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Fuel Logistics Platform Requirements to Support Naval Surface Combatants and Expeditionary Marine Forces in INDOPACOM AOR

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Abstract

This research sets out to evaluate the existing infrastructure's adequacy and identify potential gaps, specifically focusing on bulk ship-to-shore fuel delivery, a cornerstone for the successful implementation of the Expeditionary Advanced Base Operations (EABO) concept. To achieve these objectives, our research team leveraged the modeling tool Replenishment at Sea Planner, developed at the Naval Postgraduate School. The tool underwent adaptation to simulate a diverse array of operational scenarios, estimating surface combatants' fuel demand to support EABO forces. By addressing critical gaps in the logistical framework, this study ensures the transition to the EABO paradigm is underpinned by an efficient and robust fuel supply chain. This study significantly contributes to enhancing the Navy and Marine Corps' operational readiness and effectiveness in the challenging U.S. Indo-Pacific Command theater.

Introduction

In response to evolving challenges in the Pacific theater, the U.S. Navy and U.S. Marine Corps are undergoing a strategic transformation, shifting towards the Expeditionary Advanced Base Operations (EABO) paradigm. This approach, marked by decentralization and distribution, aims to bolster operational capabilities across the expansive Indo-Pacific Command (INDOPACOM) area. Within this strategic shift lies a crucial concern: ensuring efficient logistical support for naval surface combatants and expeditionary marine forces dispersed across vast island chains. The need to effectively supply fuel and other essentials to these geographically scattered forces raises significant questions about the current state of fuel logistics capabilities.

In the modern landscape of warfare, adversaries wield extended-range weapons coupled with precision munitions, intensifying challenges faced by the U.S. military. The imperative for the Department of Defense (DoD) to organically support its forces abroad becomes even more pronounced, especially considering potential constraints on using foreign ports and contracted sources during conflicts. The 2022 National Defense Strategy (NDS) underscores the necessity for a future force capable of secure and effective logistics and sustainment, even in the face of adversary disruption—a requirement this study endeavors to fulfill (DoD, 2022). Aligned with the 2022 NDS Force Planning Construct, we address the logistical supportability of EABO concept of operations (CONOPS) within the INDOPACOM Area of Responsibility (AOR) in a contested environment.

Objectives

This study undertakes a comprehensive analysis of fuel consumption in EABO configurations and assesses the capability of EABO refueling support by the Combat

Logistics Force (CLF), utilizing Next Generation Logistics Ships (NGLS) in contested environments. The following objectives guide this research:

- **Identifying Capability Gaps**: Determine known and predicted capability gaps for bulk ship-to-shore fuel delivery in the INDOPACOM AOR, which is critical for supporting EABO operations in contested environments.
- **Impact of Single Fuel Concept**: Investigate how switching to a single fuel operating concept, specifically adopting JP-5, affects logistics needs and capabilities, including fuel availability in theater.
- **Impact of Logistics Support Ships**: Evaluate the impact of procuring different or additional logistics support assets on logistics capabilities within the INDOPACOM AOR, specifically focusing on their role in supporting EABO operations.

Approach and Significance

Our approach entails an analysis of in-theater fuel demand, considering the movement of fuel from ports to combatant forces. Through a comprehensive spectrum of demand scenarios, encompassing various operational contexts, the researchers identified existing gaps and gained insights into the challenges delivering fuel with the floating assets under consideration: the NGLS. The study models a future logistics fleet, integrating nominal vessels with diverse capabilities necessary to facilitate fuel movement and delivery to forward-deployed Navy and Marine forces.

The simulations incorporate a standardized fuel demand table for a simulated EABO mission set. The simulations yield data for a contested environment adopting JP-5 as the single fuel. A specific restriction is enforced: the CLF force remains outside the Weapon Engagement Zone (WEZ), limiting fuel delivery inside the WEZ to Medium Landing Ships (LSM) to effectively mitigate mission risks.

This report continues with a background of maritime logistics focused on fuel logistics and on the fuel delivery assets; a discussion of petroleum fuel used in the U.S. Navy, focused on JP-5 as the single fuel for all naval operations; a discussion of the simulation methodology, describing a generalizable EABO network and the characteristics of the fuel delivery assets; a consolidation of the simulations in sustained and surge scenarios, highlighting the different levels of success of each asset configuration;[1] and a summary of the results and recommendations.

Background

The current capacity of the Navy's amphibious fleet, while significant, falls short in meeting the escalating demands in the dynamic operational environment. As the nature of warfare evolves, so must our naval capabilities. By integrating logistics and emphasizing operational effectiveness, the DoD can bolster readiness for future challenges. The solution does not solely lie in heavy-hitting vessels. The Navy must also focus on lighter, more agile ships to complement its capabilities. The absence of a fleet of light amphibious warships within the Navy's portfolio hampers its operational flexibility. Vessels designed to navigate shallower waters could facilitate rapid troop and equipment movement and seamlessly integrate into the Navy's distributed force, providing strategic advantages. In essence, the Navy must expand its fleet, adapt to emerging challenges, and foster innovation to effectively operate in a broader range of

[1] These results were previously presented in the MBA thesis by Rodriguez et al. (2023).

environments. To meet these demands, the Navy must embrace a proactive approach, prepared to face the uncertainties of the future with adaptive strategies and innovative solutions.

Distributed Maritime Operations (DMO)

In 2018, former Chief of Naval Operations (CNO) Admiral John Richardson introduced Distributed Maritime Operations (DMO) in Design for Maintaining Maritime Superiority 2.0 (Design 2.0). DMO is a pivotal naval warfare strategy that involves decentralizing naval forces across vast areas. It capitalizes on the principles of distribution, integration, and maneuvering, enabling naval forces to concentrate combat power at crucial points (Filipoff, 2023). Operating at a theater level, DMO strategically positions distributed and networked assets, allowing for offensive strikes against imminent threats and fortified targets (Clark & Walton, 2019).

At its core, DMO's decentralized nature perplexes adversaries by scattering naval forces, making it challenging to discern priority targets. This approach not only enables preemptive strikes but also imposes significant operational dilemmas on adversaries (Filipoff, 2023).

DMO serves as the guiding principle for EABO, emphasizing the dispersion of forces across extensive areas to enhance resilience and diminish vulnerability. In Design 2.0, ADM Richardson highlighted the necessity of a robust refueling capability, emphasizing the importance of fuel logistics in supporting this decentralized strategy.

Expeditionary Advanced Base Operations

EABO revolutionizes naval strategy through the integration of Fleet Marine Force (FMF) and Navy capabilities to support the warfighter comprehensively (United States Marine Corps [USMC], 2023b). It encompasses skills such as sea denial, sea control, and fleet sustainment in contested environments, countering adversaries' Anti-Access/Area-Denial (A2/AD) strategies by projecting naval forces inland and disrupting their A2/AD capabilities in confined spaces.

EABOs are designed for adaptability, featuring low signature bases, mobility within enemy A2/AD environments, and support for command, control, communications, computing, cyber, intelligence, surveillance, reconnaissance, and targeting (C5ISRT) capabilities. General David Berger emphasized the synergy between anti-submarine warfare (ASW) and EABOs, sustaining or widening the joint force's advantage in ASW and holding enemy submarines at risk (Berger, 2020).

Unlike conventional expeditionary operations, EABO combines various mission capabilities in a distributed, unpredictable manner within the WEZ. As a pivotal DMO component, EABO deploys Marine Littoral Regiments (MLRs) near potential conflict zones, equipped with mobile assets to enhance sea control and denial capabilities. It emphasizes forward presence, rapid response, and power projection across vast maritime theaters. EABO's innovative approach and adaptability redefine expeditionary operations in contested environments.

Fuel Logistics

Efficient maritime logistics are integral to the success of DMO and EABO. Supporting diverse missions across distributed and expeditionary bases demands a robust logistics infrastructure, involving fuel, ammunition, spare parts, and personnel transportation for operational readiness and effectiveness.

Fuel logistics hold a pivotal position within maritime operations. Ensuring a stable and efficient fuel supply chain is essential for sustaining naval forces. This involves addressing challenges related to fuel storage, transportation, and distribution in diverse and dynamic operational environments. Optimizing fuel logistics is crucial for supporting extended missions, enhancing operational flexibility, and maximizing the Navy's combat effectiveness.

To implement the DMO and EABO concepts in alignment with the NDS, the Navy requires essential resources for refueling, rearming, and repairing naval forces, especially in contested environments. Presently, the Navy operates 31 CLF ships designed for at-sea replenishment, enabling operational reach without port reliance. However, the current hub-and-spoke model is insufficient for widely distributed and contested fleets, revealing vulnerabilities (Minding the Gap, 2021).

Amid rapid transformation and evolving security challenges, combining Navy Logistics Integration (NLI) with maritime logistics becomes pivotal. This integration aligns with the NDS, fostering innovative logistical solutions for widely distributed and contested fleets. This shift is critical, enabling the Navy to adapt, sustain operations, and fulfill its core mission effectively, even amidst evolving threats and complex operational environments.

Consolidation Operations and Lightering

Fuel consolidation (CONSOL) and lightering operations are integral components of maritime logistics, enhancing the efficiency and sustainability of naval operations. CONSOL operations play a vital role in minimizing transit time and extending operational endurance for CLF ships and combatants. Specially equipped large tankers swiftly travel to CLF vessels, allowing multiple refueling sessions before the tankers themselves require refueling. The establishment of specific refueling stations, identified by predetermined coordinates, streamlines the process, enhancing operational flexibility and enabling sustained missions in critical areas (Smith, 2015).

Similarly, lightering operations are crucial for the swift transfer of cargo or fuel between vessels, whether at anchor or while underway. These operations involve meticulous pumping and employ specialized fenders to prevent damage during the transfer process. By enabling the seamless exchange of essential supplies and resources, lightering operations ensure naval forces' readiness. The precision and coordination demonstrated in these operations are essential for maintaining operational efficiency and supporting sustained maritime missions, highlighting their significance in the broader context of maritime logistics.

Single Fuel Concept

The NLI framework unifies procurement, transportation, storage, distribution, maintenance, and disposal, creating an efficient support structure for DMO and EABO. The addition of the Single Fuel Concept (SFC) with Logistics Subsidiarity enhances EABO effectiveness. SFC's simplicity, coupled with resolving logistics issues at the local level, optimizes integration and operational efficiency, ensuring agile and resilient EABOs.

The SFC initiative, developed in response to the complexities of managing multiple fuel types, gained prominence in the late 1980s with the goal of standardizing fuels used by NATO allies. The adoption of JP-8 by the U.S. Army in 1986 and the DoD's mandate in 1989 for JP-8 standardization in land and air operations marked significant milestones in this effort. Despite challenges related to differing fuel types aboard ships and aircraft, historical evaluations highlighted the advantages of a unified fuel supply, including reduced maintenance, infrastructure savings, enhanced flexibility, and improved readiness. Recent assessments have indicated that transitioning naval vessels to JP-5 as the universal fuel for naval operations could simplify fuel logistics with minimal impact on engines, opening avenues for enhancing efficiency in the maritime domain.

The SFC simplifies logistical processes, reducing the complexity associated with managing multiple fuels and enhancing efficiency. This simplification becomes especially crucial in distributed environments such as those in DMO, where it reduces the logistical footprint, mitigates supply disruption risks, and enhances operational flexibility. Studies assessing the feasibility of transitioning shipboard units to a single fuel type, particularly JP-5, have highlighted numerous benefits, including enhanced naval capability for major contingency operations (Giannini et al., 2002; Guimond, 2007; Jimenez et al., 2020; Witt, 2022).

The convergence of DMO and the SFC represents a strategic and logistical innovation in naval warfare. By aligning the adaptable strategy of DMO with the streamlined efficiency of SFC, a resilient and robust logistical framework is created, ready to confront the challenges of EABO in the modern era. This synergy not only addresses the demands of today's maritime operational environment but also anticipates and overcomes future challenges, ensuring the Navy's readiness and effectiveness in complex and contested maritime scenarios.

Next Generation Logistics Ships

The Next Generation Logistics Ships program exemplifies the Navy's commitment to evolving maritime logistics, addressing the complexities of modern warfare (Eckstein, 2020). Comprising the Navy Light Replenishment Oiler (TAO-L) and the Navy LSM, these vessels play a pivotal role in supporting EABO and DMO, emphasizing flexibility and cost-efficiency. Rooted in Gen Berger's Force Design 2030, the NGLS initiative responds to evolving operational requirements (USMC, 2023a). The medium amphibious ships within the medium CLF family, announced in 2020, are specifically designed for contested environments, counter A2/AD strategies, and emphasize flexibility and rapid relocation (O'Rourke, 2023a).

The core components of the NGLS initiative, TAO-L and LSM, leverage commercial designs, ensuring cost-effectiveness and adaptability. They are described below.

Light Replenishment Oiler and the Platform Supply Vessel

The Light Replenishment Oiler program introduced smaller, maneuverable vessels crucial for at-sea resupply capabilities, especially in confined spaces. These vessels, designed to provide petroleum, oils, and lubricants (POL) support, are equipped with advanced technology, enabling seamless refueling operations in open seas. The TAO-L program is focused on the variant Platform Supply Vessel (PSV), which ensures access to shallower waters and tighter spaces that are vital in contested or congested maritime environments (see Figure 1). Ideally, the PSV has a sustained speed of 15 to 17 knots, a range of about 3,500 nautical miles, a fuel capacity of around 1,575,000 gallons, and a cargo capacity of 800 to 900 short tons, making it capable of delivering approximately 210,000 gallons of fuel in under 2 hours at sea. Moreover, the PSV can deliver 15 loads/hour of ammunition and cargo while refueling, making it a versatile asset within the WEZ (O'Rourke, 2023a).

Figure 1. Platform Supply Vessel (SEACOR, n.d.)

Medium Landing Ship

The LSM is designed to fill the capability gap between multipurpose amphibious warfare class ships and smaller complementary landing craft (see Figure 2). Engineered to embark, transport, land, and reembark small Marine Corps units and their supplies, the LSM possesses the range, endurance, and speed needed to support and conduct DMO and EABO effectively. It has a sustained speed of 14 knots, a travel range of greater than 3,500 nautical miles, a fuel storage capacity of greater than 90,000 gallons, and can transfer fuel at a rate of 3,000 gallons per minute. Additionally, the LSM features a deck cargo area similar in size to the PSV (8,000 to 12,000 sq ft) and includes a ramp and crane to assist in loading and unloading cargo and ammunition. The vessel can conduct up to 11 days of missions without replenishment, ensuring adaptability and agility in the face of emerging threats (O'Rourke, 2023b).

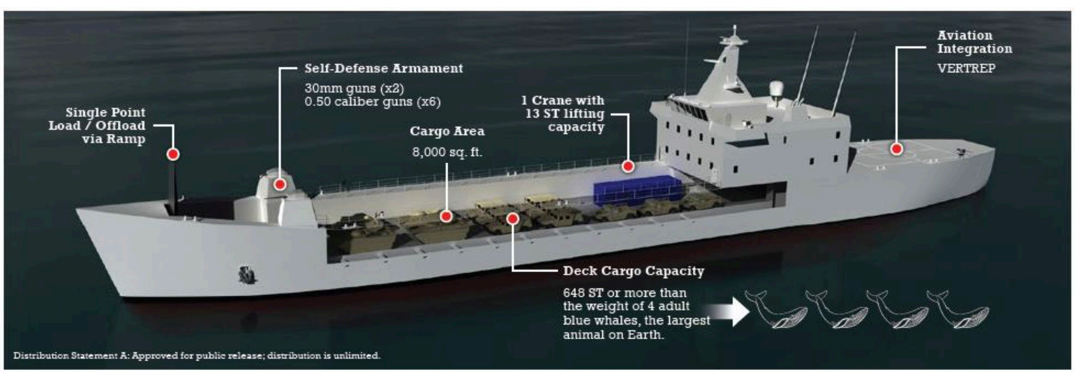

Figure 2. Medium Landing Ship (O'Rourke, 2023b)

Liberty Lifter

Liberty Lifter (LL), an innovative strategic lift concept developed by the Defense Advanced Research Project Agency (DARPA), is a cutting-edge 21st-century aircraft (see Figure 3). It is a long-range, low-cost seaplane capable of performing strategic and tactical lifts (Kent, 2023). The aircraft's key attributes include the ability to perform fast, flexible, and survivable strategic lifts. Primarily designed for EABO, the LL provides a notional range and speed that enable more flexible movement. It is anticipated to enhance DMO by rapidly moving forces with reduced refueling requirements. Additionally, its ability to swiftly reconfigure for various missions and tasks enhances its utility, making it more survivable by minimizing time spent at fixed, targetable locations (Kent, 2023).

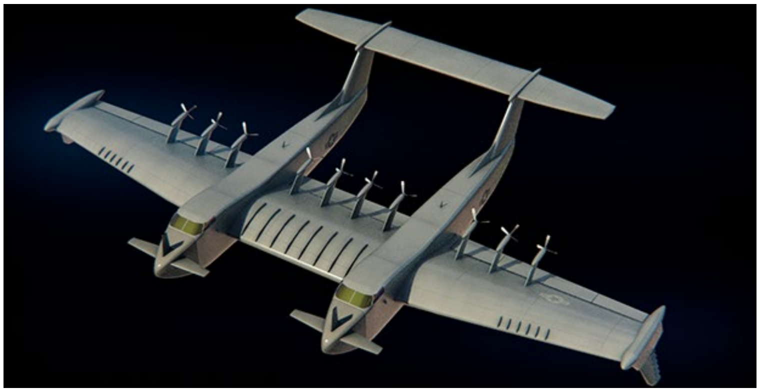

Figure 3. Liberty Lifter Concept Design (Kent, 2023)

The LL program is currently in its initial phase of development, as part of an 18-month collaboration between DARPA and two prime contractors. The primary goals include perfecting the conceptual design, maturing the overall design, and conducting component and subscale testing. The LL team is projected to transition to Phase 2 in mid-2024 and Phase 3 in 2026, with the goal of transitioning to the manufacturing and sustainment phase by the end of 2028.

Once operational, the LL is expected to achieve a sustained speed ranging from 145 to 180 knots, with the range of approximately 8,000 nautical miles (Kent, 2023). The aircraft's estimated carrying capacity is 180,000 lb over 1,440 sq ft, allowing it to accommodate 12 463L air cargo pallets. This translates to the capability of transporting up to 20 U.S. Marine Corps (USMC) *SIXCON* fuel storage tanks, 900 gallons each, providing a total capacity of 18,000 gallons of fuel per load (weighing about 125,000 lb, which is less than the aircraft's carrying capacity). Alternatively, the LL could carry 300 passengers or two USMC Amphibious Combat Vehicles along with their 32 crew members (Kent, 2023).

Highlighting its versatility, the LL concept is intended to take off and land in a sea state of 4, with the capability to conduct on-water operations in sea states up to 5. This unique feature positions the LL as a viable alternative for strategic logistics, enabling effective support for EABO. A preliminary design concept is illustrated in Figure 4, providing a glimpse into the aircraft's potential form and functionality.

In the context of EABO, MLRs reinforce the U.S. Navy's sea-control and sea-denial capabilities in the Western Pacific. These units, deployed in forward locations, enhance fleet and Force Movement Control Center operations, diversifying the Navy's lethal capabilities. Each vessel, PSV and LSM, possesses unique capabilities and limitations, forming the basis for fuel constraints in simulations. Integrating the LL as a fuel delivery asset adds valuable flexibility for planning fuel transfers and operational deployments in contested environments.

Petroleum Fuel in the U.S. Navy

In this section, we discuss the petroleum fuel types used by the U.S. Navy and the concerns that have been raised regarding the adoption of JP-5 as the single fuel for all naval operations.

Types of Fuel Used by the U.S. Navy

The U.S. Navy primarily utilizes three fuel types for its various applications: F-76 (Naval Fuel Distillate or NATO code F-76), JP-5 (Aviation Turbine Fuel JP-5 or NATO code F-44), and JP-8 (Aviation Turbine Fuel JP-8 or NATO code F-34). They are described below.

F-76

- **Characteristics:** F-76 is a military-grade diesel fuel derived from crude oil, natural gas liquid concentrates, heavy oil, shale oil, and oil sands. It has a high flashpoint of 60°C (140°F), which represents low risk of spontaneous combustion. It contains additives to deactivate metals and to provide lubricity, which is important for engine operations.
- **Advantages:** F-76 is cost-effective, is readily available globally, and is used in conventional U.S. Navy surface ships.
- **Disadvantages:** It may promote microbial growth in fuel tanks, leading to clogged filters. Strict maintenance and surveillance are required. F-76 has a cloud point no higher than -12.22°C (10°F) to prevent equipment damage in cold environments.

JP-5

- **Characteristics:** JP-5 is the standard fuel for all U.S. Navy aircraft. It has a high flashpoint of 60°C (140°F). It contains additives to prevent gum or peroxide formation, inhibit corrosion and icing, dissipate static, and improve lubricity.
- **Advantages:** It is safe for shipboard use, and it has similar performance to JP-8. It can be used in many naval vessel engine fuels.
- **Disadvantages:** Some loss of fuel efficiency compared to JP-8.

JP-8

- **Characteristics:** JP-8 is widely used in the DoD and in military aviation engines. It is similar to commercial aviation's Jet A-1 fuel but with specific additives suitable for military use.
- **Advantages:** It is a low-cost fuel, available worldwide, with minimal differences from Jet A-1, which ensures a stable supply chain and reduced costs for extended fuel logistics support.
- **Disadvantages:** Its low flashpoint of 38°C (100°F) makes it unsafe for shipboard use due to the increased risk of spontaneous combustion.

Naval aircraft are compatible with JP-8, the jet fuel used by the U.S. Air Force and U.S. Army. However, its low flash point makes it unsafe to store in naval vessels. For this reason, our focus is on JP-5. Table 1 compares F-76 and JP-5. All values were sourced from Tosh et al. (1992), except density data, which were derived as the ratio of the respective energy contents.

Table 1. Energy and Density Properties of JP-5 and F-76 (Tosh et al., 1992)

Property	F-76	JP-5	Difference
Specific Gravity	0.844	0.819	-3.0%
Density*	7.005 lb/gal	6.862 lb/gal	-2.0%
Energy content by weight	18,456 BTU/lb	18,356 BTU/lb	-0.54%
Energy content by volume	129,291 BTU/gal	125,965 BTU/gal	-2.6%

It is important to remember that all petroleum fuels have small variations depending on the source of the raw material (petroleum) and on the refinery that produced them. These variations do not impact utilization as long as key parameters stay within acceptable limits established by the respective MIL standards.

Concerns with the Adoption of JP-5 as the Single Fuel

The ongoing debate surrounding the conversion to single-fuel operations in the U.S. Navy has been shaped by eight significant concerns related to the potential adoption of JP-5 as the exclusive fuel. These concerns, ranging from technical challenges to financial implications and geopolitical considerations, contribute to the complexity of the ongoing dialogue surrounding the potential conversion to JP-5 as the single fuel for U.S. Navy operations (Garrett, 1993).

The literature provides extensive analysis addressing several concerns related to the adoption of JP-5 as the exclusive fuel for the U.S. Navy (Giannini et al., 2002; Guimond, 2007; Jimenez et al., 2020). Here is a summary of the findings from the literature:

1) **Physical–Chemical Properties of JP-5**: JP-5's lower lubricity, volumetric energy content, cetane number, and viscosity compared to F-76 have raised concerns about accelerated wear in engines, increased fuel consumption, cold-start problems, power loss, and internal leakage in fuel systems (Giannini et al., 2002; Guimond, 2007). All physical–chemical concerns raised with JP-5 have been studied, as follows:

- **Impact of lower lubricity**: No documented failures of fuel injectors and pumps have been recorded. Studies indicate that if lubricity-related problems should occur, they would be minor and manageable (Guimond, 2007).
- **Impact of lower volumetric energy content:** Theoretical predictions of increased JP-5 consumption do not align with practical experience, and there is no evidence of reduced range or increased consumption when JP-5 is used as bunker fuel. Guimond (2007) recommended a rigorous field test to assess if there is any measurable difference.
- **Impact of lower cetane number:** No reduced acceleration or maximum power issues have been identified in Navy diesel engines when operated on JP-5. However, Guimond (2007) recommended that a minimum cetane level should be required of JP-5 if it were used as a single fuel.
- **Impact of lower viscosity:** While hot starting problems were observed in certain diesel engines due to low viscosity, robust designs were not affected. Other studies found no negative performance consequences in naval diesel engines.

2) **Shipboard Piping Union Alloys Interaction**: Prolonged exposure of JP-5 to cupronickel alloys, present in the fuel lines, could lead to thermal stability issues and potential failure, with no known mitigation systems in place. However, the source of copper does not affect JP-5 thermal stability significantly. The combined effect of storage in the presence of copper is crucial, regardless of the type of soluble copper or storage conditions (Putnam, 2018).

3) **Impact on Combatant Ship Design**: Transitioning to JP-5, which has lower density (specific gravity) than F-76, may negatively affect the buoyancy and centers of gravity of naval combatant ships. One mitigation strategy suggested is altering engineering manuals to allow ships to carry more ballast water in propulsion fuel tanks to counterbalance the decreased weight of JP-5. However, current U.S. Navy policy prohibits water-ballasting of JP-5 fuel tanks. On the other hand, the difference between the JP-5 and F-76 density is approximately 2%, as shown in Table 1. That would mean a very small fraction of the weight of any weapon system, so it is unlikely that this concern is significant.

4) **Cost Considerations**: This concern has several facets, such as JP-5's perceived higher cost per gallon, increased fuel consumption due to lower energy content, potential rise in contract prices driven by higher demand, and erosion of purchasing power amid military downsizings. Any combination of these challenges could make conversion financially prohibitive. However, the price differential between JP-5 and F-76 has inverted, with JP-5 being less expensive in recent years. The lower energy content, shown in Table 1, does not translate into consumption that is higher than typical variability (Giannini et al., 2002). The most significant cost consideration remains the conversion cost, which can be associated with the time to convert the fleet using existing maintenance schedules (Zheng & Ventura, 2022).

5) **Regional JP-5 Shortages**: The shift to JP-5 may lead to regionalized shortages, considering historical difficulties in meeting peacetime aviation requirements and fewer ports supplying JP-5 compared to F-76. However, studies indicate a sufficient JP-5 fuel supply base available for conversion (Giannini et al., 2002). The adoption of a phased rollout plan could address potential shortages by giving time for the supply chain to adapt to the increased demand.

6) **Refinery Hesitancy**: Refineries have been reluctant to expand JP-5 production due to the short term of the supply contracts and to the uncertainty that they will be renewed in the following year, which hinders their efforts to invest in increased supply. Mitigation strategies could include implementing multiyear or guaranteed renewal contracts with JP-5 refineries to establish longer-term commitments. In addition, as JP-5 gets adopted by an increasing number of floating assets (in addition to aircraft), many refineries will find it an attractive commodity to produce.

7) **Fuel Line and Storage Tank Modifications**: Finalizing fuel consolidation requires cleaning and reconfiguring fuel lines and storage tanks to prevent contamination with residual F-76, ensuring that stored JP-5 meet the stringent requirement for use in aviation. Recent studies have provided estimates for reconfiguring U.S. Navy amphibious assault vessels and DFSP indicating costs and time frames associated with cleaning and repairing F-76 pipelines and fuel tanks (Zheng & Ventura 2022).

8) **Lack of Significant Operational Benefits**: Some opponents of JP-5 have stated that single fuel would offer minimal operational advantages, with claims that significant benefits may not be realized. In addition, Tosh et al. (1992) stated,

> The lower energy density of JP-5 translates directly into a 2.6-percent reduction in range, but also means an increase in the amount of fuel purchased. Since combustion efficiency in all systems is generally close to 100 percent at all but idle conditions, little opportunity exists for improvements in specific fuel consumption to offset the lower heating value of JP-5. In most engines, the fuel controls can be adjusted to regain maximum power, but a larger volume of fuel will still be required. Burning fuels with lower cetane numbers will result in small increases in thermal efficiency in some diesel engines, but generally not enough to offset the lower heating value. Therefore, should a conversion be made to JP-5, potentially an additional 2.6-percent fuel quantity would be needed to support the Navy requirements.

Recent studies have shown the opposite: despite reduced energy content, conversion to JP-5 would result in increased maritime refueling service capacity, improved endurance, and greater operational range for battle groups due to the supply chain phenomenon known as "pooling effect." It would also reduce the number of tankers and CLF ships needed to sustain major combat operations, leading to substantial logistical benefits. In an analysis of fleet support in the INDOPACOM AOR, Jimenez et al. (2020) stated,

> When compared to the dual fuel CONOPS the Navy currently operates under, fewer fleet oilers and tankers would be required to provide the same level of service and logistics refueling capability during high-intensity operations, and task force endurance would be increased.

In addition, in an analysis of fuel consumption during a displacement in the EUCOM AOR, Witt (2022) concluded,

> Our analysis showed a consistent reduction in the required number of RASs and CLF trips to port at all JP-5 energy efficiencies in the scenarios evaluated. The added flexibility gained from fewer RASs and CLF trips to port allows for groups of ships to remain at operations and on standby for longer periods of time. Among the benefits of fewer RASs and CLF trips to port is a cost savings to the Navy; water, sewage and power costs are incurred whenever a ship goes to port. These reduced periods in port could help offset the minor cost increase in utilizing JP-5 instead of F-76 to power the ships.

In summary, most concerns associated with JP-5 adoption as the single fuel have been extensively evaluated in previous studies. An important exception is conversion costs, partially addressed by Zheng and Ventura (2022), which still deserves further analysis.

Potential Impact on Intra- and Inter-Governmental Relations

Extensive research was conducted to understand JP-5 adoption as the single fuel, emphasizing potential benefits and strategies to mitigate challenges. There is one more concern that has not been discussed: the impact on governmental relations remains an unexplored aspect of the ongoing dialogue. This impact would likely be multifaceted, influencing various stakeholders and international relationships in different ways. While specific studies on this topic are lacking, we can estimate potential implications based on existing knowledge and general trends. Here are some possible effects:

Intra-Governmental Relations:

- **Enhanced Collaboration**: A unified fuel policy can lead to better collaboration and synchronization among different government agencies and departments. Consistency in defense strategies and joint military operations can be achieved, fostering more effective coordination.
- **Financial Implications**: The transition to JP-5 could impact budget allocations within the DoD. Adjustments might be necessary to accommodate the costs associated with the transition and the ongoing operations. Proper financial planning and resource allocation would be crucial.

Inter-Governmental Relations:

- **Strengthened Alliances**: If JP-5 aligns with the preferences of U.S. allies, especially within NATO, it could strengthen military alliances. Common fuel standards would simplify joint military exercises, operations, and logistics, enhancing interoperability among allied forces.
- **Shift in Trade Dynamics**: The shift in demand for JP-5 could influence international trade in fuel products. Countries exporting JP-5 might experience increased trade opportunities, while those exporting F-76 could face decreased demand. This change might lead to economic shifts and trade challenges.
- **Impact on Suppliers**: Nations heavily reliant on exporting military-grade fuels, such as F-76, might be economically affected. This could potentially lead to diplomatic challenges and changes in trade dynamics. Geopolitical relationships could be influenced by these economic shifts.
- **Streamlined Military Operations**: A unified fuel standard would streamline military operations during international crises or peacekeeping missions. This consistency could enhance the effectiveness of multinational military efforts, ensuring a smoother collaboration among allied forces.
- **Reduced Dependence**: Standardizing military fuels and diversifying sources, including JP-5, could enhance U.S. energy security. Reducing dependence on specific regions or nations for fuel supply can increase resilience and stability in military operations.

The actual impact of the switch to JP-5 would be complex and contingent on numerous factors. Considerations such as geopolitical context, economic dynamics, technological advancements, and policy agreements would play crucial roles. Detailed studies on intergovernmental relations would be essential to comprehensively assess and navigate the implications of such a significant policy change. However, it is well understood, based on past studies, that significant logistical benefits would be derived from the conversion to JP-5, with minimal impact on ship maintenance and resilience.

Methodology: Modeling, and Simulation

Understanding the complexities of transitioning the U.S. Navy's fuel standardization to JP-5, especially in the contested Western Pacific region within the INDOPACOM AOR, requires a comprehensive analysis involving computer modeling, simulation, and experimentation. This section outlines the systematic approach taken to unravel the interplay of logistical requirements, surface asset configurations, and operational scenarios. Replenishment at Sea Planner (RASP) was employed, alongside theoretical scenarios, to provide insights into the supportability of a distributed MLR operating in contested environments.

Replenishment At Sea Planner Model

RASP is a crucial tool for optimizing the Navy's logistics capabilities by focusing on crafting schedules that minimize travel distances for supply ships during at-sea replenishments. Brown et al. (2013) underscored the significance of planning optimal maritime routes, enabling replenishment while the fleet is in motion, thereby accelerating deployment and generating substantial annual savings.

The evolving landscape of naval warfare, characterized by distributed operations, expeditionary bases, and innovative logistics concepts, demands a meticulous understanding of fuel logistics and supply chains. RASP provides opportunities to optimize naval logistics operations, ensuring a seamless and sustainable fuel supply chain to support the Navy and Marine Corps' missions in contested environments (Stewart, 2013).

Utilizing a transportation linear programming model, RASP generates foundational data that, when integrated with its analytical capabilities, enhance the research process, offering a holistic perspective on naval logistics. RASP addresses the critical question of optimizing refueling schedules, aligning the logistic fleet with established demands from the linear programming model.

RASP's core design focuses on refining the planning and scheduling of replenishment operations at sea, aiming to minimize disruptions to naval operations. In evaluating the optimal combination of LSM and PSV vessels supporting the MLR within the contested WEZ, RASP's linear optimization capabilities were employed to explore various scenarios and initial conditions, emphasizing different levels of surface asset support with a focus on LSMs and PSVs. RASP's schedule optimization played a pivotal role in identifying effective combinations of these assets, shedding light on how adjustments influenced the MLR's operational capabilities.

Fuel Consolidation Stations and Delivery Assets

This study employs advanced features to systematically address the complexities of at-sea replenishment, with a specific focus on enhancing naval operational effectiveness with a generalizable Expeditionary Advanced Base (EAB) configuration. We setup a hypothetical EAB Company+ and four EAB Platoons in the AOR. Company+ features a limited-capacity Forward Arming and Refueling Point (FARP), supporting rotary wing aircraft refueling. The Third Marine Logistics Regiment (3d MLR) spearheads EABO in the second and first INDOPACOM island chains, employing a strategic logistics framework of hubs, spokes, and nodes to extend the range and precision of warfighters, shown in Figure 4.

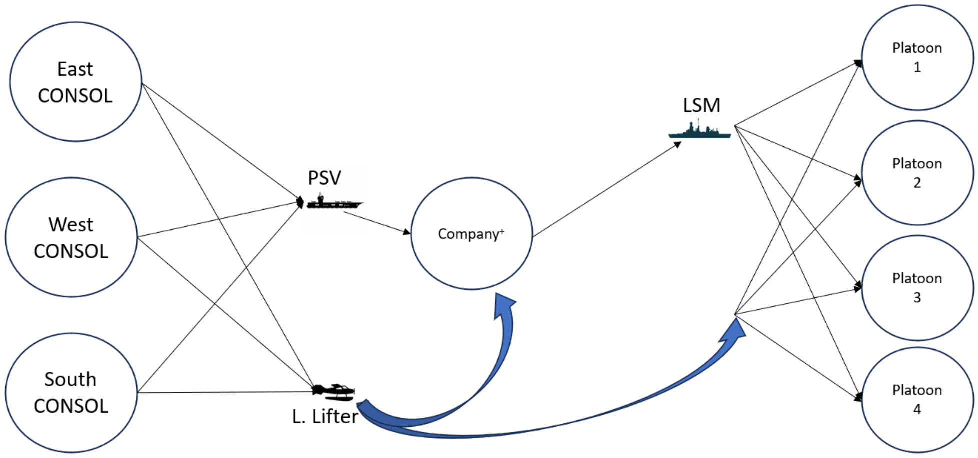

Figure 4. EABO Fuel Distribution Network (Rodriguez et al., 2023)

The simulation assumes that all delivery assets, crucial components in this scenario, exclusively utilize JP-5 as the single fuel. The core hub, functioning as the tactical and logistics command center, is fortified under a theater ballistic missile defense shield. The secondary hub, represented by the EAB Company+, operates at airfields and demands refined logistics. Meanwhile, the nodes, embodied by EAB Platoons, serve as adaptable pit stops in austere terrains, facilitating swift refueling and rearming for the aircraft fleet.

The focal point of this scenario is on refueling support for the Company+ and designated EAB Platoons. In this context, three hypothetical CONSOL stations—CONSOL East, CONSOL South, and CONSOL West—are strategically positioned outside the WEZ, aligned with the Company+ location. These CONSOL stations are instrumental in providing JP-5 support for all EABOs within the contested AOR. The effective reach of delivery assets to their intended destinations is directly influenced by the distances between these CONSOL stations, details of which are outlined in Table 2.

Table 2. Distance Between Locations in the Simulated EABO Network (Rodriguez et al., 2023)

	W CONSOL	S CONSOL	E CONSOL	EAB CO+	EAB PL 1	EAB PL 2	EAB PL 3	EAB PL 4
W CONSOL	0	2440	3978	1596	2161	2091	1477	1276
S CONSOL	2440	0	2713	2022	1868	1329	1277	2031
E CONSOL	3978	2713	0	2708	2280	2011	2545	3271
EAB Co +	1596	2020	2780	0	665.1	733.6	978	658.2
EAB PL 1	2161	1868	2280	665.1	0	579.4	989.3	1206
EAB PL 2	2091	1329	2011	733.6	579.4	0	658.4	1297
EAB PL 3	1477	1277	2545	978	989.3	658.4	0	1017
EAB PL 4	1276	2013	3271	658.2	1206	1297	1017	0

Fuel Demand, Delivery Assets and Storage Capacity

RASP is a crucial tool for optimizing the Navy's logistics capabilities by focusing on crafting schedules that minimize travel distances for supply ships during at-sea replenishments. Brown et al. (2013) underscored the significance of planning optimal maritime routes, enabling replenishment while the fleet is in motion, thereby accelerating deployment and generating substantial annual savings.

Fuel demand analysis relies on a Mechanized Allowance List (MAL) tailored for Company+ and the EAB Platoons. The assessment considers EAB fuel demand, incorporating equipment-specific fuel consumption, operating hours, and equipment quantity, at an 80% readiness level. Aircraft fuel demand is determined based on fuel consumption, daily flight hours, and aircraft availability at a 70% readiness level. EAB Platoons primarily support organic ground equipment refueling, maintaining minimum fuel for EABO agile base relocation. The assessment considers two burn rate levels, sustained and surge, with detailed daily fuel demand and capacity in Table 3.

Table 3. Consumption and Demand in the Simulated EABO Network (Rodriguez et al., 2023)

	Sustained Operation (gal/day)	Surge Operation (gal/day)	Capacity (gallons)
Company+	52,646	79,357	1,500,000
Platoon 1	1,839	2,539	15,500
Platoon 2	1,839	2,539	15,500
Platoon 3	1,839	2,539	15,500
Platoon 4	1,839	2,539	15,500

Within this operational context, the EAB Company+ relies on two primary delivery assets, the PSV and the LL, stationed at CONSOL Stations. The LSM operates within the WEZ, supporting EAB Platoons and other EAB operations. EAB Platoons receive support through the LSM, while the LLs come into play during extreme situations with insufficient LSM availability. Table 4 details the fuel capacity, speed, and range of these essential delivery assets.

Table 4. Delivery Assets Characteristics (Rodriguez et al., 2023)

	Fuel Capacity (gallons)	Speed (knots)	Range (nm)
Platform Supply Vessel (PSV)	1,575,000	15-17	3,500
Liberty Lifter (LL)	18,000	145-180	4,000-8,000
Medium Landing Ship (LSM)	90,000	14	3,500

Analysis of Simulation Results

This chapter includes the output of several fuel delivery simulations to meet demand from a generalizable EAB configuration. It identifies the utilization of assets and CONSOL stations, using the RASP model to identify the performance of each resource selection. The results presented here focus on CONSOL East scenarios. The primary objective is to optimize the selection and quantity of assets, ultimately proposing an efficient refueling strategy for EABO under both sustained and surge demand scenarios.

The simulation results in this chapter were previously presented in Rodriguez et al. (2023).

RASP Optimization Results

The RASP optimization model was employed to allocate LSMs, PSVs, and LLs in addressing surge and sustained operational demand scenarios. The objective was to identify the optimal asset mix, considering inventory safety levels, delivery route optimization, and cost-efficiency. Efficiency was gauged by minimizing the number of delivery assets required to meet demand while ensuring on-time deliveries above maximum capacity. Optimization runs were conducted for varied combinations of asset types, with sustained demand representing continuous supply needs and surge demand introducing spikes due to heightened operational tempo. The model simulated a 30-day operation, limited to 10-minute simulation runs. Different asset allocations were tested, with PSVs and LLs departing from each CONSOL station and LSMs from EAB Company+. In the outset, LLs were used only when fuel inventory in EAB Platoons were critically low.

Successful scenarios were achieved for sustained demand but not always for surge scenarios when demand could not be met using a limited number of assets. Because of the surge, we had to explore different settings with a larger number of assets: prepositioning LSMs closer to EAB Platoons and allowing the use of LL support during surge scenarios, which was sufficient to address the deficiencies. This increased model complexity significantly, and RASP could not always reach optimality in the time allocated, leading to suboptimal results. We tried increasing run time in a few scenarios from 10 to 15 minutes with limited impact on the model precision.

Performance Metrics

The optimization process focused on evaluating two key performance metrics:

1. **Fraction of Late Deliveries**: This metric gauges the percentage of deliveries that reached their destinations after their total storage capacity fell below the safety level threshold. The safety level threshold was set at 40% for sustained scenarios and 50% for surge scenarios. It serves as an indicator of the proportion of instances where fuel levels were lower than desired.

2. **Delivery Below Maximum Capacity**: This metric identifies the lowest fuel level, measured as a percentage of storage capacity, that any receiving station reached before experiencing a late delivery. This value represents the lowest percentage that at least one of the receiving stations experienced during an optimization run. Any value below 0% signifies that one or more receiving stations were left with no fuel, which equates to mission failure.

The following sections show how different asset mixes performed according to each metric.

Sustained Scenarios

In this section, all figures are paired showing the scenarios with one PSV on the left side and two PSVs on the right side.

The fuel demand for the EAB Company+ and each EAB Platoon in the sustained scenarios was shown in Table 3. The RASP optimization tool could not find an acceptable solution to yield zero late deliveries with one PSV during the sustained demand scenario when the PSV operated out of the East CONSOL. A single PSV would not be able to complete the round trip on time while keeping the EAB Company+ above the 40% safety threshold (Figure 5).

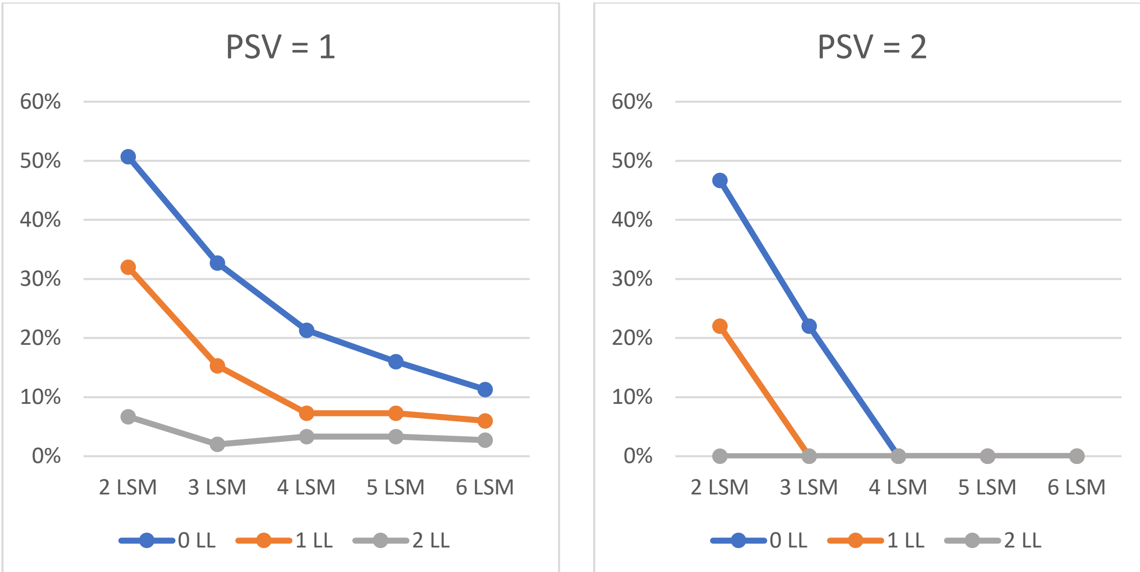

Figure 5. Sustained Demand Average Late Deliveries, East CONSOL

By adding a second PSV during sustained demand, average late deliveries from the East CONSOL yielded similar results as the optimization results from the West and South CONSOLs with a single PSV, illustrating the trade-off between distance and assets: the further the source, the more delivery assets are required to fulfill the mission. These optimization results with two PSVs showed zero late deliveries when the scenario was run with six, five, and four LSMs, regardless of the number of LLs used (Figure 5). Additionally, a combination of two LLs, two PSVs, and two LSMs showed zero late deliveries as well. Scenarios with zero LLs required at least one LSM per EAB Platoon to keep stock levels above safety thresholds.

Overall, the LL traveling speed helped maintain stock levels at EAB Platoons above their safety threshold when three LSMs were not enough to get on-time deliveries to all the EAB Platoons. However, a single LL in combination with two LSMs were not able to maintain stock levels at the EAB Platoons above the 40% safety thresholds.

Average Late Deliveries represents the fraction of instance that at least one receiving station received a delivery after reaching its safety threshold. The Below Maximum Capacity Delivery metric shows how low any one of the receiving stations reached before receiving a late delivery. It represents the lowest level of storage capacity any given station experienced below its safety threshold. This indicates the lowest fuel storage percentage that at least one of the receiving stations experienced during an optimization run. Any value below zero percent indicates that one or more receiving stations were left with no fuel, which equates to mission failure. The lower the number below zero, the greater the cumulative impact on the receiving stations. Any metric with zero value represents that all receiving stations achieved 100% on-time deliveries, or deliveries at or above their specific safety thresholds. The values above zero denote the lowest state of any given station before receiving fuel in reference to their safety threshold.

When supplying from the East CONSOL station, one PSV was not able to keep fuel levels at EAB Company+ above the safety threshold of 40% capacity. None of the data points were at 0%, as shown in Figure 6. All results above 0% represent the lowest any receiving station reached before receiving fuel. All results below the 0% mark represent that one or more receiving units ran out of fuel for one or more days, resulting in mission failure. The RASP optimization tool could not find a solution to achieve zero below maximum capacity deliveries with one PSV during the sustained demand scenario when the PSV and LLs operated out of the East CONSOL station.

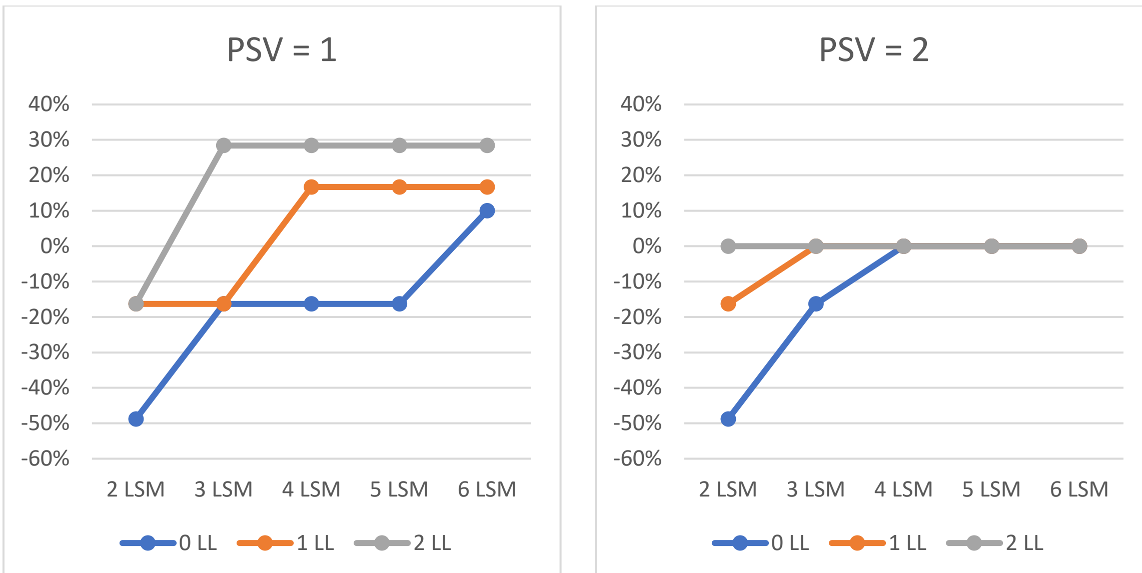

Figure 6. Sustain Demand Deliveries Below Maximum Capacity, East CONSOL (Rodriguez et al., 2023)

An additional run with two PSVs corrected this deficiency as shown in Figure 6. When using two PSVs with six, five, and four LSMs, regardless of the number of LLs, all receiving stations were filled before reaching their safety threshold. Additionally, a combination of two or three LSMs, supported by two LLs and two PSV, also showed zero deliveries below threshold. All other combinations resulted in mission failure. Without the LLs, stations would run out of fuel when using fewer than four LSMs and two PSVs.

Surge Demand Scenarios

During surge demand scenarios, it was not possible to achieve a combination of assets that would result in 0% late deliveries with the same initial conditions of the sustained scenario. Fuel demand in the surge scenario was set 51% higher at the EAB Company+, and 38% higher at each EAB Platoon, compared with sustained demand, as seen in Table 3.

Higher demand and higher safety stock level (raised from 40% to 50% of storage capacity at each location) affected on-time deliveries by forcing an increase in the shipment frequency, stressing the fuel delivery network beyond its capacity. Optimization runs with surge demand yielded zero instances in which any station received fuel below its safety threshold. It was not possible to achieve a combination of assets that would result in 0% late deliveries with the same initial conditions of the sustained scenario. In every simulation, at least one station received fuel below the safety stock threshold. Supplying from the East CONSOL location with one PSV, receiving stations ran out of fuel in 10 out of 15 scenarios, experiencing mission failure.

The Average Late Deliveries Surge Demand optimization with one PSV yielded no results with zero late deliveries, although all results improved whenever LLs were present, as shown in Figure 7.

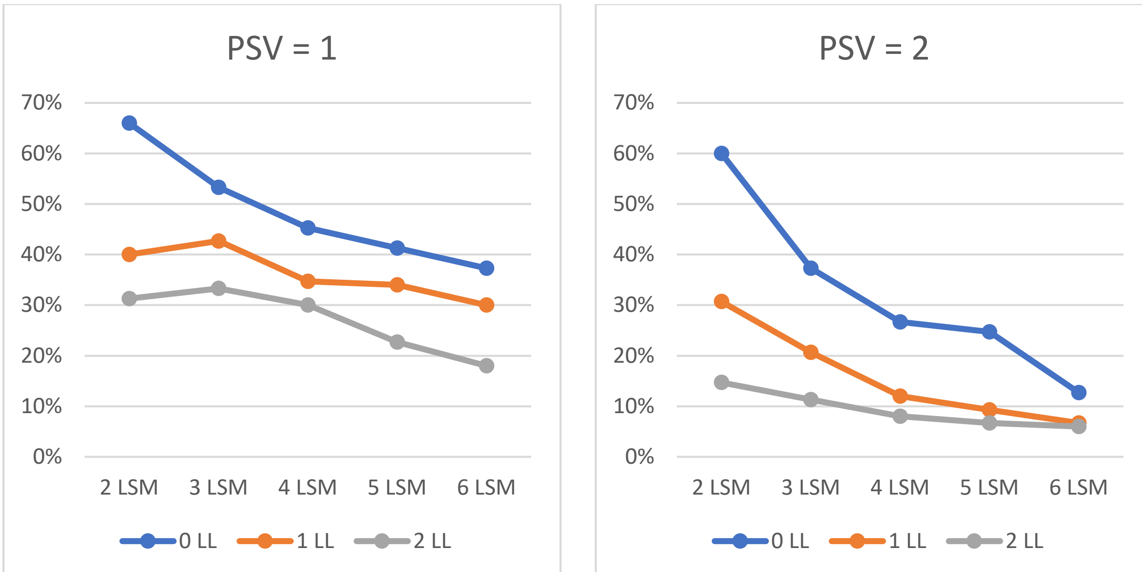

Figure 7. Surge Demand Average Late Deliveries, East CONSOL (Rodriguez et al., 2023)

Unlike in the sustained scenario, adding the second PSV reduced the number of mission failure scenarios, but none achieved 0% below maximum capacity delivery, as shown in Figure 8.

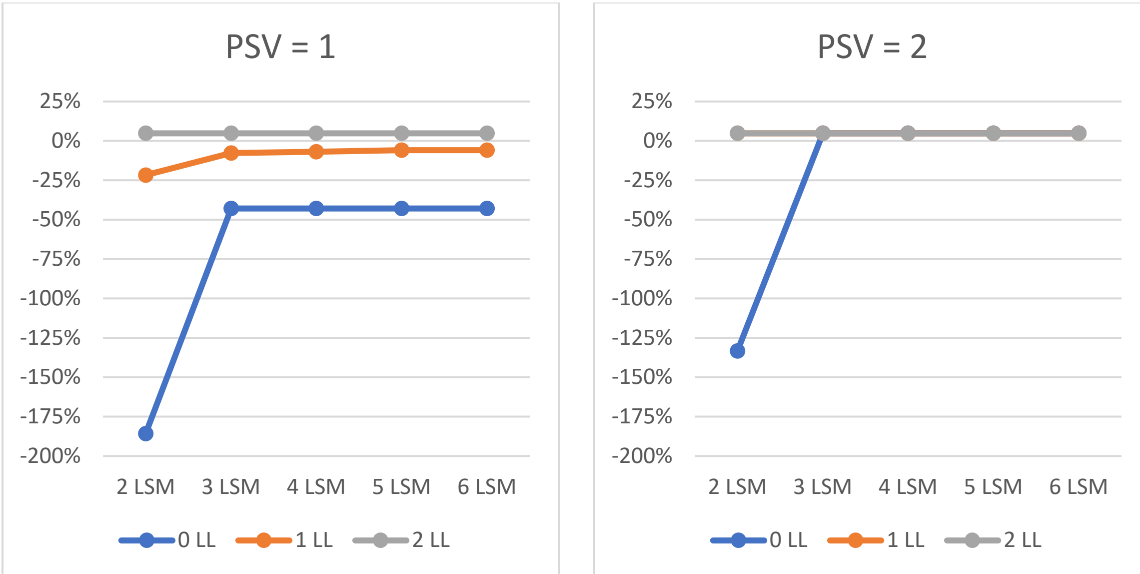

Figure 8. Surge Demand Deliveries Below Maximum Capacity, East CONSOL (Rodriguez et al., 2023)

Surge Scenarios with Prepositioned Assets

To achieve 0% average late deliveries in the surge demand scenario, two LSMs were prepositioned closer to the EAB Platoon locations at the start of the simulations, one to the north and another to the south relative to the EAB Company+. Additionally, LLs were allowed to conduct deliveries within the WEZ, if necessary. Optimization runs for the surge demand scenarios with prepositioned assets were conducted with one and two PSVs. These changes resulted in improved results across all locations. However, as in the sustained demand scenario, the East CONSOL location could not achieve zero late deliveries if only one PSV were available.

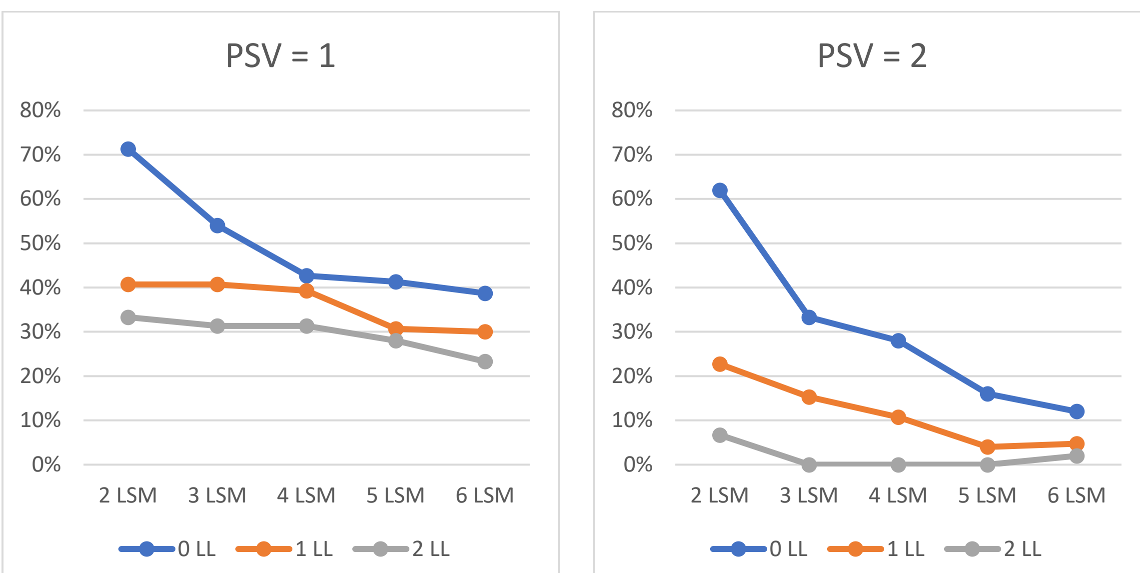

Figure 9. Surge Demand Average Late Deliveries, East CONSOL, With Prepositioned Assets (Rodriguez et al., 2023).

Adding a second PSV to the surge scenario improved the results. Figure 9 shows an anomaly: using two PSVs, three LSMs and two LLs, it is possible to achieve zero late deliveries. However, if the number of LSMs is increased, performance seems to deteriorate. That shouldn't be possible, but the explanation is simple: due to the complexity of the model, the results are less reliable when more assets are available. It would be necessary to increase substantially the time available for each simulation run. We tried increasing the run time from 10 to 15 minutes without significant improvement. Nonetheless, we can be sure that increasing the number of assets will always provide the same performance or better.

To achieve 0% below maximum capacity deliveries in the surge demand scenario, we repeated the procedure by prepositioning two LSMs closer to the EAB Platoon, one to the north and another to the south. We also allowed LLs to deliver fuel inside the WEZ as needed.

As in the sustained demand scenario, the East CONSOL location could not achieve zero deliveries below maximum capacity with one PSV, as shown in Figure 10.

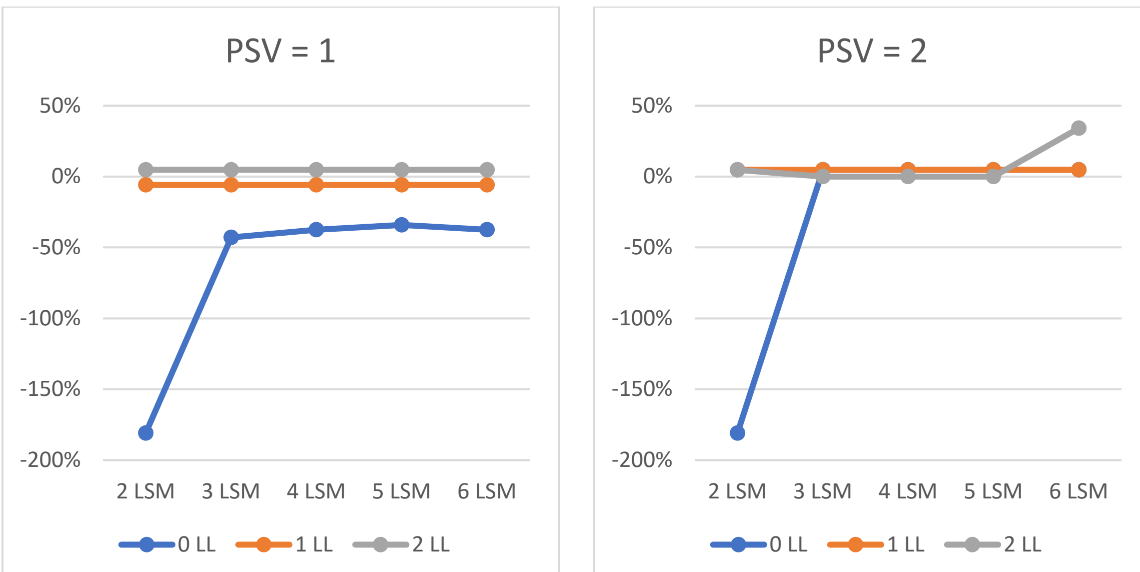

Figure 10. Surge Demand Deliveries Below Maximum Capacity, East CONSOL, With Prepositioned Assets (Rodriguez et al., 2023)

Adding a second PSV improved the results. CONSOL East achieved 0% delivery below maximum capacity by using three, four, or five LSMs, two PSVs, and two LLs, as shown in Figure 10. However, due to the model complexity, the 10-minute optimization run was insufficient for RASP to find a solution to the scenario with six LSM and two LLs.

Conclusion

This study demonstrates how fuel demand can impact asset selection for supporting different EAB configurations. For comparison, we standardized demand level at the EAB Company+ as 45,172 gallons of fuel per day during sustained operations, while each EAB Platoon needed 1,794 gallons per day. During surge conditions, the standard fuel demand at Company+ increased 50% to 69,045 gallons per day, and each Platoon's requirement increased nearly 40% to 2,477 gallons per day. These changes in fuel consumption would be driven by the operational tempo and the readiness level of equipment and aircraft, highlighting how fuel consumption is influenced by the size and composition of the EAB units and whether operations are ongoing or intensifying.

We used the RASP optimization model under multiple asset configurations to assess their respective performances. It was clear that fuel consumption patterns would shift significantly based on operational scenarios, the size of EAB units, and equipment selection and usage. By leveraging RASP, naval planners can determine the right combinations of replenishment ships and dynamic deployment approaches to sustain EABOs across a range of demanding, real-world conditions. The tool provides data-driven asset allocation recommendations to meet varying operational requirements while keeping EABs at or above safety capacity thresholds. RASP was also used to indicate when the asset configuration was insufficient to meet demand under the desired performance metrics.

To meet demand, the analysis identified the optimal mix of replenishment assets for each scenario. It was clear that almost no combination of LSM and PSV would be sufficient to meet demand at the EABOs; one or more LL would always be required. During sustained operations, as few as two LLs, two LSMs, alongside one PSV, could satisfy requirements from the East and South CONSOL stations, assuming 100% delivery asset availability. However, to meet the demand during surge operations necessitated pre-positioning LSMs closer to EAB Platoons and adopting LLs dynamically to share the replenishment burden. Under these conditions, the model showed that three to six LSMs, two LLs, and two PSVs were required for on-time deliveries from any CONSOL stations. The importance of the LLs to supplement floating delivery assets cannot be overstated. Key insights include

- LSMs and PSVs can act as the core assets for continuous sustainment needs, if available in the right numbers.
- LLs are essential for meeting periodic surge demands.
- Distance between stations affects the number of delivery assets, regardless of assets' load capacity. The EAB Platoons could require dedicated assets if the delivery intervals are short.
- Pre-positioned assets are required to meet fuel demand during surge scenarios.

With these considerations, EABOs require at least the following support:

- **Medium Landing Ships:** Four units are required to provide lift capacity from EAB Company+ to each EAB Platoon.
- **Platform Supply Vessels:** One unit would suffice to maintain support on EAB Company+ with a 1.5 million–gallon storage capacity at the stated sustained and surge demands if the CONSOL station were within 2,300 nautical miles of the hub. However, because our study focused on the East CONSOL station, further away, another PSV would be required to maintain the fuel stock at EAB Company+ above safety level thresholds.
- **Liberty Lifters:** The LL speed makes it a multiplying force, enabling quick drops to EAB Platoons in remote areas, supplementing the PSV delivery capacity.

To allow flexibility during surge operations, a fifth LSM and a second PSV would be recommended in the expansive geography of the INDOPACOM AOR. The ideal mix, however, depends on the risk tolerance of the decision-maker.

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