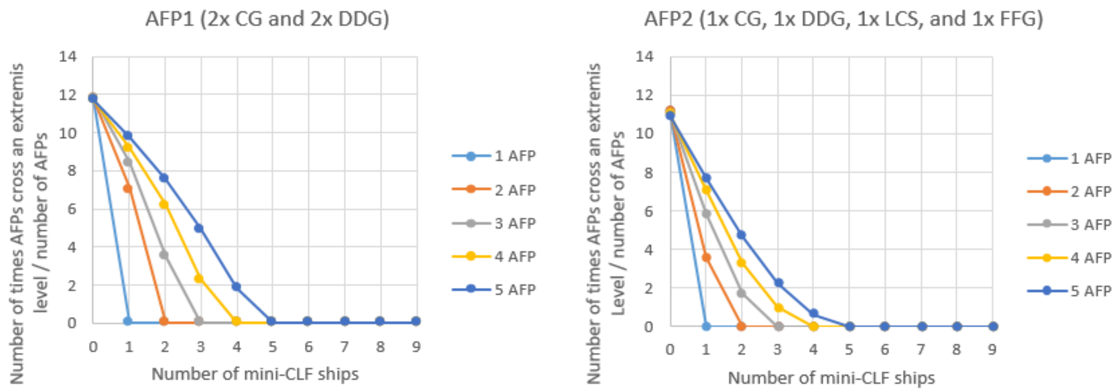

Figure 20. Average number of times one AFP cross an extremis level in 180 days for peacetime operations, a 1,000 NM ASBM range, a 1.0 refill mini-CLF ship configuration, and varying numbers of AFPs in the system

B. WARTIME OPERATIONS

We begin with the evaluation of the 1,000 NM and 2,000 NM ASBM missiles ranges for the case of three AFPs operating over the course of 60 days. We also consider attrition, which is the probability of non-survival of a vulnerable port or mini-CLF ship by the end of 60 days. We assume each day, each mini-CLF ship or port still in operation is destroyed with a certain probability, and we assume destruction is independent across each day, mini-CLF ship, and port. The one-day destruction probabilities are chosen such that the 60-day probability of non-survival is 10%, 25%, or 50%. After the selection of the best mini-CLF ship configuration for wartime, a sensitivity analysis assesses it further.

1. Scenario Anti-Ship Ballistic Missile Threat Range of 1,000 Nautical Miles

Figure 21 is broken up into three graphs to show mini-CLF ship configuration performance by the port and mini-CLF ship probability of non-survival. The utilization rate is the average of all three AFPs. The y-axis represents the AFP utilization rate, which is the percentage of time an AFP is operating on station and has not crossed a commodity safety level. The x-axis represents the number of mini-CLF ships present in the scenario. Each colored line represents a different mini-CLF ship cargo configuration in terms of how many times it can refill the largest AFP that has consumed 10% more than its safety level of commodities. The upper bound represents the highest value the utilization rate can be based on mini-CLF ships with unlimited commodities, AFPs operating with missions that maximize the time an AFP is on station and above its safety level, and no attrition of ports and mini-CLF ships. We observe that as the attrition increases, the average AFP utilization rate decreases for the same number of mini-CLF ships operating. For probabilities of non-survival less than or equal to 50%, the utilization rate levels off for all mini-CLF ship configurations when there are four mini-CLF ships operating.

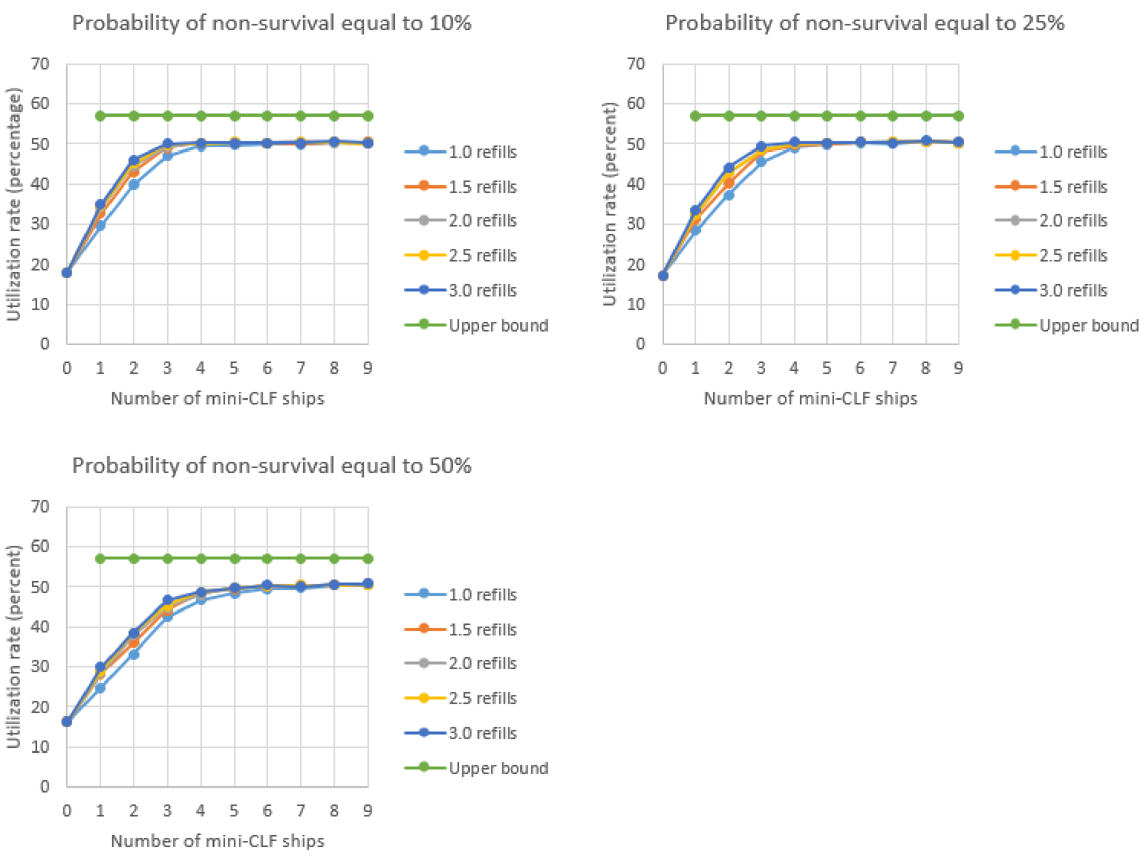

Figure 21. Average utilization rate for wartime operations, a 1,000 NM ASBM range, and varying port and mini-CLF ship probabilities of non-survival

AFP1's utilization rate is as much as 11 percentage points higher than AFP2 across the range of attrition rates as shown in Figure 22. This difference is 9 percentage points lower than the peacetime scenario due to increased ordnance consumption during wartime causing all AFPs to require VLS replenishment at a PNV. This causes a reduction in the disadvantage caused by AFP2's LCS inport maintenance because LCS maintenance is completed simultaneously with VLS replenishment.

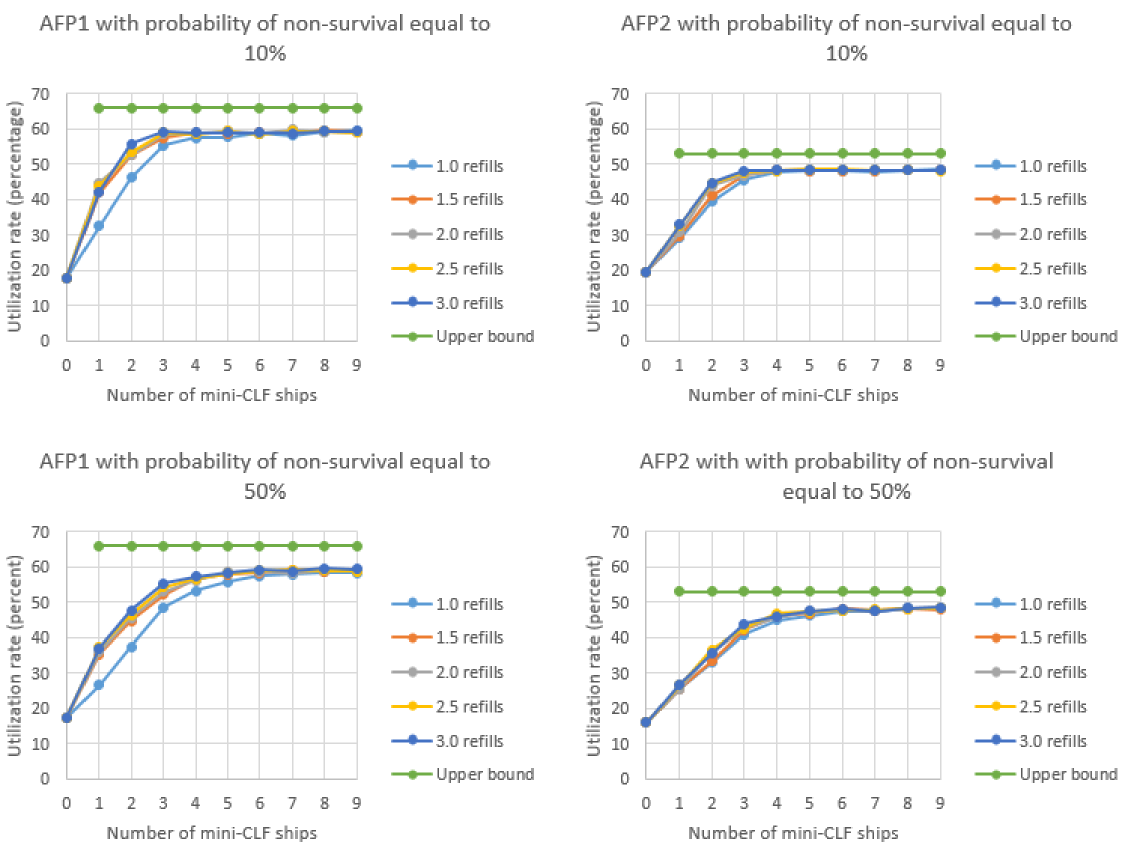

Figure 22. Average utilization rate for wartime operations, a 1,000 NM ASBM range, and varying port and mini-CLF ship probabilities of non-survival

Figure 23 is broken up into three graphs, separated by the probability of non-survival for ports and mini-CLF ships, to show the average number of times a single AFP crosses a commodity extremis level by the end of 60 days. We want to minimize this number as the extremis level puts a ship at a greater risk of running out of a commodity because it has less time available to resupply before it runs out. This risk increases for wartime because ports and mini-CLF ships may be destroyed requiring the AFP to transit to an ARL or PNV for replenishment. We observe that as the attrition rate increases, the average number of times an AFP crosses a commodity extremis level increases. This is because the availability of mini-CLF ships for replenishment decreases as the attrition rate increases. For port and mini-CLF ship probabilities of non-survival of up to 50%, operating with four mini-CLF ships keeps the number of times an AFP crosses an extremis level to an average of less than 0.23 times per 60-day period.

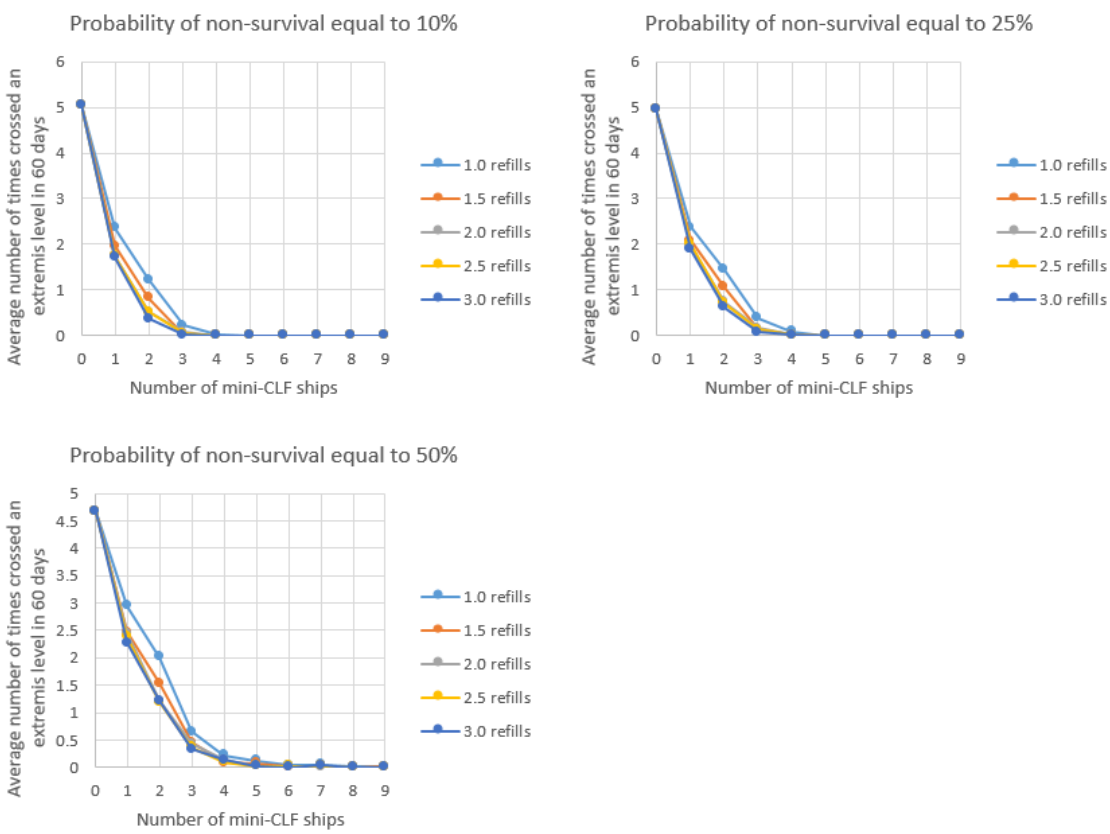

Figure 23. Average number of times an AFP crosses an extremis level in 60 days for wartime operations, a 1,000 NM ASBM range, and varying port and mini-CLF ship probabilities of non-survival

CLF ship usage increases significantly when compared to peacetime scenarios. Figure 24 shows the average total number of times CLF ships are used by either a mini-CLF ship or AFP at an ARL for replenishment. This is based on a mini-CLF ship configuration with 1.0 refill. Probabilities of non-survival of 10%, 25%, and 50% represent wartime scenarios that cover a 60-day period. The probability of non-survival of 0% represents a peacetime scenario that covers a 60-day period. We observe that CLF ship usage goes from unlikely to likely when going from peacetime to wartime scenarios across the range of probabilities of non-survival examined. This is because as ports and mini-CLF ships attrite, the next preference for replenishment is the CLF ship at an ARL for AFPs and mini-CLF ships.

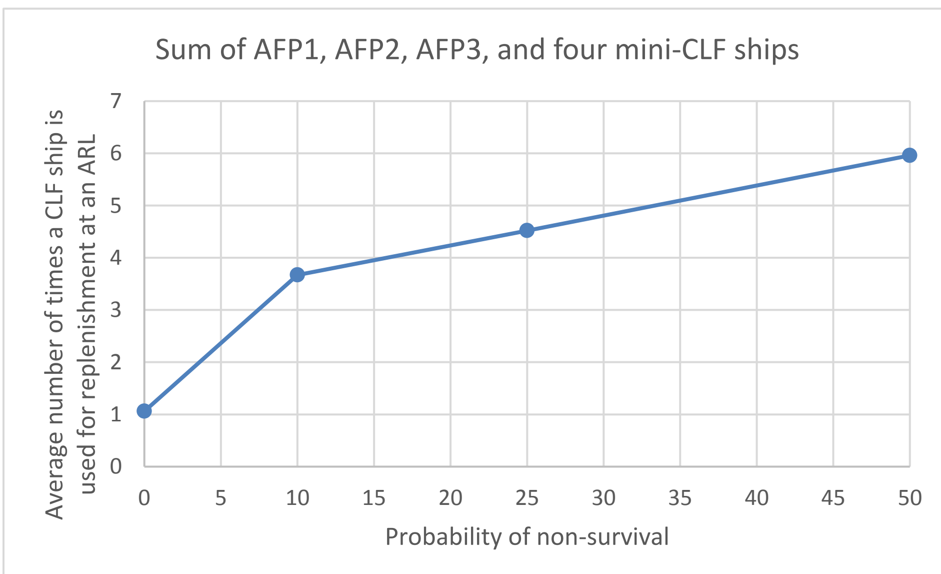

Figure 24. Average total CLF ship usage by AFPs and mini-CLF ships for wartime operations, a 1,000 NM ASBM range, and varying port and mini-CLF ship probabilities of non-survival

Based on the analysis, we recommend four mini-CLF ships to support three AFPs in wartime. This provides some resiliency against port and mini-CLF ship non-survival probabilities of up to 50%. We also recommend the 1.0 refill mini-CLF ship configuration as it occupies the smallest footprint, maintains almost the same AFP performance as the other configurations when four mini-CLF ships are operating, and is consistent with our peacetime recommendation. Consistency with our peacetime recommendation is important because we cannot quickly build new mini-CLF ships that can be available at the start of a conflict. At least one CLF ship should also be operating outside of the ASBM threat range at the ARL to provide additional replenishment support to AFPs and mini-CLF ships.

2. Scenario Anti-Ship Ballistic Missile Threat Range of 2000 Nautical Miles

In this scenario, we keep all of the parameters the same except the ASBM missile range is 2,000 NM, the ARL is 2,500 NM from the FOS, and the ARL is 2,000 NM from the FOS. Figure 25 shows the average AFP utilization rate with a 1.0 refill mini-CLF ship configuration. The colored lines represent the ASBM range and the port and mini-CLF ship probability of non-survival. We observe that the utilization rate decreases as the ASBM range increases. The difference tends to increase as the attrition increases. However, the decrease was small with the largest value of five percentage points occurring when the attrition was 50%. As a result, this scenario does not change our mini-CLF ship configuration recommendation.

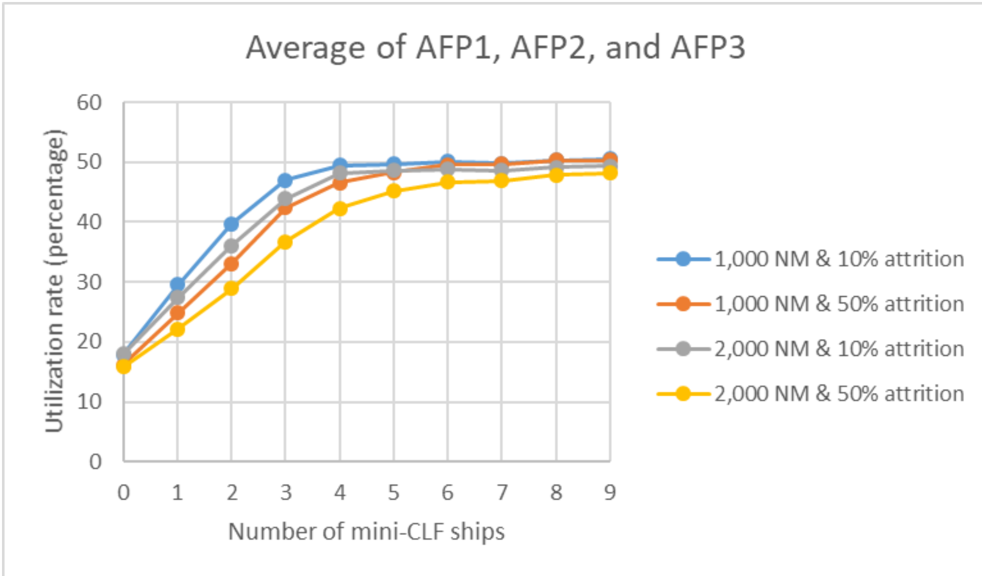

Figure 25. Average utilization rate for wartime operations, a 1.0 refill mini-CLF ship configuration, varying ASBM ranges, and varying port and mini-CLF ship probabilities of non-survival

3. Sensitivity Analysis

Since we recommended the 1.0 refill mini-CLF configuration in the 1,000 NM and 2,000 NM ASBM wartime scenarios, we use it as the basis for our sensitivity analysis. We begin by removing access to PVs and end with varying the number of AFPs operating.

a. Removing Access to Vulnerable Ports

We test the impact of removing all PVs from the network. Figure 26 shows the average AFP utilization rate, broken up by the probability of port and mini-CLF ship non-survival at the end of 60 days of 10% and 50%, by comparing scenarios with varying ASBM ranges and the availability of PVs. Figure 27 is similar to Figure 26 but shows the average number of times a single AFP crosses an extremis level at the end of 60 days. We observe that there is very little change to the AFP utilization rate and the average number of times a single AFP crosses an extremis level when removing the PVs in the 1,000 NM ASBM scenario for both levels of attrition. However, removing PVs in the 2,000 NM scenario decreases AFP utilization by as much as 16 percentage points and increases the average number of times a single AFP crosses an extremis level by as much as one when at least one mini-CLF ship is operating for both levels of attrition. This occurs because without PVs available for replenishment, mini-CLF ships will have to transit farther to a CLF ship at an ARL. This reduces the availability of the mini-CLF ship at the FRL for AFP replenishment. Also, DDGs and CGs must transit farther to the PNV for VLS replenishment and LCSs must transit farther to the PNV for inport maintenance. We also observe that the no PV scenario with a 2,000 NM ASBM range crosses an AFP commodity extremis level fewer than the other three scenarios. This is because, without PVs or mini-CLF ships available, AFPs spend much more time transiting to ARLs or PNVs for replenishment. As a result, AFPs have fewer opportunities to operate on station and cross an extremis level.

AFP use of CLF ships for replenishment tends to increase when there is no PV available until sufficient mini-CLF ships enter the network. This behavior is shown in Figure 28. We observe that AFP use of CLF ships can be mitigated by increasing the number of mini-CLF ships available. This behavior is due to AFP replenishment priorities. If a mini-CLF ship is not available for replenishment, the AFP tries to use a PV. Since PVs are not available, the AFP tries to use a CLF ship at the ARL.

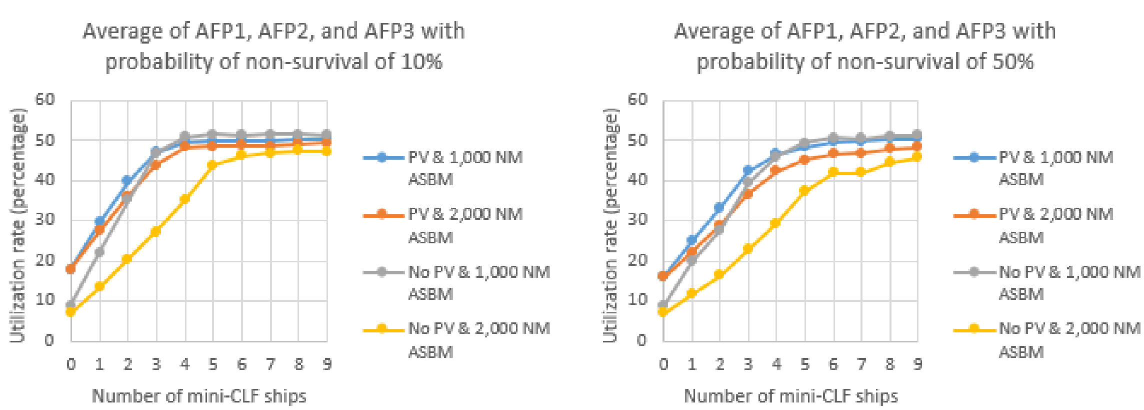

Figure 26. Average utilization rate for wartime operations, varying the ASBM range, a 1.0 refill mini-CLF ship configuration, varying availability of vulnerable ports, and varying port and mini-CLF ship attrition rates

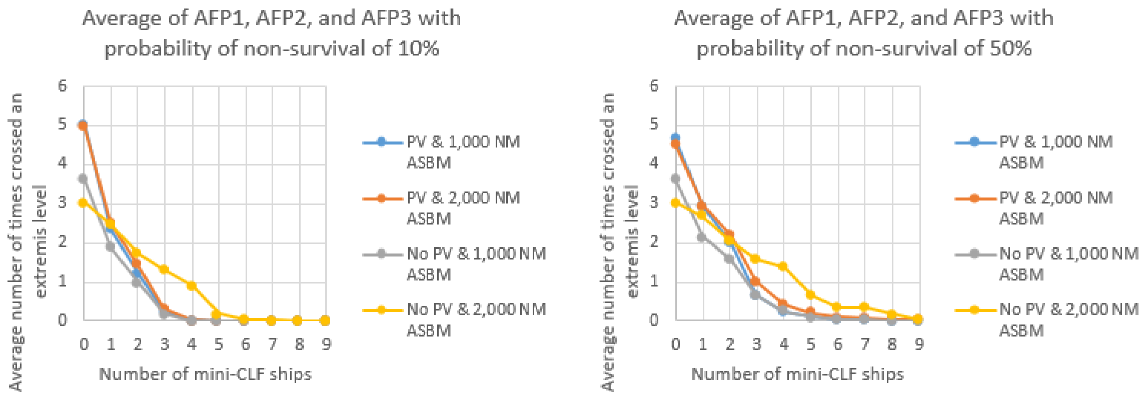

Figure 27. Average number of times a single AFP crosses an extremis level in 60 days for wartime operations, varying the ASBM range, a 1.0 refill mini-CLF ship configuration, varying availability of vulnerable ports, and varying port and mini-CLF ship attrition rates

Mini-CLF ship use of CLF ships for replenishments increases significantly when there is no PV available as shown in Figure 29. This difference does not go away as we increase the number of mini-CLF ships operating across the range of attrition values assessed. This behavior is due to the mini-CLF ship replenishment priorities. Mini-CLF ships normally prioritize using PVs for replenishment. When the PV is not available, the mini-CLF ship tries to use a CLF ship at the ARL.

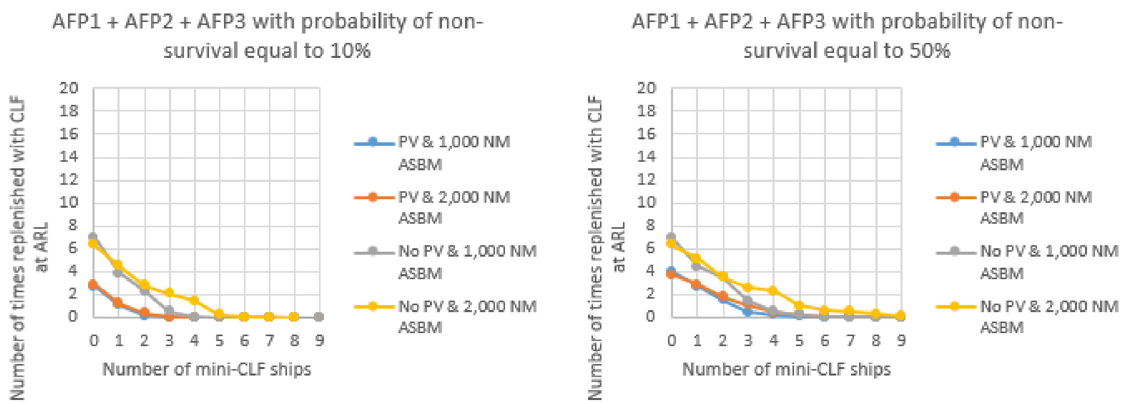

Figure 28. Average number of times all AFPs replenish with a CLF ship at an ARL in 60 days for wartime operations, varying ASBM ranges, a 1.0 refill mini-CLF ship configuration, varying availability of vulnerable ports, and varying port and mini-CLF ship attrition rates

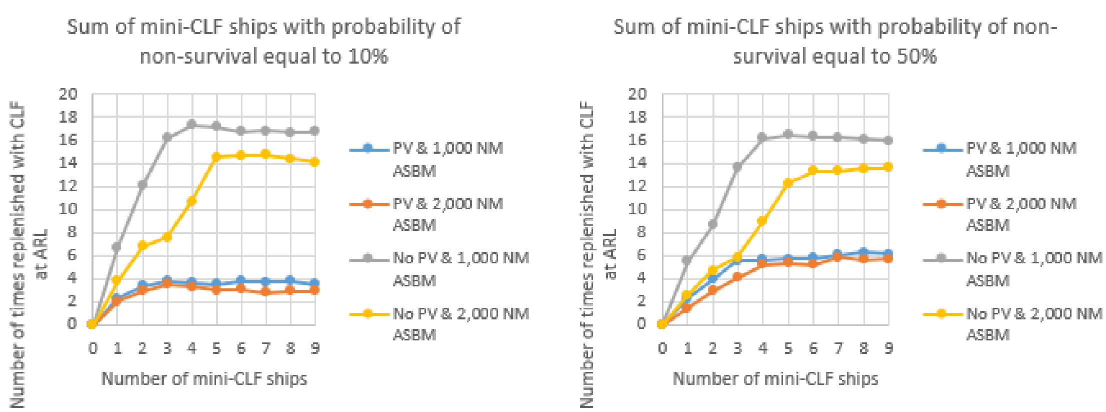

Figure 29. Average number of times all mini-CLF ships replenish with a CLF ship at an ARL in 60 days for wartime operations, varying ASBM ranges, a 1.0 refill mini-CLF ship configuration, varying availability of vulnerable ports, and varying port and mini-CLF ship attrition rates

In summary, mini-CLF ship usage of CLF ships increases significantly when PVs are removed from the network. AFP performance is almost unchanged with the removal of PVs in the 1,000 NM ASBM scenario with attrition up to 50%. However, AFP performance drops significantly when the ASBM range is increased to 2,000 NM. The AFP performance drop and the number of times AFPs use CLF ships for replenishment can be mitigated by operating with additional mini-CLF ships.

b. Varying the Number of AFPs

We test the impact of varying the number of AFPs between one and five with AFP compositions of either entirely AFP1 or AFP2 for the 1,000 NM ASBM range and port and mini-CLF ship probabilities of non-survival by the end of 60 days of 10% and 50%. Figure 30 shows the average number of times one AFP crosses an extremis level in 60 days. When the number of mini-CLF ships is one plus the number of AFPs operating, the average number of times an AFP crosses an extremis level in 60 days is less than one for up to 50% attrition. Adding more mini-CLF ships only provides a small improvement.

Figure 31 shows the average AFP utilization rates. We observe that with 10% attrition, there is only a minimal improvement to the AFP utilization rate when the number of mini-CLF ships is greater than one plus the number of AFPs operating. At 50% attrition, this same behavior can be observed for AFP2 only. AFP1 at 50% attrition, while operating with three or more AFPs, continues to benefit from increasing the amount of mini-CLF ships to up to four more than the number of AFPs operating. However, the benefit of an additional 9 percentage points in the AFP utilization rate is not worth almost doubling the number of mini-CLF ships operating.

Based on the analysis, we recommend the number of mini-CLF ships to be one plus the number of AFPs operating for wartime scenarios when the probability of port and mini-CLF ship non-survival is less than or equal to 50%. Although this policy provides some resiliency against port and mini-CLF ship attrition, high attrition will cause a reduction in AFP utilization that is difficult to alleviate. However, a degree of attrition mitigation can be achieved by having a sufficient number of CLF ships operating at the ARL for AFP and mini-CLF ship replenishment.

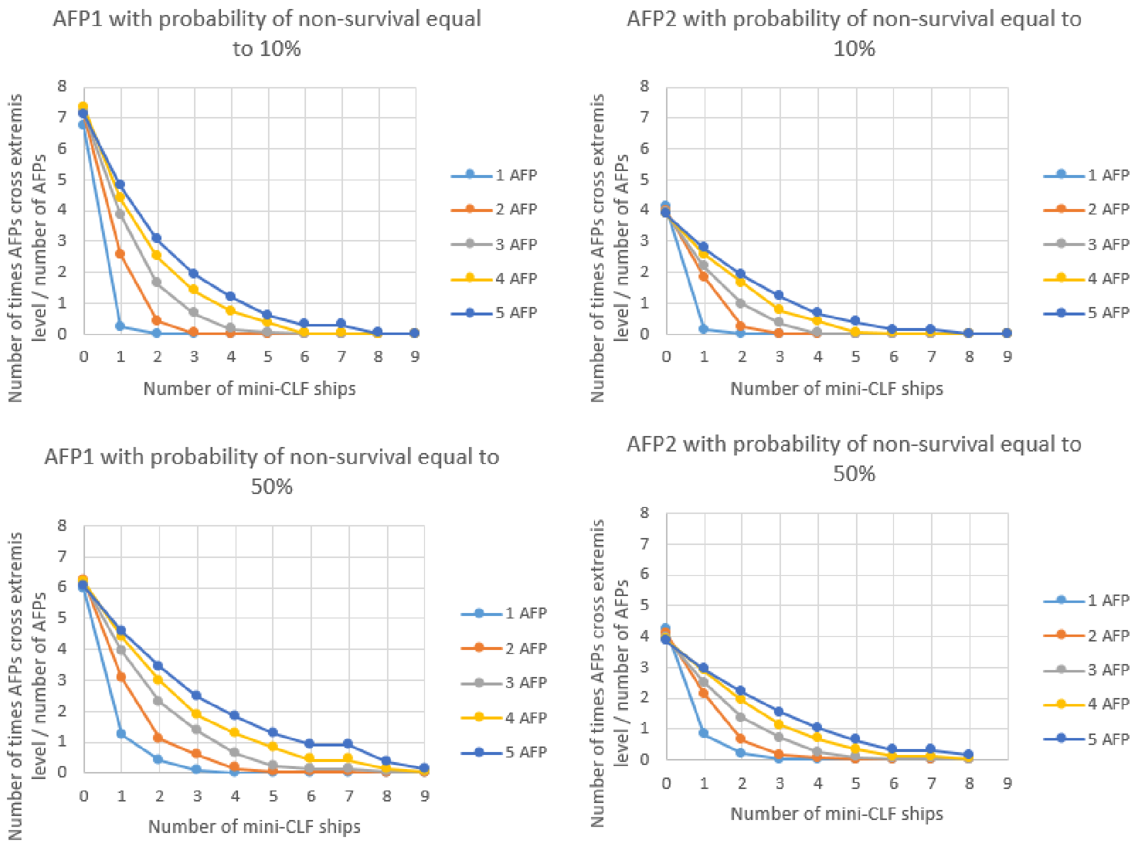

Figure 30. Number of times AFP1 and AFP2 cross an extremis level divided by the number of AFPs for wartime operations, a 1,000 NM ASBM range, a 1.0 refill mini-CLF ship configuration, varying port and mini-CLF ship attrition rates, and varying numbers of AFPs in the system

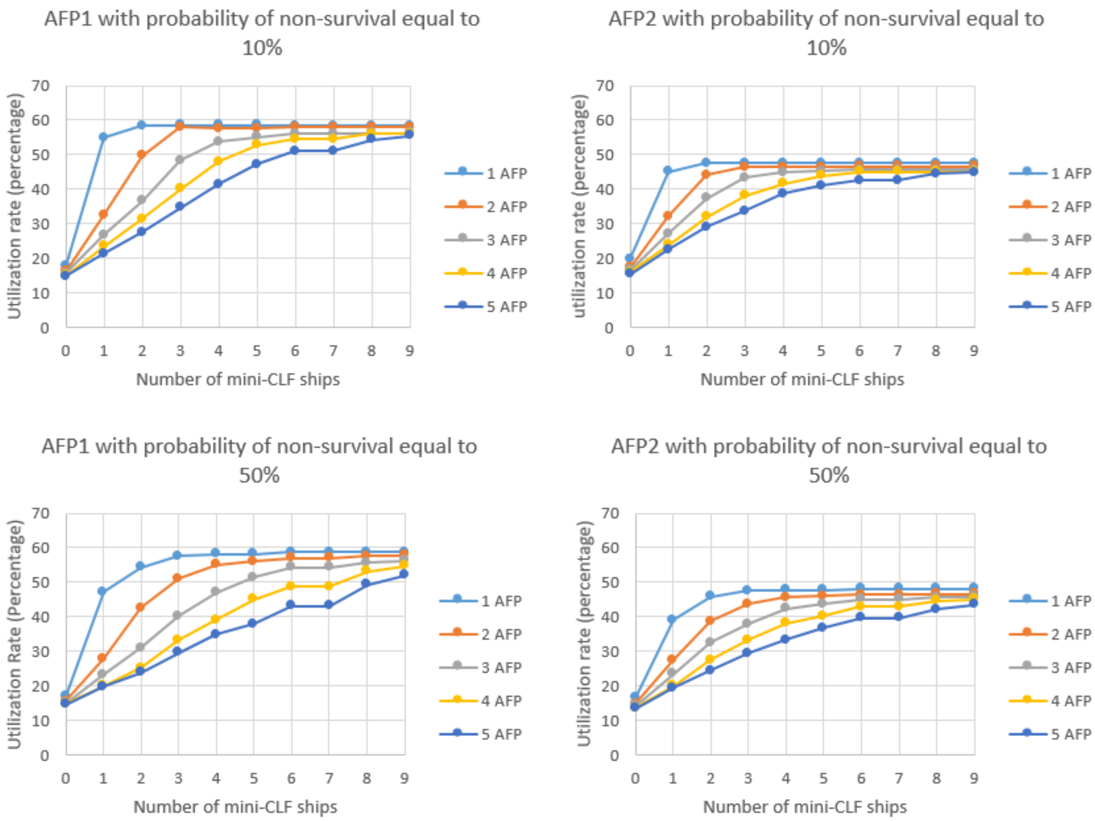

Figure 31. AFP1 and AFP2 utilization rates for wartime operations, a 1,000 NM ASBM range, a 1.0 refill mini-CLF ship configuration, varying port and mini-CLF ship attrition rates, and varying numbers of AFPs in the system

V. CONCLUSIONS, RECOMMENDATIONS AND FOLLOW-ON STUDIES

This chapter discusses our conclusions, recommendations, and follow-on studies.

A. CONCLUSIONS

Mini-CLF ships are a feasible option to support AFP SAGs operating in a DL posture and in an A2 environment due to the presence of ASBMs. The use of a simulation to model a wide range of operating scenarios provides insights and decision support on how to employ mini-CLF ships for theater-level logistics and helps inform decision makers in determining the future CLF structure.

Based on our simulation model and subsequent analysis we observe that an effective mini-CLF ship design should have a cargo capacity that facilitates replenishing the largest operating AFP SAG when it is 10% below all of its commodity safety levels. This cargo capacity, relative to a T-AOE, is 14% for liquid fuel and 12% for stores and ordnance. This allows the mini-CLF ship to operate as a smaller and harder- to-target version of a CLF ship. Its cargo capacity should be equal to the amount required to replenish the largest operating AFP SAG when it is 10% below all of its commodity safety levels.

Further insights are as follows:

- Multiple mini-CLF ships can effectively support AFPs operating during peacetime.

- An AFP with an LCS has a utilization rate that is up to 20% lower than an AFP without an LCS due to LCS inport maintenance requirements.

- An increase in the range of the ASBM reduces AFP performance. This is because mini-CLF ship availability at the FRL for AFP replenishment reduces due to an increase in the replenishment distance between the mini-CLF ship and the CLF ship. In wartime, DDGs and CGs must transit farther to a PNV for VLS replenishment.

- A removal of PVs from peacetime and wartime scenarios significantly increases CLF ship usage by mini-CLF ships and AFPs for replenishment. It also reduces AFP performance due to LCSs having to transit farther to a PNV for inport maintenance. This effect is about the same for peacetime and wartime scenarios after accounting for the difference in scenario length in days.

- A port and mini-CLF ship level of attrition that is as high as 50% at the end of 60 days has a significant impact on AFP performance. However, some of the performance loss can be mitigated by the introduction of additional CLF and mini-CLF ships.

- CLF ships are rarely utilized for replenishment by mini-CLF ships and AFPs during peacetime with the availability of PVs and a sufficient number of mini-CLF ships operating.

B. RECOMMENDATIONS

Based on our analysis of AFP SAGs in a generic operating area with varying ASBM ranges and geographic distances between the FOS and PNV during peacetime and wartime scenarios, we recommend further research into developing a mini-CLF ship to provide DL logistics support. Our preliminary recommendations regarding the size of mini-CLF ships and their number are as follows:

- A mini-CLF ship with a cargo capacity equal to 1.0 times the amount required to replenish the largest operating AFP SAG, when DFM, JP-5, stores, and ordnance reach 10% below commodity safety levels.

- A one-to-one ratio of mini-CLF ships to AFPs during peacetime scenarios with access to PVs.

- A quantity of mini-CLF ships equal to one plus the number of AFPs during wartime scenarios with access to PVs and levels of port and mini-CLF attrition of up to 50% at the end of 60 days.

- The removal of CLF ships from peacetime scenarios with access to PVs and sufficient mini-CLF ships operating.

C. FOLLOW-ON STUDIES AND IMPROVEMENTS

Recommendations for follow-on work are as follows:

1. Scenario Diversification

The geography of our model was generic and was not based on any specific operating area. To improve on the operating characteristics of the mini-CLF ship concept, we recommend theater specific AFP compositions and safety levels as well as adapting the geography of the model to specific operating areas where decision makers need logistics that support DL in A2 environments.

2. VLS At-Sea Reloading

During wartime scenarios, the need to replenish VLS weapons can take a CG or DDG off station for a significant amount of time because it has to transit to a friendly port. Integrating a notional at-sea replenishment system into the model can help determine the value of developing this capability.

3. Mini-CLF Ship Self-Defense Capability

Mini-CLF ships with a limited self-defense capability do not need to rely solely on AFP warships for defense. This may allow additional methods for the employment of the mini-CLF ship such as allowing it to transit to the AFP station or travel with an AFP as a station ship.

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