NPS-LM-23-226

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Analysis of Fuel Logistics Support of a Marine Littoral Regiment Operating in the INDOPACOM AOR

June 2023

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

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ABSTRACT

With the emergence of China as a competitor for global dominance, the United States has adopted new military concepts such as Expeditionary Advanced Based Operations (EABO), Distributed Maritime Operations (DMO), and Littoral Operations in a Contested Environment (LOCE) to counter Chinese aggression in the INDOPACOM AOR. As a result, the United States Marine Corps (USMC) created Marine Littoral Regiments (MLRs). This study analyzed the employment of Light Amphibious Warships (LAWs), Next Generation Logistics Ships (NGLSs), and the potential logistical and readiness benefits of adopting a JP-5 Single Fuel Concept (SFC) to support a MLR operating in a contested environment. A scenario involving a MLR operating with United States Navy (USN) ships in a contested environment in INDOPACOM was applied to the Naval Postgraduate School (NPS)-developed Replenishment at Sea Planner (RASP) model. From RASP, the authors determined the best number of LAWs and NGLSs to support the MLR under a dual fuel concept and an optimized support schedule. The team ingested these results into the NPS developed Fuel Usage Study Extended Demonstration (FUSED) model to examine the potential benefits and efficiencies gained by switching from a dual fuel concept to a JP-5 SFC. This study determined, through experimentation, the most successful combination of future platforms to support a MLR operating in a contested environment over a thirty-day span and quantified the benefits of adopting a JP-5 SFC.

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ACKNOWLEDGMENTS

We would like to express sincere gratitude to the people who have helped us with this thesis research. First and foremost, we want to thank our advisors, Dr. Geraldo Ferrer and Dr. Alejandro Hernandez, for their invaluable guidance, support, and feedback throughout the entire process. Their expertise and insights have been instrumental in shaping our research and guiding us through completion.

We are also deeply grateful to Ms. Mary McDonald, Mr. Anton Rowe, and Mr. Stephen Upton for their contributions to the Replenishment at Sea Planner (RASP) modeling. Their assistance was crucial in analyzing the data and drawing meaningful conclusions from the results. In addition, we want to thank Mr. Brandon Naylor for his help with the Fuel Usage Extended Demonstration (FUSED) modeling, which provided important insights into fuel consumption patterns.

We would like to express our sincere appreciation to Mr. Matthew Aylward from the U.S. Marine Corps Operations Analysis Directorate (OAD) for his data inputs and guidance in building our scenario. His input helped us to gain a deeper understanding of the subject matter and ensured the accuracy and reliability of our findings. Without his help, this research would not have been possible.

Lastly, we would like to thank our families for their unwavering support throughout this graduate program and our thesis research. Their constant encouragement, understanding, and patience have been instrumental in helping us navigate through this journey. We couldn't have accomplished this without their love and support.

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TABLE OF CONTENTS

LIST OF FIGURES

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LIST OF TABLES

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LIST OF ACRONYMS AND ABBREVIATIONS

ACE	Aviation Combat Element
AO	Area of Operations
AOR	Area of Responsibility
ARG	Amphibious Readiness Group
ASCM	Anti-Ship Cruise Missile
BOSC	Battlegroup Optimum Speed Calculator
Bbl.	Barrel (1 Bbl. = 42 Gallons)
BTM	Below Threshold Max (Percent)
BTV	Below Threshold Value (Percent)
C4I	Command, Control, Communications, Computers, and Intelligence
CCDR	Combatant Commander
CLF	Combat Logistics Force
CMC	Commandant Marine Corps
CNO	Chief of Naval Operations
CONSOL	Consolidated Cargo Replenishment at Sea
CRS	Congressional Research Service
CSG	Carrier Strike Group
DFM	Diesel Fuel Marine
DLA	Defense Logistics Agency
DMO	Distributed Military Operations
DOD	Department of Defense
DON	Department of the Navy
EAB	Expeditionary Advanced Base
EABO	Expeditionary Advanced Basing Operations
EUCOM	United States European Command
F-76	Naval Distillate Fuel 76
F-44	High Flash Kerosene Aviation Turbine Fuel
FARP	Forward Arming and Refueling Point
FUSED	Fuel Usage Study Extended Demonstration
FSV	Fast Support Vessel

GCC	Geographical Combatant Commander
GCE	Ground Combat Element
INDOPACOM	Indo-Pacific Command
JFC	Joint Functional Command
JP-5	Jet Propellant-5
JP-8	Jet Propellant-8
LAAB	Littoral Anti-Air Battalion
LAW	Light Amphibious Warship
LED	Light Emitting Diode
LCT	Littoral Combat Team
LCS	Littoral Combat Ship
LOCE	Littoral Operations and Combat Element
MSC	Military Sealift Command
MEB	Marine Expeditionary Brigade
MEF	Marine Expeditionary Force
MEU	Marine Expeditionary Unit
MLR	Marine Littoral Regiment
MOS	Military Occupational Specialty
NATO	North Atlantic Treaty Organization
NDAA	National Defense Authorization Act
NDS	National Defense Strategy
NGLS	Next Generation Logistics Ship
NPS	Naval Postgraduate School
NSTM	Naval Ship Technical Manual
OAD	Operations Analysis Directorate
OIE	Operations in the Information Environment
OPNAV	Office of the Chief of Naval Operations
OTTER	Optimized Transit Tool and Easy Reference
OV	Objective Value
POL	Petroleum Oil and Lubrication
PRC	People's Republic of China
PSV	Platform Support Vessel

RAS	Replenishment at Sea
RASP	Replenishment at Sea Planner
RP	Replenishment Points
SAG	Surface Action Group
SIF	Stand-In Forces
SFC	Single Fuel Concept
T-AKE	Dry Cargo/Ammunition ship
T-AO	Fleet Replenishment Oiler
T-AOE	Fast Combat Support Ship
TFP	Transit Fuel Planner
TLR	Top-Level Requirement
UNREP	Underway Replenishment
USN	United States Navy
USMC	United States Marine Corps
UV	Unmanned Vehicle
WEZ	Weapons Engagement Zone

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I. INTRODUCTION

After the end of the Cold War, the United States operated as an uncontested force around the globe, exerting its influence wherever it was necessary (Department of the Navy (DON), 2017). The emergence of China as a global competitor and a major military and economic force in recent decades has required the United States to rethink and reshape its military and economic strategies (PACOM, n.d.). To counter the threat and growing influence of China, the United States adopted new military strategies and concepts. Distributed Maritime Operations (DMO) and Expeditionary Advanced Based Operations (EABO) focused on distributing our forces throughout the INDOPACOM and required our forces deployed in the region to be able to operate in contested environments (Feichert, 2022). Military leaders have identified the need for a new logistics construct with more resiliency and self-defense capabilities to be able to sustain new distributed forces called Marine Littoral Regiments (MLRs) (Walton et al., 2019). With the creation of these new platforms and units to support these new concepts, military leaders need more data-driven information that informs how these new forces will operate and how they will need to be sustained in the future.

The nature of military operations in the INDOPACOM AOR requires consistent reassessment of alternatives in a constantly changing (and sometimes unexpected) geopolitical environment to understand, prepare, and mitigate impacts to operations.

The logistics support measures required to sustain expeditionary units are often challenging to execute for prolonged periods due to the limited capacity onboard supporting replenishing ships for certain classes of supplies. The ships must travel long distances, often multiple times, to reload sufficient fuel and food to support operational units due to the size of INDOPACOM AOR (Jimenez et al., 2020).

JP-5 is currently used by all military aircraft with the ability to embark on afloat units. The viability of using a single fuel in ground and support equipment has been proven to be possible (Garrett, 1993). JP-5 has also been deemed the only fuel versatile enough to be universally applicable to a significant percentage of naval and marine units' engines and equipment operations (Guimond, 2007). It can also be used by ground support vehicles with minimal adjustments or problems (Giannini et al., 2002). There is a demand at the higher echelon of Navy leadership at the Office of the Chief of Naval Operations (OPNAV) for additional research efforts to assess the viability of transitioning to JP-5 as the single fuel in theater. There is a need to understand the potential implications and impacts of the transition on logistics and readiness of deployed units, including availability of fuel to sustain current and future operational forces.

This research investigates how logistics support of an MLR in the INDOPACOM would look. Areas of analysis include an investigation into required numbers of supporting Light Amphibious Warships (LAWs) and Next Generation Logistics Ships (NGLSs) and the potential impacts and opportunities of switching to a JP-5 single fuel concept (SFC) for logistics support and readiness of afloat units. Specifically, the research questions of this study are as follows:

1. Given that LAWs and NGLSs will support the MLR, what combination of these platforms will prove most successful in supporting a MLR in a contested environment in the INDOPACOM AOR?
2. What are the logistical and readiness benefits of a JP-5 SFC in comparison to a dual fuel approach to sustain a MLR in a contested environment in the INDOPACOM AOR?

These research questions both inform policy on how MLRs are best supported by the planned platforms that are being built, as well as give insight to senior military leaders on the incremental impacts of how MLRs are affected when there are more or fewer LAWs and NGLS to support, if the MLR is more or less distributed, and the potential efficiencies gained from a SFC compared to a dual fuel concept.

To gain insight into each of the research questions, an example MLR operational scenario is simulated in two different Naval Postgraduate School (NPS) developed models. The first, the Replenishment at Sea Planner (RASP), allows for a linear optimization model to be built considering constraints such as the locations of MLR operations and the fuel usage of the MLR and afloat platforms while varying the number of LAWs and NGLSs.

This simulation considers a traditional dual fuel concept where surface ships operate on F-76 and MLR ground assets operate on JP-5. The result of this model is an understanding of the most successful number of each platform to best support a MLR under the examined conditions, as well as the effects of incrementally increasing or decreasing the number of available support platforms on the operational capability of the MLR.

The second model in this study is the Fuel Usage Study Extended Demonstration (FUSED) model. This model considers all fuel burn and location inputs used in the RASP model and incorporate the resulting number of LAWs and NGLSs, identified from the RASP model as constants to evaluate fuel supportability of the MLR under both the legacy dual fuel concept and a JP-5 SFC. Outputs from this model are compared for both fuel concepts to demonstrate the potential benefits of MLR supportability when adopting a JP-5 SFC.

The baseline scenario investigated in this study involves a single MLR distributed between multiple locations inside of a Weapons Engagement Zone (WEZ) in the INDOPACOM AOR. The MLR uses fuel at each location to sustain operations and thus requires fuel support. The MLR's locations are supported by LAWs as ship-to-shore connectors and the LAWs are supported by NGLSs that resupply outside of the WEZ. The scenario is fully defined and further discussed in Chapter IV.

This chapter introduced the study and outlined the scenario investigated in this study. Chapter II provides a more detailed background on the problem, an overview of the INDOPACOM AOR, the future structure of USMC Force Design 2030 and USN Battle Force 2045, a historical snapshot of legacy dual fuel usage in the fleet, and further information on previous SFC studies. Chapter III reviews the relevant literature. Chapter IV describes the models and methodology utilized in simulating the scenario. Chapter V outlines and summarizes the results of the simulated scenario. Chapter VI discusses conclusions that can be drawn from the results of the simulations and recommendations based on these conclusions.

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II. BACKGROUND

A. INTRODUCTION TO INDOPACOM AOR

The United States Indo-Pacific Command (USINDOPACOM) is the largest of six geographic combatant commands of the United States Military and is increasingly becoming the most influential and critical. Its Area of Responsibility (AOR) covers significantly more square miles, is the most geographically diverse, is home to over 50% of the world's population and several of the world's largest militaries, it contains many of the world's nuclear powers, has some of the largest economies in the world, has the two most populous nations and the largest democracy among a host of other distinct characteristics (PACOM, n.d.).

The region is a vital driver of the global economy and as such, security issues in this region have significant impacts on the global economy. States such as China and Russia have increasingly become more heavily militarized, attempting to compete with the United States economically and militarily, and attempting to reduce the United States' influence in the region while attempting to grow their own. Given these conditions and the strategic importance of the region, it is important for the United States to be able to respond to tensions and provocations through several means including military presence and deterrence to protect our allies and interests in the region (PACOM, n.d.).

B. MARITIME LOGISTICS

A maritime force's ability to sustain itself at sea is a critical component to the success of its operations. Without the ability to sustain itself, the force is unable to continue its operations. The greater the ability to sustain itself across multiple domains and with fewer constraints, the greater its ability to project power and to exist as a supreme naval force. For the last several decades, the United States has operated around the globe uncontested, and its current method of maritime logistics and sustainment for its forces reflects that. Currently, the principal sustaining force for our ships and units abroad is the Combat Logistics Force (CLF). The CLF is comprised of 29 vessels that replenish and sustain the Carrier Strike Groups (CSG), Amphibious Readiness Groups (ARG), and other independently steaming ships and naval forces via replenishments-at-sea (RAS). Our current maritime logistics structure uses forward operating bases as hubs in which contracted Merchant Marine vessels supply the bases with fuel and other commodities, from where it is then loaded onto designated CLF ships for further transport to the CSG or other end use customers operating with the CLF. Figure 1 is a depiction of the existing maritime logistics construct that this study uses.

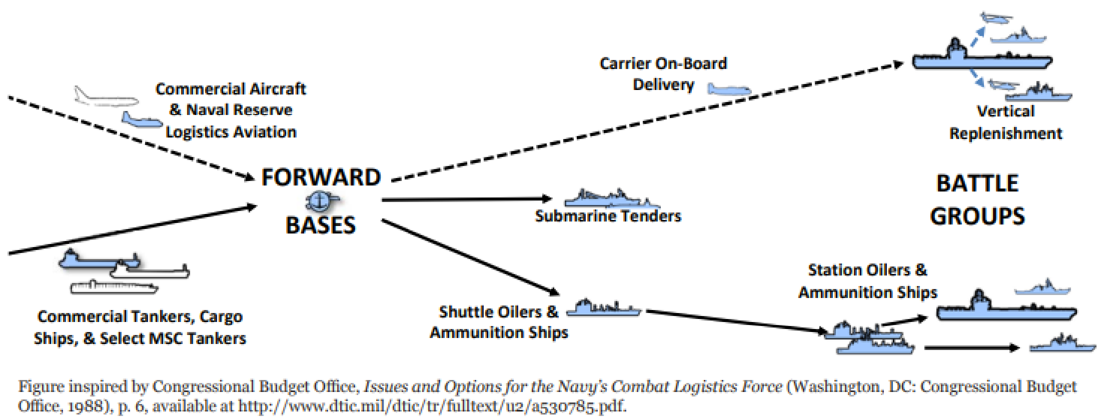


Figure 1. Modern U.S. Maritime Logistics Network, from Shore to Ship. Source: Walton (2019).

Historically, this type of construct has worked well with the United States operating as an uncontested force around the globe. However, with the emergence of China and Russia as global competitors, the United States has shifted its operating concepts to incorporate the challenges in contested environments. This shift requires adapting the maritime logistics approach to support deployed forces while minimizing vulnerabilities in contested areas. Our CLF ships are currently soft targets if operating in contested areas because they lack the necessary self-defense capabilities to evade attacks and maneuver through the contested environment. This capability gap has generated a requirement for logistics ships with enhanced defense capabilities and a different approach to sustain our more distributed forces operating in the Indo-Pacific region (Walton et al., 2019). Incorporating these new requirements and concepts brings our maritime logistics construct more in line with the 2022 National Defense Strategy that demands our force to be more sustainable, survivable, agile, and responsive (Department of Defense [DOD], 2022).

C. USMC FORCE DESIGN 2030

To create greater force alignment with the National Defense Strategy (NDS), the United States Marine Corps (USMC) developed the Force Design 2030 initiative. The purpose of this initiative is to shift focus toward Littoral Operations in Contested Environments (LOCE) and EABO. In making this shift, the USMC is eliminating multiple Military Occupational Specialties (MOS) (Tank Battalions, Law Enforcement Battalions, and Bridging Companies), and deactivating aviation squadrons with plans to reduce its personnel by a total of 12,000 by 2030. Additionally, the USMC is reorganizing at higher echelons to modernize the III Marine Expeditionary Force (MEF) headquartered in Okinawa, Japan by creating three MLRs to augment the III MEF's ability for denial and control of the sea in a contested environment and three Marine Expeditionary Units (MEU) capable of deploying globally both with nontraditional Amphibious Readiness Groups (ARG) and as a traditional EABO force (Feichert, 2022).

1. LITTORAL OPERATIONS IN CONTESTED ENVIRONMENTS

With the re-emergence of great-power competition in the Indo-Pacific region, the United States has shifted its focus to enhance its capabilities of operating in the Indo-Pacific in contested environments. Our adversaries in recent years have sought to enhance their abilities to establish sea control and sea denial through aggressive posturing throughout various island chains throughout the Indo-Pacific. For the United States to maintain its maritime superiority through this new era, and to counter aggression from adversaries throughout the maritime domain, the ability to operate in and from the Littoral battlespace has emerged as an essential capability to counter our adversaries. In 2015, the concept of LOCE was created with a more focused attention on operating in and from the littoral battlespace rather than conducting amphibious operations from sea. The distinction between these two is that LOCE focuses on sailors and marines fighting at sea from the littorals while amphibious operations focus on moving marines from the sea to the shore (Feichert, 2022).

2. EXPEDITIONARY ADVANCED BASE OPERATIONS

The EABO concept is a key change in doctrine for how the U.S. Navy and U.S. Marine Corps will operate in the Pacific now and in the future. The EABO concept was implemented as a way for U.S. Forces to deter aggression, ensure free access (ex. shipping lanes and navigation transit in international waters), and maintain stability in the region. *The Tentative Manual for Expeditionary Advanced Base Operations* specifically defines EABO as "a form of expeditionary warfare that involves the employment of mobile, low-signature, persistent, and relatively easy to maintain and sustain naval expeditionary forces from a series of austere, temporary locations ashore or inshore within a contested or potentially contested maritime area in order to conduct sea denial, support sea control, or enable fleet sustainment" (DON, 2021, p. 1-3). This is the new operational concept of expeditionary warfighting, which will be implemented using an evolved approach that is adaptable to any operational environment. The concept of Stand-in Forces (SIF) is a new and dynamic approach for U.S. Marines to be able to deter the threat or actual actions by an adversary military power in any location worldwide by establishing forces designed to persist forward within a contested area while supporting fleet, joint forces, allies, and partners with more options to counter adversary's strategy (United States Marine Corps [USMC], 2021). The MLR will be the primary forward fighting unit of the expeditionary forces utilizing the EABO warfare as a SIF. This will enable them to maintain and sustain prolonged presence in the contested area by keeping a low signature, providing mobile and lethal support to joint forces, allies, partner or interagency units as requested (Feichert, 2022).

3. MARINE LITTORAL REGIMENT

The MLR is a newly created organizational unit within the USMC that would be responsible for conducting EABO in any location worldwide including contested areas. The MLR is designed to be a scalable and modular force that can operate independently for prolonged periods in austere environments while maintaining a very low signature, being sufficiently lethal to provide a range of functions including Sea Denial, Reconnaissance, Counter-Reconnaissance, identification of enemy's weakness and vulnerabilities. The MLR's primary mission is to establish and maintain advanced bases in austere, contested environments, including littoral regions, to enable follow-on forces to operate from a secure position. The MLR would use a variety of capabilities, including ground combat, unmanned systems, and naval fires, to achieve its mission.

MLR's ability to establish and maintain advanced bases in contested areas, particularly in the littoral regions, is critical to the success of the EABO concept. By denying enemy forces the ability to establish footholds or conduct offensive operations, the MLR helps ensure that U.S. forces maintain a competitive edge in the region and can effectively counter any threats to U.S. interests.

MLRs will consist of "1,800 to 2,000 Marines and Sailors" subdivided into three distinct elements: the Littoral Combat Team (LCT), the Littoral Anti-Air Battalion (LAAB), and the Littoral Logistics Battalion (LLB) (Feichert, 2023). He states further, the first MLR which was officially established in March 2022 and homebased in Hawaii will be designed to operate and maneuver quickly within contested environments across island chains and maritime domains. Collectively, the elements in each MLR will have the capabilities to conduct surveillance and reconnaissance, OIE, screen/guard/cover, deny or control key maritime terrain, surface warfare operations, air and missile defense, strike operations, sustainment operations, and Forward Arming and Refueling Point (FARP) operations. (Feichert, 2023).

D. USN BATTLE FORCE DESIGN

The United States Navy released the updated force structure goal contained in the Battle Force Design document that aimed at achieving and maintaining a 355-ship fleet comprising different platforms to position the force to meet the FY2018 National Defense Authorization Act (NDAA) objectives. The number of ships required by the Navy was derived from a force structure assessment conducted in 2016, which reviewed the capabilities required by Combatant Commanders (CCDRs) and the requisite naval platforms to implement the objectives contained in the National Defense Strategy and National Military Strategy documents. The initial document was quickly rendered inadequate with the rapid change in peers' capabilities and near-peer competition and would be inadequate to maintain the necessary military advantage to succeed in fighting future engagements. This development led to the revision of Navy's ship building plan to position the fleet to achieve the NDAA objectives. The newly developed fleet composition was future-proof in the light of rapid modernization of the People's Republic of China's (PRC) naval fleet and the constantly evolving nature of war.

The new FY2023 30-year (FY2023–FY2052) shipbuilding plan was released on April 20, 2022, to include the new fleet architecture. This was planned to be a one-time fleet architecture change that was meant to address a shifting global security and operational realities. The new fleet architecture is intended to: be appropriate to effectively respond to the improving capabilities of other countries, particularly China; be able to leverage emerging technologies like unmanned vehicles (UV); operate as part of a distributed maritime force; and it must be affordable. The revised shipbuilding plan now features fewer large ships and smaller, lighter, and faster ships of diverse sizes and will include a newly introduced element of large UVs. This new plan will comprise 312 to 372 ships and 77 to 140 large UVs (O'Rourke, 2022a).

1. LIGHT AMPHIBIOUS WARSHIP

There is a need to revamp the force architecture to appropriately support a distributed approach to warfighting. The LAW was first developed in response to Navy and Marine Corps' shift to the new Distributed Maritime Operations (DMO) and EABO concepts. These new operational concepts were developed to enable the force to respond effectively to emerging competition from peers and near-peers, especially China. A resulting initiative is the development of different amphibious platforms that can effectively support the execution of DMO and EABO operations.

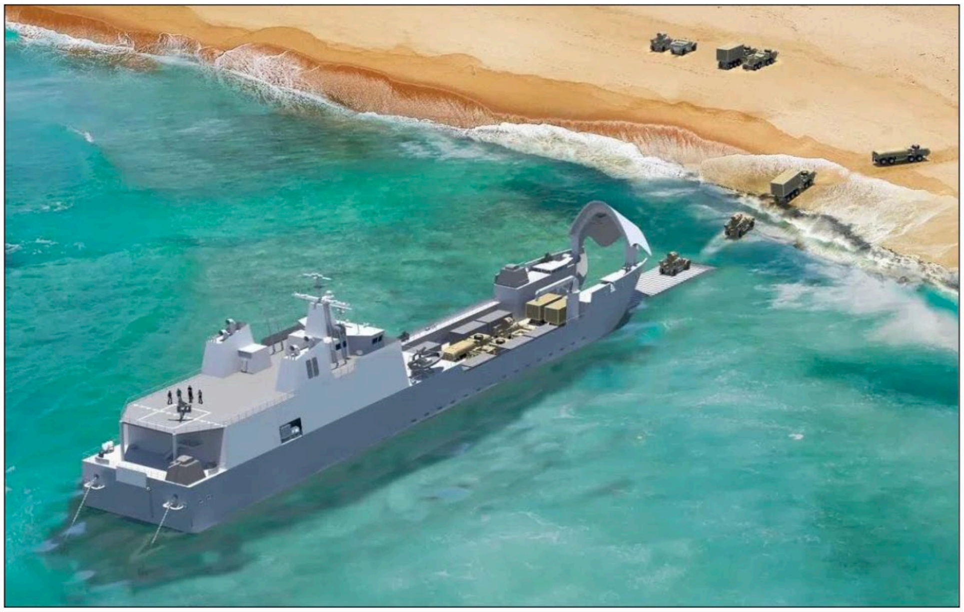
The LAW is envisioned to operate in a littoral environment supporting movement of expeditionary forces in, around and out of shallow and coastal waters. It is specifically expected to be able to move Marines in and out of the numerous islands that abound in the East and South China Seas to counter increasing Chinese aggression in the area. It is expected to be an integral part of the Naval support element to the newly established MLR.

The ships are unlike any other ships currently operated by the Navy. Though meant for amphibious operations, they are different from the typical large amphibious platform in all regards. The LAWs will be much smaller and designed to be well suited for littoral combat operations. The initial design specifications show that it will field Anti-Ship Cruise Missile (ASCM) and other appropriate armament to provide ship self-defense. According to a recent report by the Congressional Research Service (CRS), the LAW will have the following design characteristics (O'Rourke, 2022b, p. 28):

- It will be crewed by no more than 40 Navy sailors.
- Length of 200 feet to 400 feet.
- Maximum draft of 12 feet.
- Displacement of up to 4,000 tons.
- An ability to embark at least 75 Marines.
- 4,000 to 8,000 square feet of cargo area for the Marines' weapons, equipment, and supplies.
- Stern or bow landing ramp for moving the Marines and their weapons, equipment, and supplies from ship to shore (and vice versa) across a beach.
- A modest suite of C4I equipment.
- A 25mm or 30mm gun system and .50 caliber machine guns for self-defense.
- Transit speed of at least 14 knots, and preferably 15 knots.
- Minimum unrefueled transit range of 3,500 nautical miles.
- A "Tier 2+" plus level of survivability (i.e., ruggedness for withstanding battle damage), broadly comparable to that of a smaller U.S. Navy surface combatant (i.e., a corvette or frigate), that would permit the ship to absorb a hit from an enemy weapon and keep the crew safe until they and their equipment and supplies can be transferred to another LAW.
- Ability to operate within fleet groups or deploy independently.
- 20-year expected service life (O'Rourke, 2022b, p. 28).

Figures 2-5 depict the various iterations of designs concepts by ship builders based on the intended mission and operations of the LAWs. Some of the renderings were presented during the Sea Air Space 2021 Exposition. The LAWs were also referred to as Medium Landing Ships (LSM) in the latest versions of the CRS report.

Artist's rendering



LAW supporting an amphibious beach landing in a rendering.

Figure 2. An Illustration of Austal USA's Design for LAW at 2021 Sea Air Land Exposition. Source: O'Rourke (2022b).

Photograph of model displayed at trade show

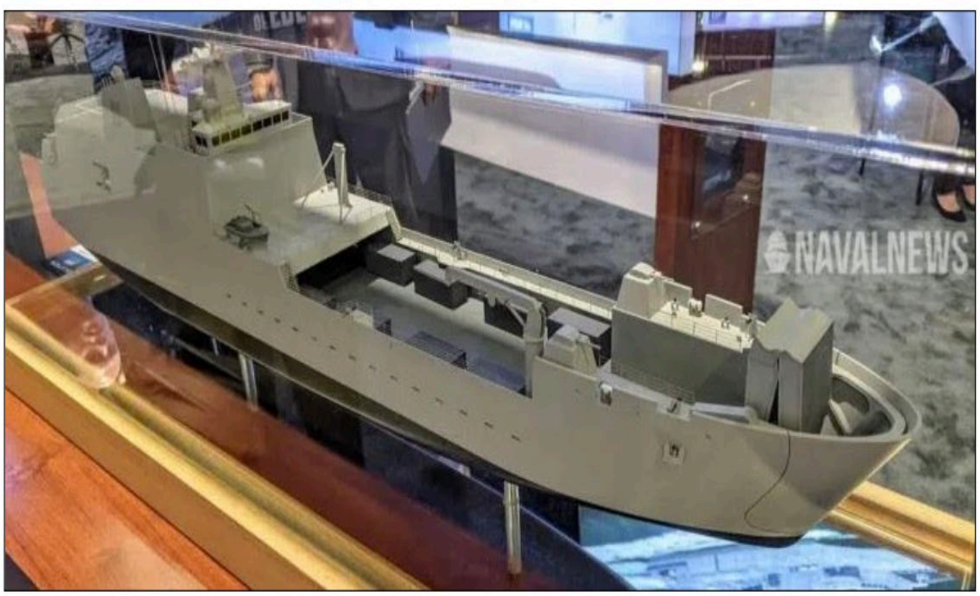


Figure 3. Photograph of a Model of Austal USA's Design for LAW at 2021 Sea Air Space Exposition. Source: O'Rourke (2022b).

Photograph of model displayed at trade show

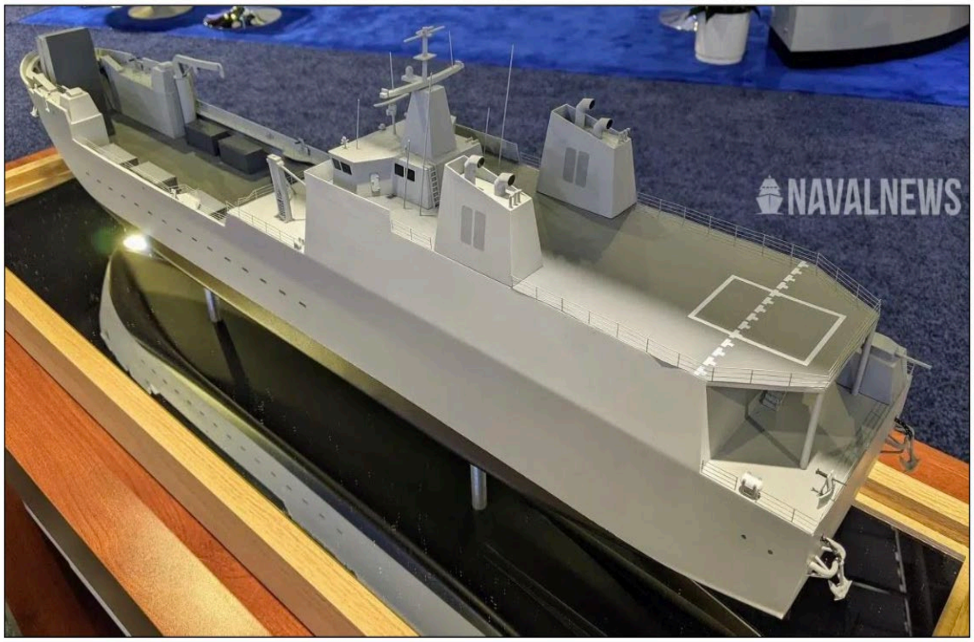


Figure 4. Austal USA's Design for LAW at 2021 Sea Air Space Exposition. Source: O'Rourke (2022b).

Figure 5. Artist Rendering of the LAW. Source: Grady (2023).

Note that the LAW is still in its initial design stage with the contract for the prototype development awarded in FY2022. The Navy's new five-year ship procurement plan (FY2023–FY2027) documented in the FY2023 budget plan has the planned procurement deferred by two years for commencement in FY2025. The contract for the first ship will be awarded in December 2024 and another in each year thereafter until the planned four ships have been procured. The first ship is estimated to be delivered in July 2028 (O'Rourke, 2022b).

2. NEXT GENERATION LOGISTICS SHIP

In line with Navy and Marine Corps DMO and EABO operational concepts and revised fleet architecture, new types of naval resupply or replenishment platforms will be required to support the combat elements. The DMO concept is one that avoids the potential for the enemy crippling combat operations by concentrating firepower on an essential element of the combat force. New replenishment ships must have the capability to support and sustain operations in a variety of combat environments with particular emphasis on littoral operations in the Western Pacific, which is expected to be the next frontier of combat operations. This led to the initiation of the Next Generation Logistics Ship (NGLS) program.

The NGLS is envisaged to be a medium size replenishment ship that is much smaller and cheaper than traditional CLF ships but can provide the same types of logistics support as the larger ships, albeit on a smaller scale. The NGLS can be integrated to work with the fleet of larger CLF ships or can work independently to resupply Navy and Marine Corps combat operations worldwide. The initial cost estimate for the NGLS is expected to be about $150 million each, which is significantly less than the cost of a traditional T-AOE or T-AKE. This should make it much easier to procure given the limited financial outlay required (O'Rourke, 2022c).

This ship is especially critical to the new operations as it is expected to be integrated into the logistics support/supply chain for the Marine Corps EABO concept. The ship is expected to be able to conduct underway replenishments like other CLF ships to bring much needed supplies and materials to expeditionary forces. Its smaller size and displacement make it more suitable to supporting the distributed maritime operation in an austere expeditionary environment. It can easily go in to resupply the troops and expeditiously withdraw from the area. It will also have a smaller physical presence and less operational impact if attacked by the enemy (O'Rourke, 2022c).

E. LEGACY FUEL USAGE IN THE FLEET

The USN currently utilizes a dual-fuel model for fleet operations. Surface combatants, logistics resupply ships, and planned future iterations of these operate on Naval Distillate Fuel (F-76). Naval aviation assets are fueled by Aviation Turbine Fuel Grade Jet Propellant 5 (JP-5). Additionally, USMC ground assets are operated with Aviation Turbine Fuel JP-8. Under the current operating conditions, at a minimum, Naval surface assets supporting MEUs or Aviation assets must carry two fuel types (F-76 and JP-5) to be fully operational. This requires these assets to be resupplied if they are low on one of two fuels, not necessarily requiring both at time of resupply.

Previous studies have demonstrated the feasibility of adopting JP-5 as the single fuel at sea since it is an approved fuel alternative to both JP-8 and F-76 (Giannini et al., 2002). There has been resistance to adopting JP-5 as the fuel in a SFC for both efficiency and cost reasons. Giannini et al. found that due to a lower energy density of JP-5, the range of a ship operating on JP-5 is reduced by 2.6% when compared to F-76. This difference was found in a testing environment and is thus not guaranteed to directly translate in an operational environment. Giannini also notes that the Army saw a similar reduction in efficiency when comparing legacy DF-2 fuel to the proposed JP-8, but this decrease was never realized in operations. Regarding price, the Defense Logistics Agency (DLA) standard prices for petroleum products, dated February 1, 2023, shows the similarity in costs of the two fuel types, listing F-76 at $3.92 per gallon and JP-5 at $3.93 per gallon (McCord, 2023). This study builds on previous investigations into the feasibility of JP-5 as the resource for a SFC with a focus on future force structure and needs.

F. FUEL TYPES, CHARACTERISTICS, AND DESCRIPTIONS

1. F-76 (PREVIOUSLY KNOWN AS DIESEL FUEL MARINE)

This is a military-grade fuel used for a variety of heavy-duty applications and is the standard fuel used in all conventional USN surface ships. It is called Naval Fuel Distillate or NATO code F-76. As a diesel fuel, F-76 has a high flashpoint of 60°C (140°F) which minimizes the risk of spontaneous explosion or fire, making it safe for shipboard use. F-76 is derived from crude oil, natural gas liquid concentrates, heavy oil, shale oil, and oil sands and contains additives to deactivate metals present in the fuel and provide lubricative properties (DOD, 2012).

An advantage of the use of the F-76, in addition to its high flash point, is its cost effectiveness. DLA, F-76 is less expensive than other types of military-grade fuels such as JP-5 and JP-8 (McCord, 2023). Additionally, F-76 is readily available in ports and depots around the world due to widespread global use. This ensures availability for all military vessels, vehicles and other applications and world-wide support.

Disadvantages of F-76 include the potential to promote microbial growth in the fuel tanks which can lead to clogged filter and other issues. Military units prevent this growth by keeping a very strict maintenance and surveillance regimen to ensure quality standards are adhered to and damage to engine and machinery are minimized. According to Naval Ship Technical Manual (NSTM) chapter 541, F-76 is required to have a cloud point no higher than -12.22°C (10°F) to prevent or minimize equipment damage which is important when operating in cold environments (Kube & Kinser, 2021).

2. JP-5 (NATO CODE F-44)

The standard fuel in all USN aircraft is aviation turbine fuel JP-5, NATO code F-44. JP-5is safe for shipboard use because of its high flashpoint of 60°C (140°F). This characteristic minimizes risks of spontaneous explosion or fires and does not pose a fuel vapor inhalation risk to personnel. JP-5 is a refined hydrocarbon distillate fuel oil which contains additives such as antioxidants to prevent formations of gums or peroxides, metal deactivator, corrosion and icing inhibitor, static dissipater, and lubricity improvers (DOD, 2016). JP-5 is an approved alternative fuel to both F-76 and JP-8 (Kube & Kinser, 2021).

The high flashpoint in JP-5 compared to JP-8 makes this the only acceptable aviation turbine fuel onboard U.S. Navy afloat units. It provides comparable performance to JP-8 but without any disadvantages or health and operations. JP-5 can also be used as a fuel for naval vessel engines due to the similarities with F-76, which is the primary fuel used by naval units, but F-76 cannot be used as aviation fuel (Kube & Kinser, 2021). The only noted disadvantage is a negligible loss of fuel efficiency compared to JP-8.

3. JP-8 (NATO CODE F-34)

Aviation turbine fuel JP-8 is widely used across the U.S. Department of Defense enterprise due to its low cost and suitability as a kerosene-blend substitute for Diesel (Jimenez et al., 2020). JP-8 is also widely used in aviation engines and applications due to the similarity in its chemical composition to kerosene-based Jet A-1 fuel that is used in commercial aviation applications. It is the most widely used fuel by USMC ground support vehicles and equipment. In the 1990s, the U.S. Army, U.S. Air Force and NATO jointly adopted JP-8 as their single fuel of choice (McKee et al., 2005). The primary difference between JP-8 and Jet A-1 is the specific additives in JP-8 which make it more suitable for military use according to military specifications. (Defense Logistics Agency [DLA], n.d.).

Additionally, the minimal difference between JP-8 and Jet A-1 fuel implies worldwide availability of the product wherever commercial aircraft are supported. This implies minimal risks to supply chain disruptions and reduced cost for extended fuel logistics support ensuring mission accomplishment for U.S. and NATO forces worldwide.

The major disadvantage of JP-8 is its low flashpoint. This fuel is not safe for shipboard use with a low flashpoint of 38°C (100°F), which does not meet the threshold of 60°C (140°F) required to be used onboard USN surface ships. The primary difference between JP-5 and JP-8 is their flashpoints. While JP-8 contains additives similar to those in JP-5, it lacks the icing inhibitor found in JP-5 (Kube & Kinser, 2021). U.S. Navy afloat units routinely operate in regions with austere and extreme temperatures. JP-8's lower flash point means it has a higher potential to be vaporized, posing a significant health and explosion risk to personnel in an afloat operating environment.

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III. LITERATURE REVIEW

A. SINGLE FUEL CONCEPT WITHIN THE EUCOM AREA OF RESPONSIBILITY

Witt (2022) uses experimentation through simulation to investigate potential benefits to the USN surface fleet from switching to a SFC in the EUCOM AOR. The NPS developed FUSED model was used to simulate a transit from Souda Bay, Greece to Loch Striven, Scotland for multiple different surface combatant groups that performed a variety of operations during the transit. The combatant groups were supported via RAS events by CLF ships. Under both a legacy dual fuel concept of JP-5 and F-76 and a JP-5 SFC, the total fuel delivered, total fuel burned, number of trips to port by the CLF ships, and number of RAS events conducted were all measured. Comparisons between the results of these metrics under both a JP-5 SFC and legacy dual fuel concept demonstrate that, due to the pooling effect generated under a JP-5 SFC, there is greater operational flexibility afforded in the JP-5 SFC case. Specifically, for most cases investigated, the JP-5 SFC resulted in fewer CLF trips to port and fewer RAS events. This ultimately translated to greater time dedicated to operations by the groups making the transit, as well as cost savings to the USN by reduced CLF time in port. Reduced time in port leads to lower costs for husbandry and other services. This study reinforced JP-5 SFC as a beneficial change for the USN and demonstrated the capabilities of FUSED to examine dual fuel versus single fuel concepts applied to the same simulated scenario (Witt, 2022).

B. SINGLE FUEL CONCEPT FOR MARITIME OPERATIONS

Jimenez, Walters, and Lessner (2020) investigated the effects of the USN adopting a JP-5 SFC on CLF ship support of major combat operations in the INDOPACOM AOR. Initial analysis included examining historical data on F-76 and JP-5 demand that was met by CLF ships, divided among the fleets in which the demand and resupply occurred. This data was then adjusted, based on a computationally established efficiency factor between the two fuel types, to be expressed in terms of just JP-5. This effectively stated how much JP-5 would have been required to fulfill the historical demand under a JP-5 SFC. The mean and standard deviation of demand of each fuel individually, as well as the combined amount of JP-5 that would have been required under a SFC, was determined and used to calculate a Coefficient of Variation for each type of fuel. The Coefficient of Variation is the ratio between the standard deviation and mean demand and is a valuable measure of variability of a supply chain system. The lower the Coefficient of Variation, the lower the variability in demand is of that system. The JP-5 SFC proved to create a lower Coefficient of Variation in every numbered fleet examined except one. This translated to JP-5 SFC reducing demand variability, which means lower levels of safety stock of the fuel demanded could be maintained on hand, creating a cost savings for the USN based on the concept of inventory pooling (Jimenez et al., 2020).

In addition, the data aggregated to draw the variability reduction conclusion was leveraged to investigate the number of port visits for CLF ships under the dual fuel concept versus the JP-5 SFC. It was determined that under the JP-5 SFC, the number of CLF visits to port could be reduced by anywhere from 22 to 170 total visits (Jimenez et al., 2020).

The final facet of the SFC discussion investigated by Jimenez, Walters, and Lessner involved a simulated scenario of CLF ships supporting operations against the People's Republic of China (PRC). In this scenario, forces operating within the contested environment were supported by CLF ships which were further supported by Military Sealift Command (MSC) Consolidated Logistics (CONSOL) Tankers. The scenario was simulated under an F-76 and JP-5 dual fuel concept, and again under a JP-5 SFC to determine the number of CLF ships and CONSOL tankers required to conduct the mission under each set of conditions. The results concluded that, under a JP-5 SFC, the number of CLF ships and CONSOL tankers required to support the mission was reduced by one each, from 9 CLF ships to 8, and from 7 CONSOL tankers to 6. All research avenues investigated through this study build further support for the potential benefits the USN could gather by employing a JP-5 SFC in the fleet (Jimenez et al., 2020).

C. NEXT GENERATION LOGISTICS SHIPS: REFUEL

Loseke and Yarnell (2020) analyzed the optimal types and quantities of NGLS required to meet given in-theater fuel demands of Expeditionary Advanced Base (EAB) nodes and a Surface Action Group (SAG) node. In their study, they define NGLS ships being comprised of three varieties, a Platform Supply Vessel (PSV), a Fast Supply Vessel (FSV), and a LAW. To make their determinations, they created a linear optimization model in excel using constraint and capacity data obtained from top-level requirements (TLRs) of each platform [using both the threshold (T) and objective (O) values] for each type of vessel as well as demand data for the EAB and SAG nodes obtained from OPNAV N4. To solve, their model uses the minimum number of deliveries as its objective function given the constraints and demand data previously mentioned. The analysis of their solution led to several determinations which they recommended to OPNAV N4. Some of these recommendations include: the capacity of the PSV should be targeted for the objective (O) value in the acquisition process, efforts should be made to eliminate or reduce delivery time constraints, and the LAW and FSV's performances are not enhanced by going above the threshold (T) level with delivery time constraints (Loseke & Yarnell, 2020).

D. NEXT GENERATION LOGISTICS SHIPS: SUPPORTING THE AMMUNITION AND SUPPLY DEMANDS OF DISTRIBUTED MARITIME OPERATIONS

Halligan, Brown, and Carlson (2020) analyzed the optimal types and quantities of NGLS required to meet given in-theater ammunition and supply demands of EAB nodes and a SAG node. In this study, NGLS ships were comprised of three varieties: a PSV, a FSV, and a LAW. Determinations were based using a linear optimization model in Microsoft Excel using constraint and capacity data obtained from top-level requirements (TLRs) of each platform [using both the threshold (T) and objective (O) values] for each type of vessel as well as demand data for the EAB and SAG nodes obtained from OPNAV N4. Because capacities of ammunition and supplies are more dependent on space (and not defined the way fuel is), the capacity of the vessel was determined by converting the dimensions of the cargo space in the vessel to the number of pallets that can be stored onboard. Then, the demand data was converted to specific provisions of pallets in order conduct their analysis. To solve, the model uses the minimum number of deliveries as its objective function given the constraints and demand data previously mentioned. The analysis led to determinations which were recommended to OPNAV N4. Some of these recommendations include further investigating the constraint of replenishment time limits within the Weapons Engagement Zone (WEZ) and favoring the use of the LAW over the FSV when sustaining inside the WEZ (Halligan et al., 2020).

E. SCHEDULING COMBAT LOGISTICS FORCE REPLENISHMENTS AT SEA FOR THE U.S. NAVY

Brown, DeGrange, Price and Rowe (2018) explored fuel cost savings achieved by the U.S. Navy using the Replenishment at Sea Planner (RASP) program to optimize the scheduling of its Combat Logistics Force (CLF) ships. The RASP program uses integer linear optimization and a purpose-built heuristic approach to provide efficient and time critical information to aid operational decision making by the schedulers on the numbered Fleet Staff. The CCDRs, Commander Task Force and MSC staff used a manual tracking process to populate a spreadsheet that displays a dashboard with the reported levels of the various supplies aboard surface combatants. RASP considers the myriad of surface combatants' (US Navy and Allied ships) reported data (food, fuel, ordinance, and water levels) used by the CCDRs to determine the mission and crew readiness of each unit and assess their ability to sustain military operations. RASP uses the reported data to create a Replenishment at Sea (RAS) schedule for CLF ships to rendezvous with U.S. navy ships starting with those with lowest reported levels of supplies (Brown et al., 2018).

The adoption of the Replenishment at Sea Planner (RASP) in 2013 resulted in several operational efficiencies through the reduction of fuel consumed by CLF ships as they make rounds in replenishing surface combatants with the necessary supplies. Prior to the adoption of the planner, all scheduling was done manually by the schedulers in the 5th and 7th Fleet AORs located in Bahrain and Yokosuka, respectively (Brown et al., 2018). This was a laborious process and often required several hours of data input of levels of critical supplies (POL, food, water, and ordinance) from each operational unit. This data was used to create a schedule for a replenishment ship to resupply the afloat units prioritizing those with the lowest reported supplies (Brown et al., 2018).

The RASP model was used to address the traditional problems associated with manual scheduling. These include issues such as the excessive time and efforts required to generate a schedule, conflicts that often arise from capacity constraints from the receiving units or members of a SAG or CSG and unexpected changes to schedule due to emergency or changes in assigned mission. The adoption of RASP in June 2013 resulted in tremendous saving to the Navy in the form of time savings to the scheduling staff to generate an efficient schedule for CLF ships that is flexible to incorporate unplanned changes in a dynamic operational environment (Brown et al., 2018).

F. OPTIMIZED TRANSIT TOOL AND EASY REFERENCE (OTTER) AND FUEL USAGE STUDY EXTENDED DEMONSTRATION (FUSED)

In October 2009, Secretary of the Navy Ray Mabus promulgated the Department of the Navy Strategy for Renewable Energy which charged the department with ambitious energy efficiency mandate spurring several innovative developments. Several initiatives proposed and developed with the goal of increasing DON's operational energy efficiency, including the development of Stern flaps for ships, anti-fouling paint for exterior surfaces below the water line on ships, advanced engineering dashboard that monitors ship's engine performance, energy efficient Light Emitting Diode (LED) bulbs to replace incandescent lights aboard all afloat platforms etc. (Dew et al. 2017). Additional planning tools such as the Transit Fuel Planner (TFP), Battlegroup Optimum Speed Calculator (BOSC), Optimized Transit Tool and Easy Reference (OTTER) and Fuel Usage Study Extended Demonstration (FUSED) were developed to help ship operators and engineering teams manage their fuel consumptions while simultaneously accomplishing the many evolutions required in the most efficient way (NPS, 2016).

1. TFP

A team of researchers and students at Naval Postgraduate School (NPS) developed the TFP in 2007 as a tool to help ships manage their fuel with different combinations of transit speed to maximize fuel efficiencies while minimizing consumption. It helps estimate the fuel needed at a future date by using an algorithm that calculates the consumption rate, fuel efficiency, current fuel level and distance to travel to derive the total fuel quantity needed. It calculates fuel efficiency by factoring the different engine configurations and operation modes, compares fuel use on various shaft use mode on the fuel consumption curve as compared to using a single transit speed. Some of the limitations of this tool include its failure to consider the various maneuvers with mandatory speed restrictions that affect the ship. Training evolutions, ship maneuvering training, drills, changes in operational schedules, policy and practice of operations underway, etc., all have significant impacts on fuel efficiency. Other issues include limited access to real-time operational data. These issues limit the usefulness of the results to the ship's watch team for situation specific decision making (NPS, 2016).

2. OTTER

OTTER is an improved and readily accessible tool similar to TFP but without much nuance. It is a smaller file size, more user-friendly to allow easier and faster user input to facilitate better decision making by presenting a simplified dashboard. It is used to find the efficient transit speed combination while factoring the various evolutions that impact underway operations (Blackburn, 2016).

3. FUSED

FUSED is another NPS developed, Microsoft Excel/Visual Basic Analysis (VBA) based fuel consumption model that could be used to track fuel usage of a single ship or a complete CSG. It corrects major deficiencies noted with TFP in that it considers a range of real-world operational practices that could impact fuel consumption. It also provides valuable output that is relevant to operational decision making.

FUSED was developed to address other issues, such as the potential to allow the user to decide what combination of operations policy to model, analyze the effects on fuel consumption and the attendant cost savings. It is also able to predict onboard fuel storage levels based on consumption, transit speed, operational practices employed, and distance to destination. It calculates the required volume of fuel required for each type of fuel onboard every unit tracked, the optimal time to resupply, time required for each resupply or RAS through a Connected Replenishment (CONREP) and the cost of the fuel received. Additionally, the model allows the user to input scenarios to simulate operations. It provides the flexibility to change many parameters, including the minimum fuel safety levels onboard to anticipate impacts and enable logistics planning support.

FUSED provides a wealth of information for logistics support staff, operation planners onboard ships and staff of the Combined Task Force or Geographical Combatant Commanders to aid mission tasking of units assigned. The model was found operationally relevant and has been utilized by several high echelon offices such as the Office of Chief of Naval Operations Logistics Directorate (OPNAV N45) to generate predictive models to assist logistics support planning (NPS, 2016).

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IV. METHODOLOGY: COMPUTER MODELING AND SIMULATION, EXPERIMENTATION

A. REPLENISHMENT AT SEA PLANNER MODEL

To determine the best combination of LAWs and NGLSs to support an MLR inside a WEZ in the INDOPACOM AOR, our study used RASP's linear optimization capability under several differing scenarios and initial conditions. We considered different levels of supporting surface assets, specifically LAWs and NGLSs, which investigated the required fuel supportability of a distributed MLR over a 30-day period using a legacy dual fuel concept. From the results of RASP's schedule optimization, we could determine the most successful combinations of surface assets to support a distributed MLR, and how increasing or decreasing the amounts of each asset would affect the MLR's ability to operate. Results from this simulation were utilized as direct inputs to investigate the second research question, addressed in the following sections.

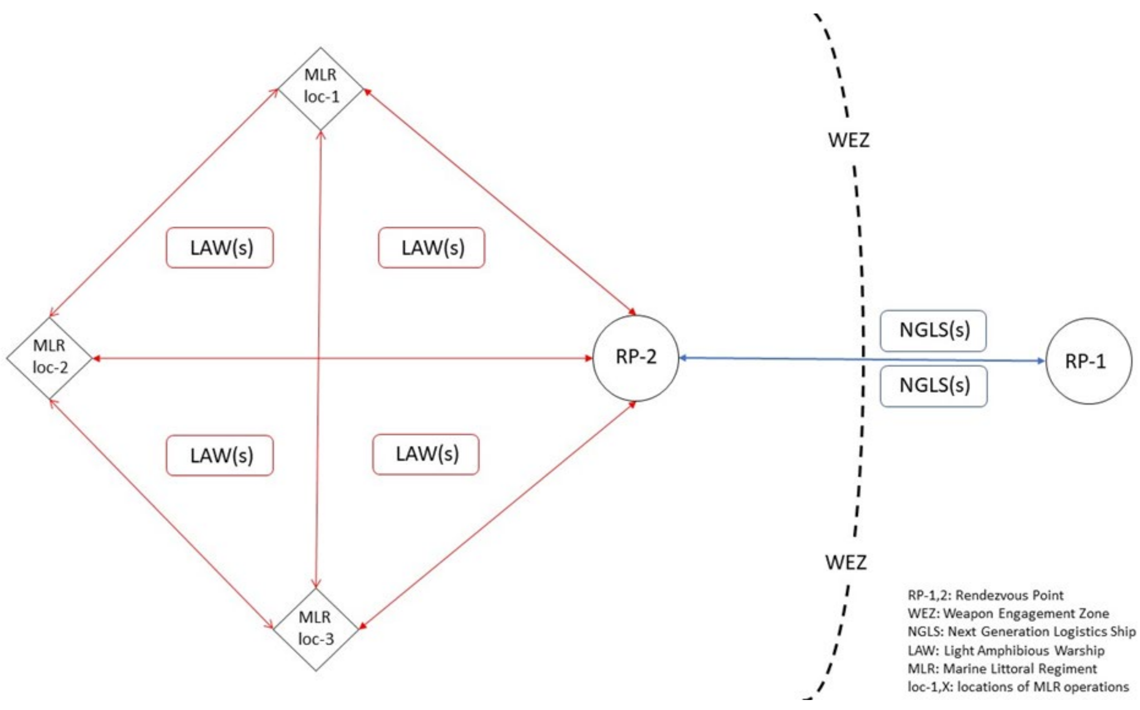
B. FUEL USAGE STUDY EXTENDED DEMONSTRATION MODEL

To determine the logistical benefits of a SFC compared to a legacy dual-fuel concept, our study used FUSED. With this model, we input the optimized schedule output from the most complex scenario investigated in RASP (Scenario 4), and the combination of LAWs and NGLSs that were determined to be the most successful at supporting the MLR in this Scenario, under two conditions. The first was a legacy dual fuel concept and the second was a single fuel concept, each supporting the associated distributed MLR for a period of 30 days. Results from each simulation allowed for points of comparison in establishing potential benefits to MLR supportability of a SFC versus the legacy dual fuel concept.

C. SCENARIOS

A set of theoretical scenarios that simulated a MLR operating in a contested environment in the INDOPACOM AOR was modeled. In each initial scenario, the MLR operated on JP-5 and the surface support assets operated on F-76, with a specific number of NGLSs resupplying JP-5 and F-76 at a rendezvous point outside of the WEZ. The method of resupply of NGLSs can be assumed to be via a CLF oiler, but this portion of the supply chain was not modeled. The NGLSs then transited into the WEZ to a second rendezvous point and resupplied a variable number of LAWs supporting the MLR. The resupply between the NGLS and LAW platforms was assumed to be a RAS event. The LAWs, as ship to shore connectors, then traveled to the various MLR locations as necessary.

The distribution of the MLR locations (MLR-locs) varied in four different configurations including a MLR dispersed between 3 locations (Scenario 1, illustrated in Figure 6), between 6 locations (Scenario 2), and between 9 locations (Scenario 3). The fourth configuration maintained the 9-location distribution of the MLR but incorporated a second NGLS and LAW rendezvous point (RP-3) (Scenario 4). Each scenario builds on Scenario 1 depicted in Figure 6 by adding either more MLR-locs or the additional NGLS and LAW rendezvous point, RP-3.



Single NGLS and LAW replenishment point and a 3 location MLR distribution.

Figure 6. Scenario 1

D. INPUT DATA

To keep this report unclassified, all distances incorporated are notional. The distances between all respective locations are presented in Table 1. Of note in the table, MLR locations 4 and 5, and locations 6 and 7 are collocated. For example, locations 4 and 5 are distributed units of the same MLR occupying the same distributed location, but with separate fuel demands and fuel capacities. The locations were initially considered to be separated by short distances (<20 nm) but were adjusted to be collocated due to limitations in the modeling programs.

Table 1. Notional Distances between Rendezvous Points (RP-1, RP-2, RP-3) and MLR-locs

Distances between points (nm)	RP 1	RP 2	RP 3	MLR LOC 1	MLR LOC 2	MLR LOC 3	MLR AREA 4 5	MLR AREA 6 7	MLR LOC 8	MLR LOC 9
RP 1	0	1,427	1,543	1,691	1,723	1,312	1,694	1,594	1,656	1,385
RP 2	1,427	0	146	295	326	145	296	196	259	87
RP 3	1,543	146	0	190	206	261	173	55	136	173
MLR LOC 1	1,691	295	190	0	394	410	361	242	324	306
MLR LOC 2	1,723	326	206	394	0	441	78	225	100	354
MLR LOC 3	1,312	145	261	410	441	0	412	311	374	124
MLR AREA 4 5	1,694	296	173	361	78	412	0	192	63	324
MLR AREA 6 7	1,594	196	55	242	225	311	192	0	154	224
MLR LOC 8	1,656	259	136	324	100	374	63	154	0	287
MLR LOC 9	1,385	87	173	306	354	124	324	224	287	0

The demand requirements and storage capacities for the MLR at each location were based on current equipment assigned and estimated daily usage data for routine operations of a MLR provided by USMC Operations Analysis Directorate (OAD). Based on this input, the overall MLR fuel demand was 22,669 gallons/day and the overall capacity was 103,620 gallons. The daily demand and capacities were distributed across the various MLR locations in a tiered manner yielding higher demand and storage at some locations to simulate operations such as FARP support and lower demand and storage at other locations to simulate lower fuel requirement operations such as anti-ship fire support. The tiered distribution is outlined in Table 2.

Table 2. Fuel Demand and Capacity by MLR Location

Scenario 1		Scenario 2		Scenarios 3 & 4	
3 MLR-locs		6 MLR-locs		9 MLR-locs	
MLR Location	% of Overall Demand	MLR Location	% of Overall Demand	MLR Location	% of Overall Demand
1	40%	1	20%	1	13.33%
2	33%	2	20%	2	13.33%
3	27%	3	16.5%	3	13.33%
		4	16.5%	4	11%
		5	13.5%	5	11%
		6	13.5%	6	11%
				7	9%
				8	9%
				9	9%

The demand trigger points for each MLR location were set such that the location required replenishment when they reached 34% of their full JP-5 fuel capacity. This value was selected to account for the potential austere nature of the MLR locations and the limited storage capacity available for the MLR overall. The LAW and NGLS surface assets had demand triggers set at 60% of each fuel capacity. Either JP-5 or F-76 could trigger a refuel in the system.

Surface asset inputs utilized in this study are outlined in Table 3. The surface assets were restricted to transit speeds of between 12–14 knots to ensure the most efficient use of fuel in support of the MLR. However, changes in operational conditions could require increased transit speeds. Additionally, an exact fuel transfer rate was not specified, but rather fuel transfer evolutions were restricted to two hours maximum per fuel transfer.

Table 3. LAW and NGLS Fuel Consumption and Capacity Values

	LAW	NGLS
Fuel Consumption (gal/hr) at:		
12 kts	164	463
13 kts	187	560
14 kts	210	658
Capacity (gal):		
F-76	105,840	861,000
JP-5	90,000	861,000

To further investigate supportability of a distributed MLR, the simulation was repeated with fuel demand of each MLR location increased from 100% to 150%, 200%, and 250% in every scenario. This increase in demand was selected to represent multiple situations including a potential transition of the force's role to one of combat operations requiring increased fuel usage, greater aviation activity in the area requiring increased fuel quantities for MLR FARP operations, or a combination of the two. Though fuel demand increased, the percentage distribution of fuel demand was maintained as outlined in Table 2. Table 4 displays the corresponding MLR Demand (and MLR Capacity, discussed later) values at the increased burn rates.

Table 4. MLR Demand and Capacity Variation for All Runs

Multiplier	MLR Demand (gal)	MLR Capacity (gal)
100%	22,669	103,620
150%	34,004	155,430
200%	45,338	207,240
250%	56,673	259,050

All above discussed data were directly utilized as inputs to the RASP model. Inputs to the FUSED model included the Scenario 4 MLR and rendezvous point distribution and associated distances, a 100% MLR demand and capacity, 34% MLR refuel trigger point, 60% surface asset refuel trigger point, and the most successful combination of LAWs and NGLSs as determined by analysis of the RASP results (7 LAWs and 2 NGLSs, discussed in Chapter V).

E. EXPERIMENTATION

1. FACTORS

In each scenario configuration, the number of NGLS and LAW platforms were varied to determine the platform combination to best support the MLR. LAW numbers were varied between 4 and 9 with the upper bound being the desired number of LAWs assigned to any MLR and the lower bound providing enough difference to understand how adjusting the number of LAWs affects MLR supportability (O'Rourke, 2022b). The number of NGLSs was either 1 or 2, as the overall number of NGLSs to be procured is currently expected to be limited (O'Rourke, 2022c).

As MLR fuel demand was increased, MLR fuel capacity was initially held constant to investigate the capability of the force to continue to operate with established capacity levels under increased demand. Then, MLR fuel capacity was increased in lockstep with the MLR fuel demand to understand how increased MLR fuel storage capacity could affect surface support vessel requirements. The potential for increasing MLR fuel capacity in alignment with their demand is an option being considered for MLRs, though the exact method of increasing demand, such as excess fuel bladders, is not yet defined. The increase in demand and capacity values are outlined in Table 4.

Overall, a total of 384 scenario variations were investigated with the RASP model to include the 4 scenarios adjusting MLR location distribution, the 4 varying fuel demand levels, the 2 options of MLR capacity either increasing with demand or staying constant, the 2 possible NGLS amounts, and the 6 possible LAW amounts. Each individual run in RASP was capped at a 3-hour time limit for the cases with 2 NGLSs and a 2-hour time limit for the cases with 1 NGLS. If an optimal scheduling solution for the considered number of each asset in any particular run was reached before the time limit, the run was considered complete. Otherwise, the run was stopped at the time limit and the best scheduling solution for the current combination of variables was captured. The only factor varied in the FUSED simulations was the fuel concept, either legacy dual fuel concept or a JP-5 SFC.

2. METRICS RETRIEVED FROM THE MODELS

The outputs from the RASP model consisted of three metrics known as "Objective Value" (OV), "Below Threshold Violations Percent" (BTV), and "Below Threshold Max Percent" (BTM). The OV is the value of the objective function driving the optimization behind RASP. For the purposes of this thesis, every instance of surface support assets being unable to provide an MLR-loc with their requested fuel resulted in a negative "penalty" against the OV. An OV equal to zero denoted a situation where all demand for JP-5 by the MLR was met, while the more negative (< 0) the objective value was, the greater the number of instances of unmet fuel demand. The BTV metric was a measure of how often any MLR-loc went without their requested demand. Whether an MLR-loc had demand not met by 1 gallon or 1,000 gallons, the demand was considered unmet. A BTV value of 0% denoted a situation where all demand for JP-5 by the MLR was met, while a value of 100% denoted that no JP-5 demand was met. Finally, the BTM metric described just how significant the missed demand was in any instance as a percentage of overall MLR-loc capacity. Thus, if the BTM were 1%, this denoted the MLR-loc was down to 33% (1% below the trigger value of 34%). A BTM of 34% denoted an MLR-loc running out of fuel entirely. This value can exceed 34% (empty) in some cases, which translates to amounts of fuel that the MLR-loc would have used to conduct planned operations, had they been provided with the fuel. The metric can be considered a running tally of missed fuel requirements in the cases where it exceeds 34%.

The outputs of FUSED consisted of the number of RAS events, total fuel burned by the LAWs, total fuel burned by NGLSs, and total fuel delivered to the MLRs. Comparison of the results under both a dual fuel concept and JP-5 SFC allowed for an understanding of the effects of supporting a MLR under each fuel concept, as well as any potential benefits or drawbacks on operational reach.

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V. RESULTS

A. RASP RESULTS

Results are broken down by Scenarios, where Scenario 1 corresponded to the MLR being distributed across 3 MLR-locs with a single NGLS and LAW rendezvous point, as illustrated in Figure 6 in Chapter IV. Scenario 2 involved the MLR being distributed across 6 MLR-locs with a single NGLS and LAW rendezvous point. Scenario 3 involved the MLR being distributed across 9 MLR-locs with a single NGLS and LAW rendezvous point. Scenario 4 involved the MLR being distributed across 9 MLR-locs with 2 NGLS and LAW rendezvous points.

Results are organized into figures displaying four quadrants with the top left detailing a single NGLS supporting the scenario with the MLR capacity fixed as demand was increased. The bottom left described a single NGLS supporting the scenario with MLR capacity increased in lockstep with the MLR demand. The top right details 2 NGLSs supporting the scenario with MLR capacity fixed as the demand increased. The bottom right detailed 2 NGLSs supporting the scenario with MLR capacity increased in lockstep with the MLR demand. In all quadrants, the x-axis displays the varying number of LAWs and each of the 4 lines corresponds to the MLR demands, or fuel burn rates of 100% (1), 150% (1.5), 200% (2), and 250% (2.5).

1. SCENARIO 1 (3 MLR-locs, 1 NGLS/LAW Rendezvous Point)

Scenario 1 considered a MLR distribution across three locations with one replenishment point inside the WEZ. Figure 7 displays the OV results, Figure 8 displays the BTV results, and Figure 9 displays the BTM results.

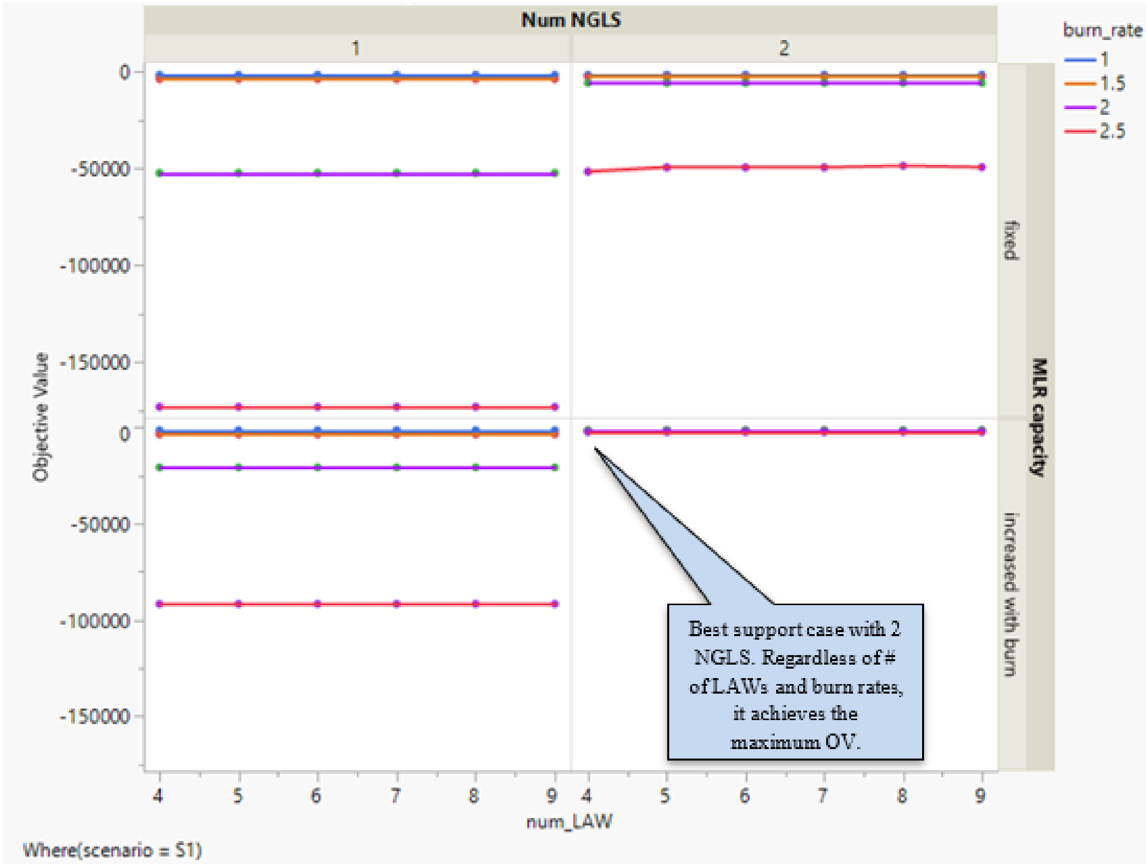

Figure 7. Scenario 1 OV Results

Figure 7 displays the OV results for Scenario 1. In this scenario, we see that varying the number of LAWs supporting the distributed MLR has minimal effect on supportability, which is indicated by the flat lines. The value of the OV remains constant for each MLR burn rate, number of NGLSs, and fixed/non-fixed capacity. The MLR is well supported with only one NGLS and fixed capacity up to the 100% and 150% burn rates. However, any burn rate higher than 150% required either an additional NGLS, an increase in capacity at the MLR site, or both to increase support to the MLR. Additionally, the results show that increasing capacity at the MLR site has a greater effect on MLR supportability than increasing the number of NGLS, with the combination of both producing the best results.

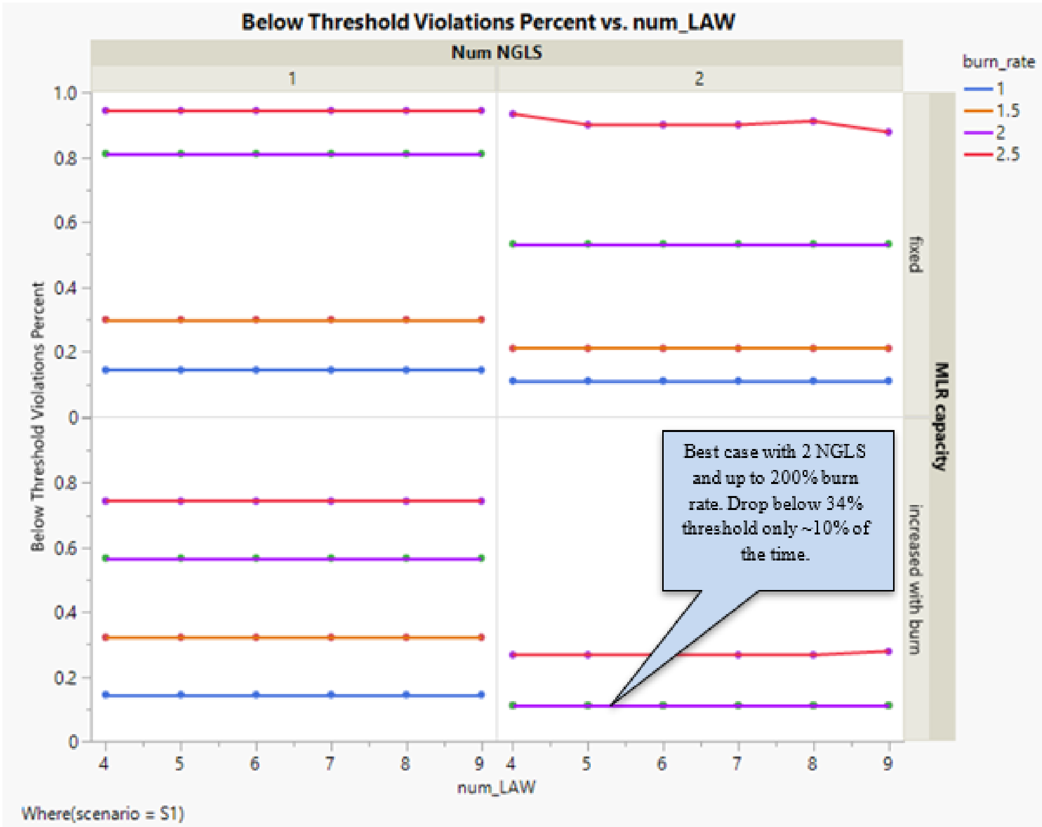

Figure 8. Scenario 1 BTV Results

Figure 8 displays the BTV results for Scenario 1. The trends for each burn rate provide similar results compared to Figure 7 in that varying the number of LAWs did not affect fuel supportability of the MLR evidenced by flat trend lines for each burn rate. A single NGLS and fixed MLR capacity is most viable at 100% and 150% burn rates, and can be improved by adding a second NGLS, increasing the MLR fuel capacity, or both to provide the most optimal result. Unlike the OV results, capacity increase has a greater effect at the 250% fuel burn rate than a second NGLS, reducing the percentage of time the MLR fuel demand was not met from above 90% to below 80%. With 2 NGLSs supporting and an increased fuel capacity, the MLR is well supported up to a 200% burn rate, with stores dropping below the safety value of 34% roughly 10% of the time. In the worst case of a 250% burn rate, support by 2 NGLSs and increased fuel capacity only resulted in the MLR dropping below safety levels 25% of the time.

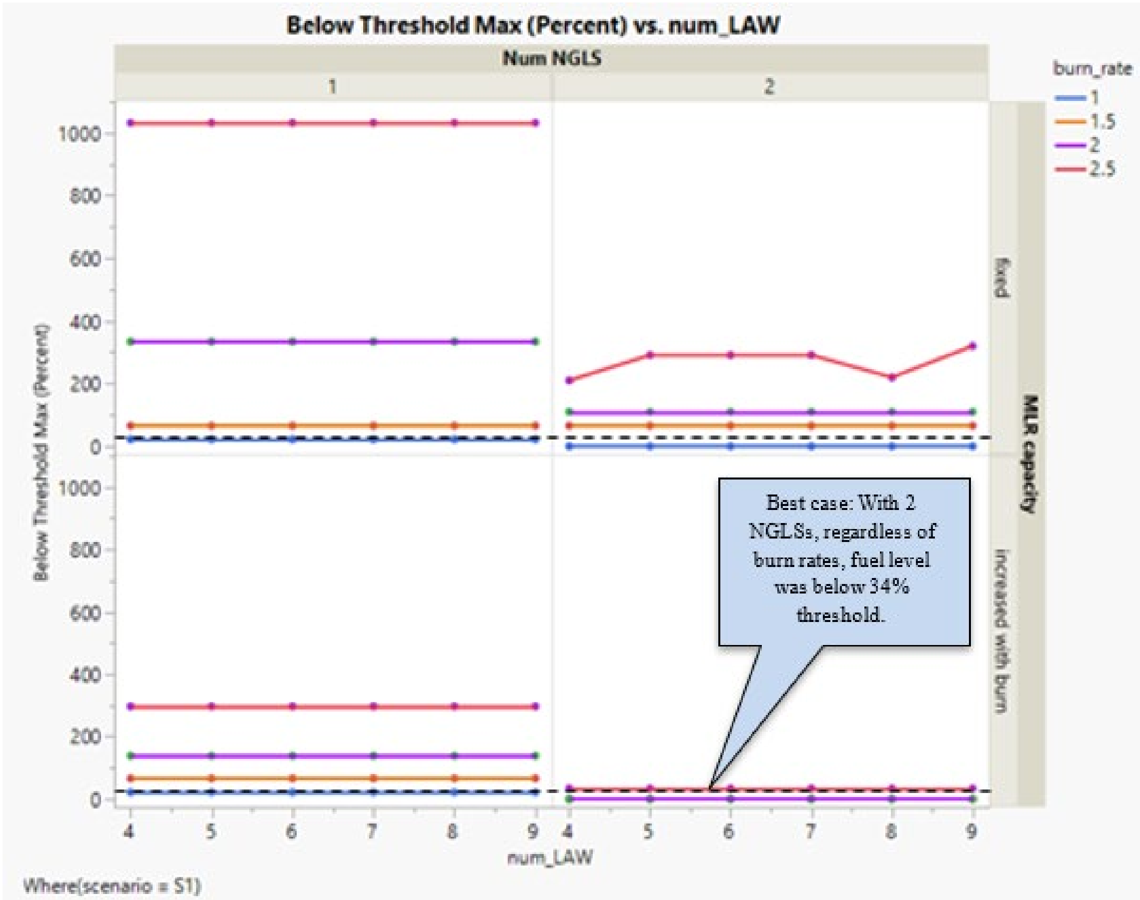

Figure 9. Scenario 1 BTM Results

Figure 9 displays the BTM results for Scenario 1 with the safety level of 34% represented by the black dashed line. Like the previous two results, varying the number of LAWs had no effect on how severe of a fuel deficit the MLR encountered. With a single NGLS, regardless of the number of LAWs employed and MLR capacity being fixed or increased, only the 100% burn rate was fully supported with a BTM of 22%, meaning fuel levels dropped to 12% of storage capacity before being replenished. With 2 NGLSs and a fixed capacity, the 100% burn rate had a BTM of 0%, indicating the MLR never fell below the trigger value of 34% of fuel stored. Only in the case of the 2 NGLS with an ability to increase capacity at the MLR was the BTM held below the trigger value for burn rates greater than 100%. The 150% and 200% burn rate yielded a BTM of 0% and the 250% burn rate reached the trigger value. This means that with 2 NGLS where a MLR can increase its fuel capacity, they would be able to operate up to the 200% burn rate without running out of fuel. If operating at 250%, they could still be supported but would fully exhaust their stores upon replenishment.

Scenario 1 results suggest that in a very simple MLR distribution of 3 locations, increasing the number of LAWs greater than 4 has little effect on MLR supportability. There is an improvement in supportability when NGLSs are increased to 2, and the only way the MLR could be supported at burn rates more than 100% is if MLR fuel capacity were allowed to increase in lock step with MLR fuel demand.

2. SCENARIO 2 (6 MLR-locs, 1 NGLS/LAW Rendezvous Point)

Scenario 2 considered a MLR distribution across six islands with one replenishment point inside the WEZ. Figure 10 displays the OV results, Figure 11 displays the BTV results, and Figure 12 displays the BTM results.

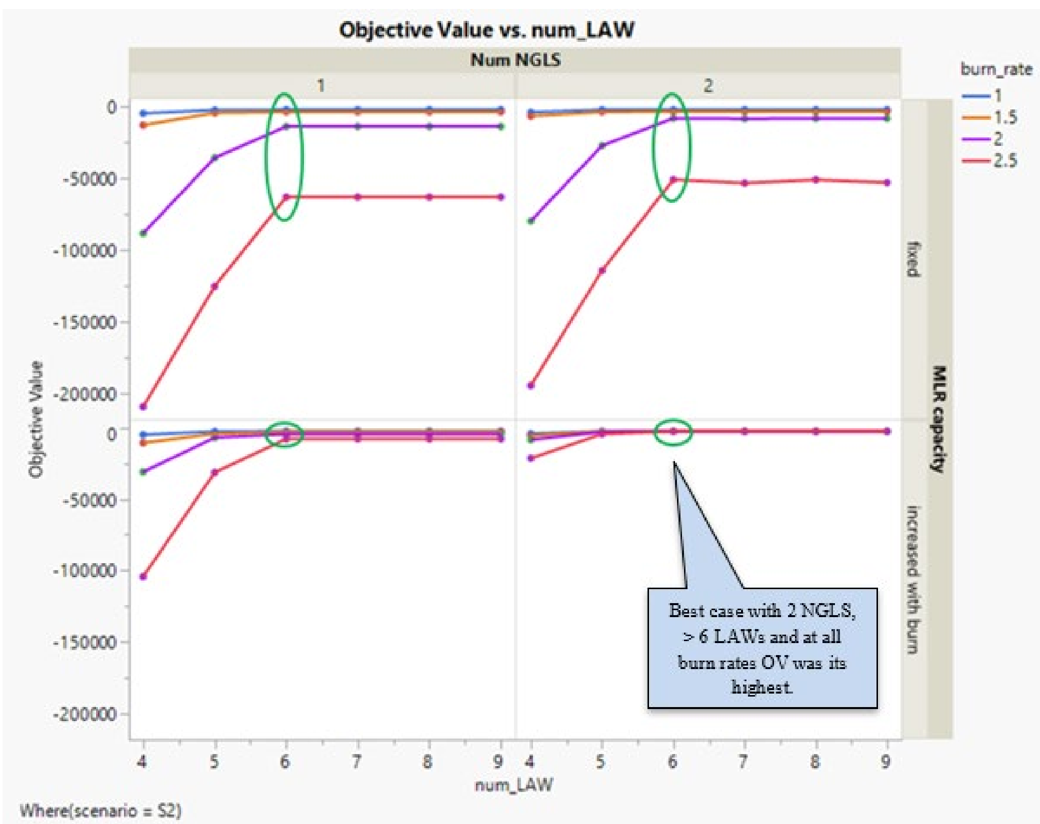

Figure 10. Scenario 2 OV Results

Figure 10 displays the OV results for Scenario 2. In all cases examined, the highest OV for all burn rates occurred at 6 LAWs, with no further increase when adding more LAWs. This point is circled in green for each curve. As the burn rates increased, the highest OV point for each curve decreased, confirming that it is more difficult to support the MLR at higher fuel usage rates, as expected. With a fixed capacity at the MLR locations and with 6 or more LAWs, the 100% burn rate was equally supported with both 1 and 2 NGLSs and the higher burn rates were slightly better supported when adding an additional NGLS. For burn rates higher than 100%, the peak OV was highest with 2 NGLSs and increased capacity, as the combination of the two compounded the overall supportability. From this metric, 6 LAWs proved the most successful at supporting the MLR considering all combinations of variables.

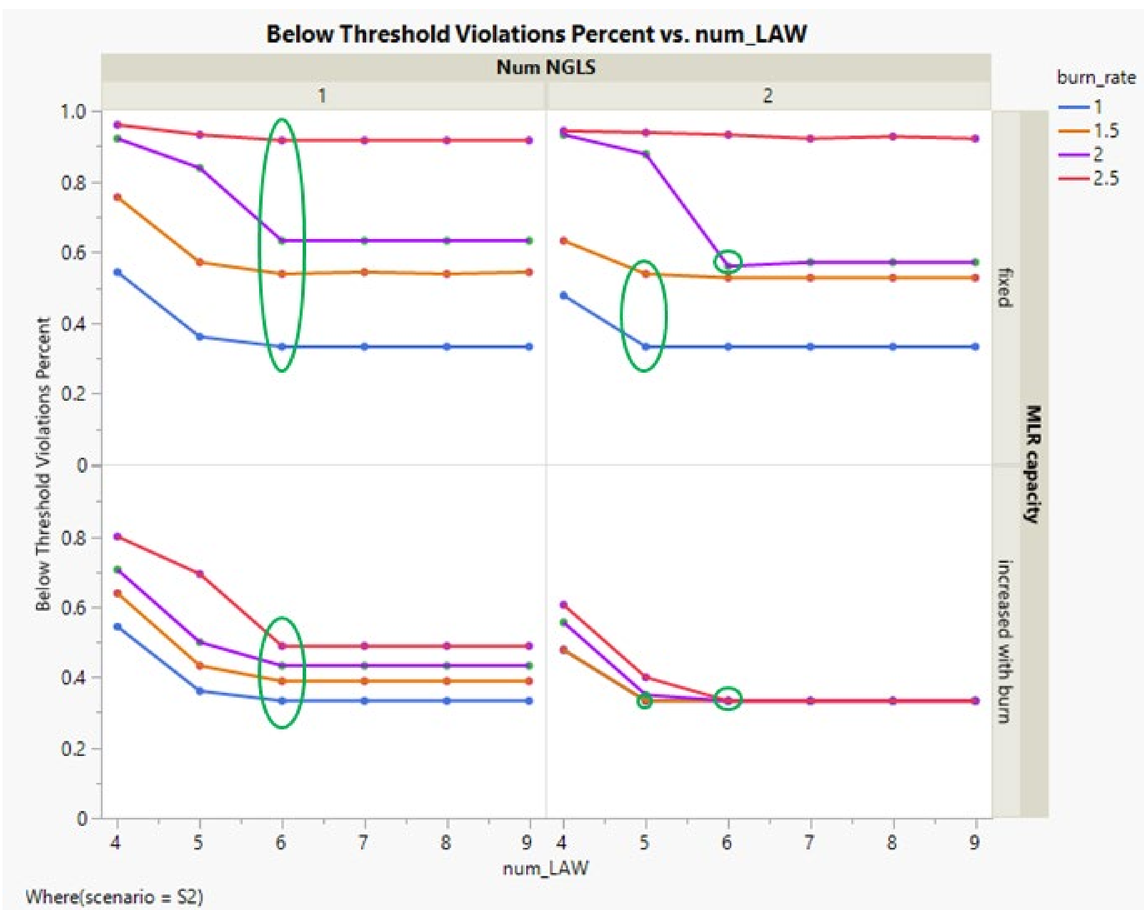

Figure 11. Scenario 2 BTV Results

Figure 11 displays the BTV results for Scenario 2. In most instances, MLR locations had their demand met most frequently when supported by 6 or more LAWs. These points are outlined in green in Figure 11. When capacity was fixed at the MLR site, the 100% burn rate yielded the best results, only going below their trigger value 33% of the time. The higher burn rates with both 1 and 2 NGLSs went below their trigger values greater than 50% of the time with the highest burn rate of 250% spending greater than 90% of the time. Adjusting the number of NGLSs to 2 lowered the number of LAWs required to 5 only for the 100% and 150% burn rates. Allowing capacity to adjust at the MLR site yielded much better results at the higher burn rates, substantially lowering the percentage of time that the MLR location spent below its trigger value. As shown in the lower right quadrant, applying 2 NGLSs and allowing MLR capacity to increase yielded the best results for MLR supportability with all burn rates spending the same percentage of time below the trigger point when 6 or more LAWs were used. At the 100% and 150% burn rates, 5 or more LAWs was acceptable to minimize percentage of time below the trigger value. Overall, these results reinforce the potential for 6 LAWs to prove most successful under all other combinations of variables.

Figure 12 displays the BTM results for Scenario 2 with the trigger value of 34% represented by the black dashed line. With a single NGLS, regardless of MLR capacity, only the MLR using fuel at a 100% burn rate was able to be maintained without exhausting all fuel stores. This case required 6 (outlined in green) or more LAWs, resulting in a BTM value of 0% with no further improvements when adding additional LAWs. Any less than 6 LAWs resulted in the MLR running out of fuel prior to replenishment. Allowing capacity to increase improved supportability considerably for higher burn rates. However, they remained above the trigger value line where all stores were exhausted prior to replenishment. Adding a second NGLS with fixed MLR capacity yielded a similar result in that only the 100% burn rate was able to be supported without exhausting fuel supply completely prior to replenishment, however this adjustment causes the number of LAWs required for supportability to lower to 5 or more with no further improvement when adding any additional LAWs. When 2 NGLSs are utilized with increasing MLR capacity, the MLR can be fully supported without exhausting all fuel stores under all burn rates, requiring 5 or more LAWs for the 100% and 150% burn rates and 6 or more LAWs for the 200% and 250% burn rates. A BTM of 0% was achieved for the 100% and 150% burn rates with 5 LAWs and achieved for the 200% burn rate with 6 LAWs. The 250% burn rate resulted in a 3% BTM, meaning the MLR dipped to just 31% of its fuel storage prior to replenishment.

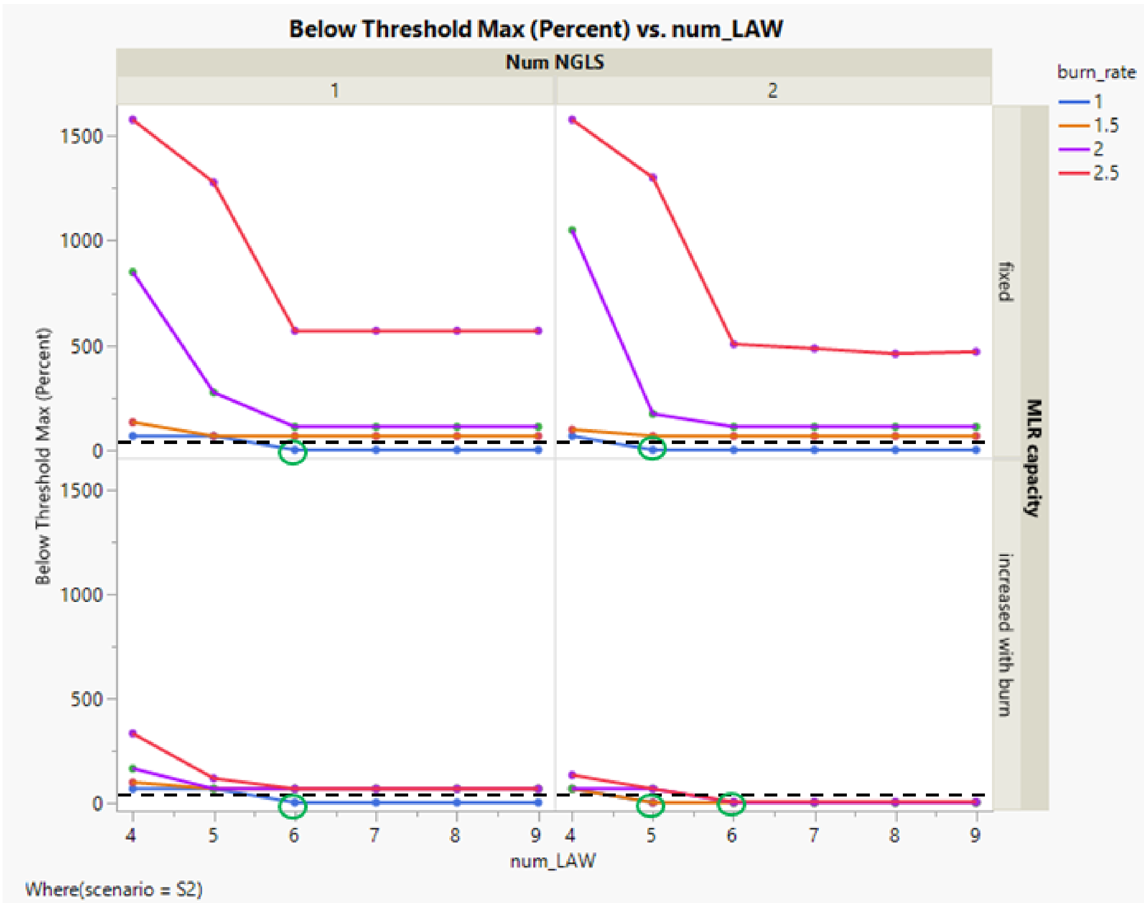

Figure 12. Scenario 2 BTM Results

The Scenario 2 results demonstrate the potential of 6 LAWs and 2 NGLSs to provide sufficient support for the MLR under most conditions. Additionally, they demonstrate the inability to provide support in all instances of MLR burn rate greater than 100% when MLR capacity is not allowed to increase with burn rate.

3. SCENARIO 3 (9 MLR-locs, 1 NGLS/LAW Rendezvous Point)

Scenario 3 considered a MLR distribution across nine islands with one replenishment point inside the WEZ. Figure 13 displays the OV results, Figure 14 displays the BTV results, and Figure 15 displays the BTM results.

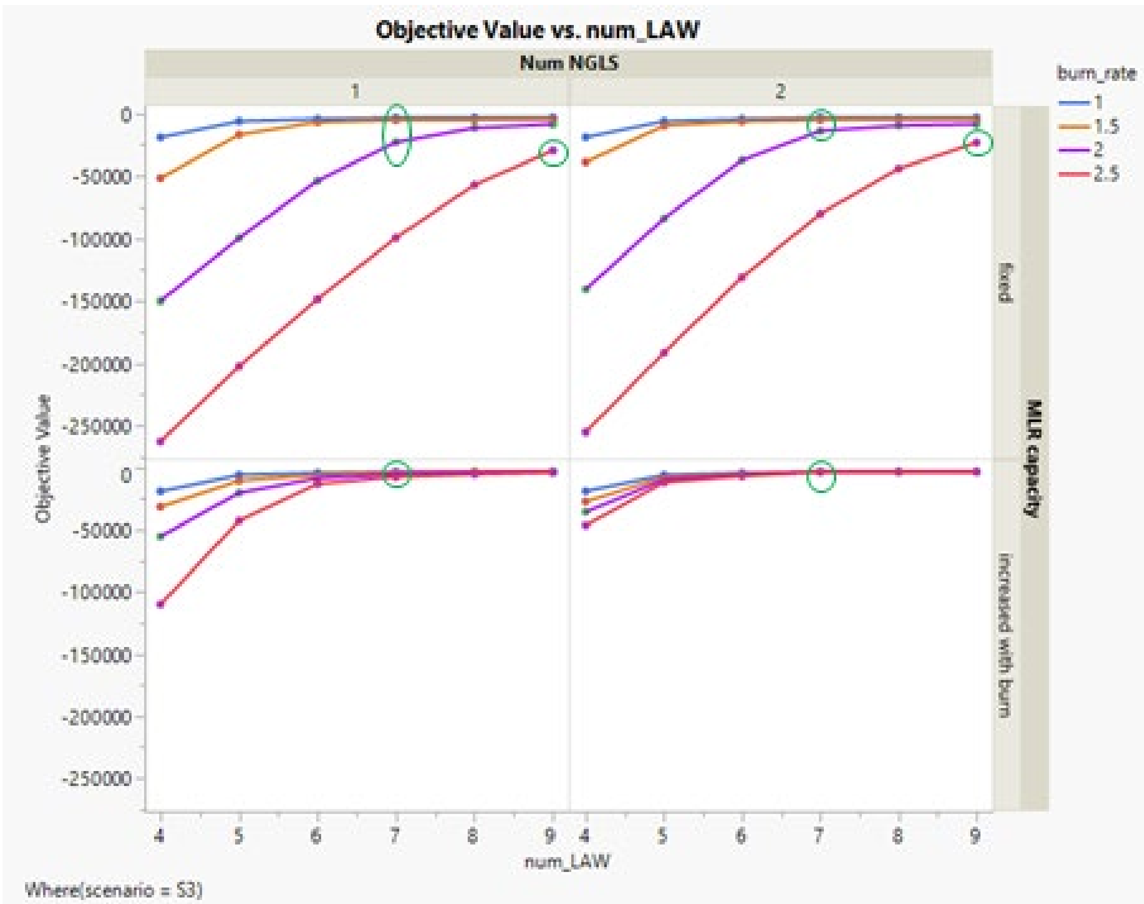

Figure 13. Scenario 3 OV Results

Figure 13 displays the OV results for Scenario 3. With a single NGLS and fixed MLR capacity, the 100% and 150% burn rates reached their peak OV with 7 LAWs employed and the 200% burn rate demonstrated a knee in the curve with 7 LAWs employed (denoted in green in the figure) indicating decreased supportability with any less LAWs. The 250% burn rate demonstrated a high reduction in supportability when any less than 9 LAWs were utilized. When capacity is allowed to increase at the MLR site, the magnitude of worst-case OV is much smaller in all cases with higher than 100% burn rates, with knees in every curve at employment of 7 LAWs, and peak OV points almost equal for all burn rates with 9 LAWs employed. With 2 NGLSs and a fixed MLR capacity, the OV results are similar to the single NGLS and fixed MLR capacity case, with the addition of a second NGLS producing minimal improvement. When MLR capacity is allowed to increase with 2 NGLSs, the greatest supportability for all conditions is observed.

All burn rates demonstrate a knee in the curve at 5 LAWs and hit their peak OV with 7 LAWs utilized. These results suggest that 7 LAWs could prove the most successful in supporting a MLR under a Scenario 3 distribution.

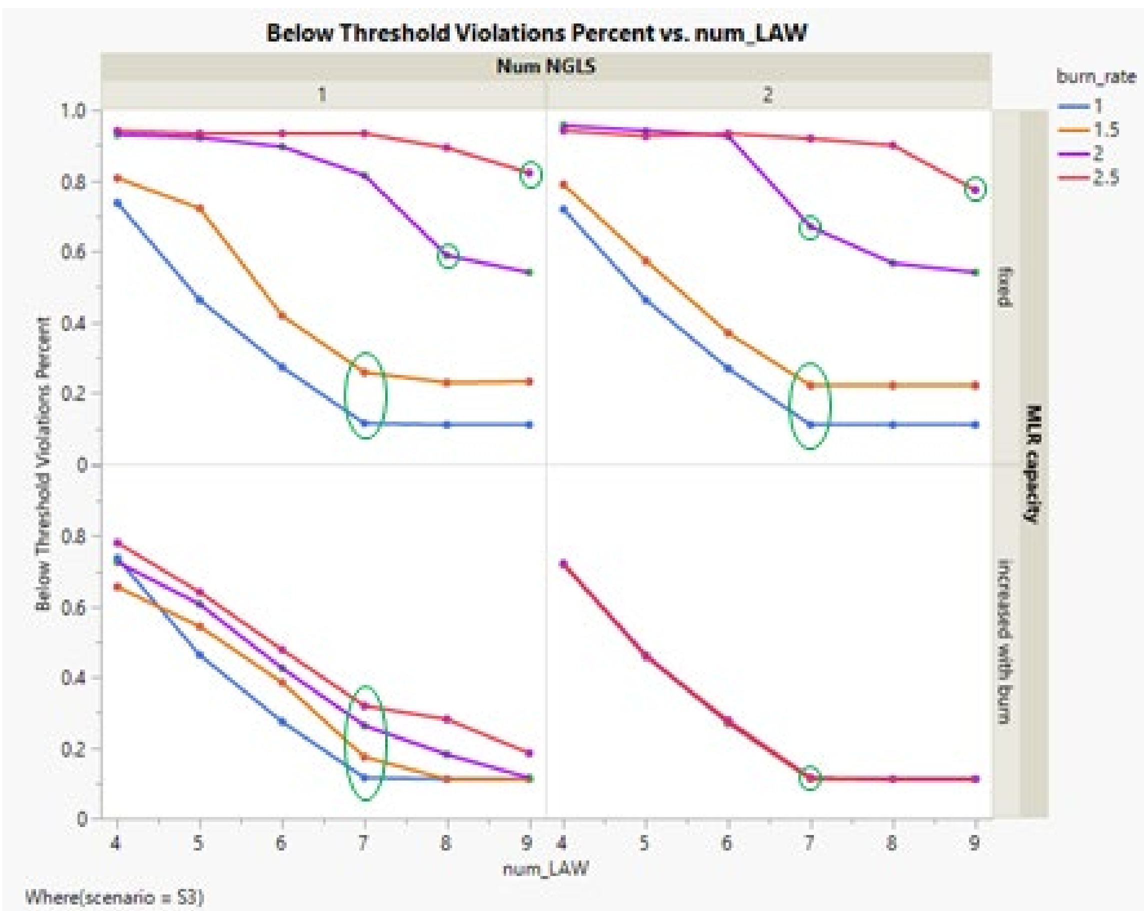

Figure 14. Scenario 3 BTV Results

Figure 14 displays the BTV results for Scenario 3. With one NGLS and fixed MLR capacity, the 100% and 150% burn rates achieved highest supportability with 8 or more LAWs but demonstrated knees in the curve at 7 LAWs (denoted in green in the figure). This knee demonstrates that increasing from 6 LAWs to 7 LAWs improved the BTV metric (or decreased the amount of time the MLR dropped below their fuel trigger value) by 15% and 16% for the 100% and 150% burn rates respectively, while increasing from 7 to 8 LAWs only improved the BTV by 1% and 3% for the 100% and 150% burn rates respectively. The 200% burn rate was best supported with 9 LAWs with a knee in the curve at 8 LAWs. The 250% burn rate saw a considerable decrease in supportability with any number of LAWs below 9 yet was below the fuel trigger value 82% of the time. When MLR site capacity was allowed to increase with burn rate, all burn rates demonstrated a knee in the curve at the employment of 7 LAWs, with much improvement in supportability when increasing from 6 to 7, although the 200% burn rates improvement was the least prominent. 100% and 150% burn rates achieved maximum supportability at 8 LAWs while 200% and 250% burn rates max were at 9 LAWs. When a second NGLS was added with a fixed MLR capacity, 100% and 150% burn rates reached their maximum supportability and the 200% rate demonstrated a knee in the curve with 7 LAWs. The 250% burn rate was best supported with 9 LAWs utilized yet was below the trigger value nearly 80% of the time. When 2 NGLSs were employed and MLR capacity was allowed to increase, all burn rates demonstrated similar results with a major knee in the curve at 7 LAWs. With 7 LAWs, maximum supportability for the 100% and 150% burn rates was achieved at 11% BTV, and the 200% and 250% burn rates at 12% BTV. These results reinforce the potential benefit of using 7 LAWs to support scenario 3.

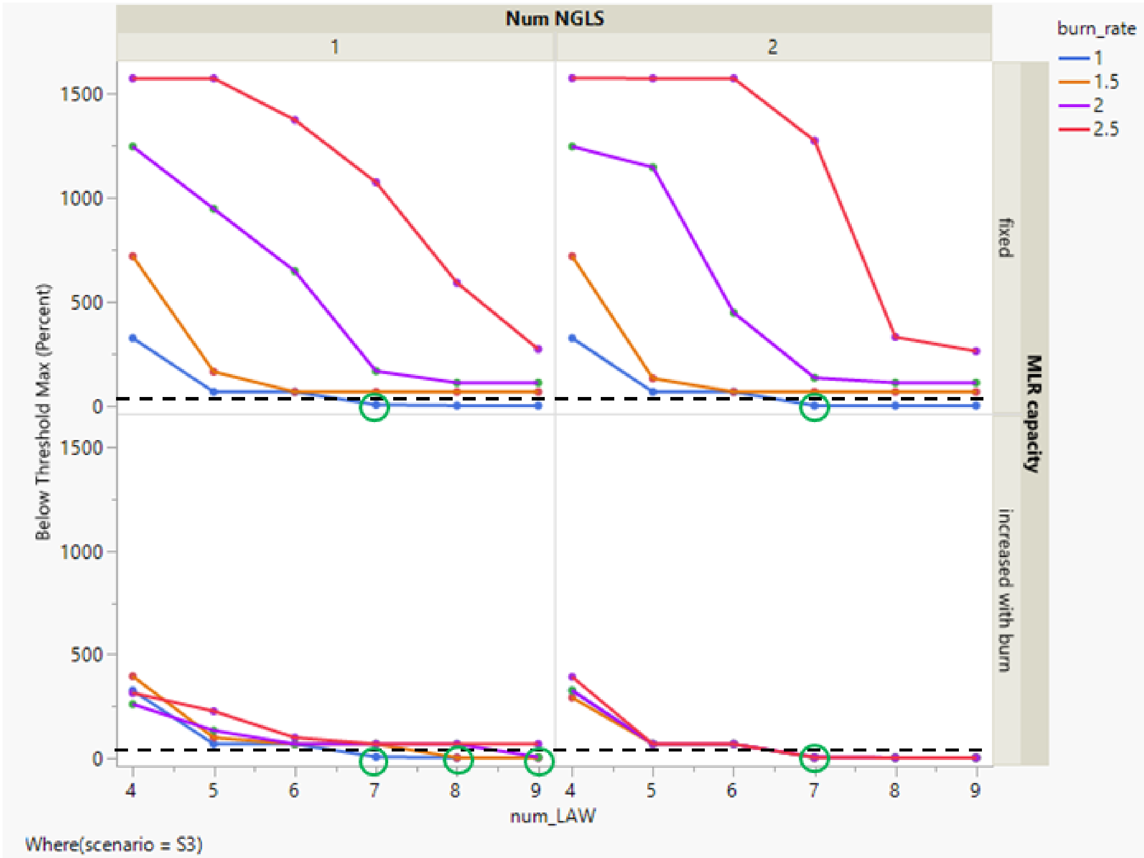

Figure 15. Scenario 3 BTM Results

Figure 15 displays the BTM results for Scenario 3 with the trigger value of 34% represented by the black dashed line. When a single NGLS was used with fixed MLR capacity, the MLR was only supported without exhausting all fuel stores at a 100% burn rate. Under this burn rate, the MLR required 7 or more LAWs to not completely exhaust its fuel, dipping to just 30% of its overall capacity before replenishment (BTM value of 4%). The BTM was 0% for any number of LAWs greater than 7 at the 100% burn rate. When capacity was allowed to increase with burn rate, the 100% burn rate had the same results as the 1 NGLS and fixed capacity case, however the 150% burn rate was able to be supported without exhausting fuel stores when 8 or more LAWs were employed, and the 200% burn rate was supported with 9 LAWs. When 2 NGLSs were used with fixed MLR capacity, only the 100% burn rate was fully supported before exhausting all fuel, resulting in a BTM of 0% at 7 or more LAWs. Any fewer LAWs resulted in the MLR running out of fuel prior to replenishment. When capacity was allowed to increase with 2 NGLSs employed, all burn rates could be supported without running out of fuel prior to replenishment. With 7 LAWs employed, the 100% and 150% burn rates were fully supported with a BTM of 0%, and the 200% and 250% burn rates had BTMs of 3% and 2% respectively, meaning overall capacity only dropped to 31% and 32% respectively. More than 7 LAWs resulted in all burn rates having a BTM of 0%.

Scenario 3 results demonstrate the effectiveness of 7 LAWs to support a MLR distributed in a more complex manner, and also demonstrated valuable improvements to supportability with 2 NGLSs employed instead of 1. Scenario 3, as with Scenario 2, highlighted that unless MLR fuel storage capacity is allowed to increase with burn rate, it is not possible to support a burn rate higher than 100%.

4. SCENARIO 4 (9 MLR-locs, 2 NGLS/LAW Rendezvous Points)

Scenario 4 considered a MLR distribution across nine islands with two possible replenishment points inside the WEZ. Figure 16 displays the OV results, Figure 17 displays the BTV results, and Figure 18 displays the BTM results.

Figure 16 displays the OV results for Scenario 4. When a single NGLS was used with fixed MLR capacity, the 100% and 150% burn rates demonstrated best supportability and the 200% burn rate demonstrated a knee in the curve at 7 LAWs. The 250% burn rate showed decreased supportability of the MLR when any less than 9 LAWs were employed. When MLR capacity was allowed to increase with burn rate, all burn rates demonstrated a knee in the curve at 7 LAWs, with supportability decreasing considerably when lowering to 6 LAWs, and only slightly increasing when raising to 8 LAWs. When a second NGLS was added with fixed MLR fuel capacity, results were similar to the 1 NGLS and fixed capacity case except the 100% and 150% burn rates demonstrated a strong knee in the curves at 5 LAWs but was supported best at 7 LAWs. The 200% burn rate demonstrated a knee in the curve at 7 LAWs, while the 250% burn rate demonstrated decreased supportability of the MLR with any less than 9 LAWs supporting. Overall, allowing capacity to increase at the MLR site had a greater impact than adding an additional NGLS in improving MLR supportability with fewer LAWs.2 NGLSs and MLR capacity allowed to increase produced the best results with all burn rates achieving their maximum supportability when 7 or more LAWs are employed, though a knee is present in all curves at 5 LAWs. These results suggest the potential success of 7 LAWs in supporting a MLR under Scenario 4.

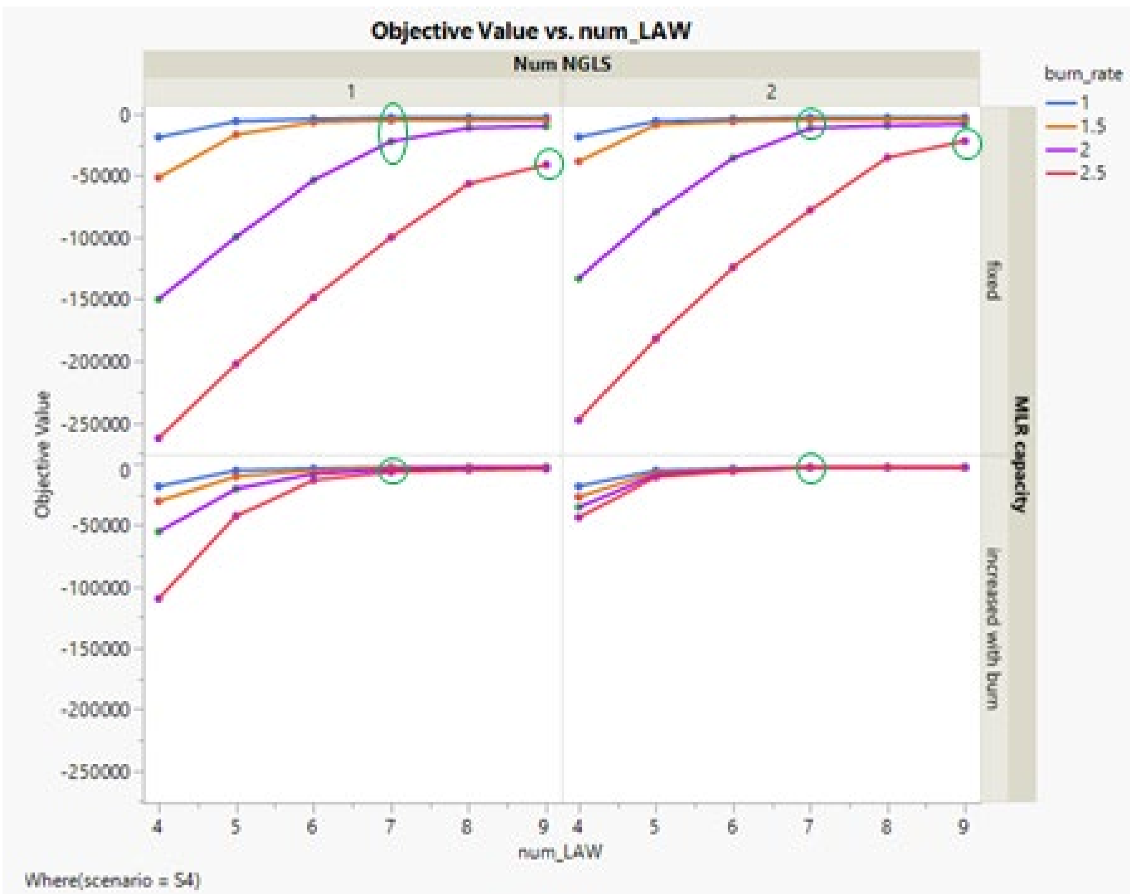

Figure 16. Scenario 4 OV Results

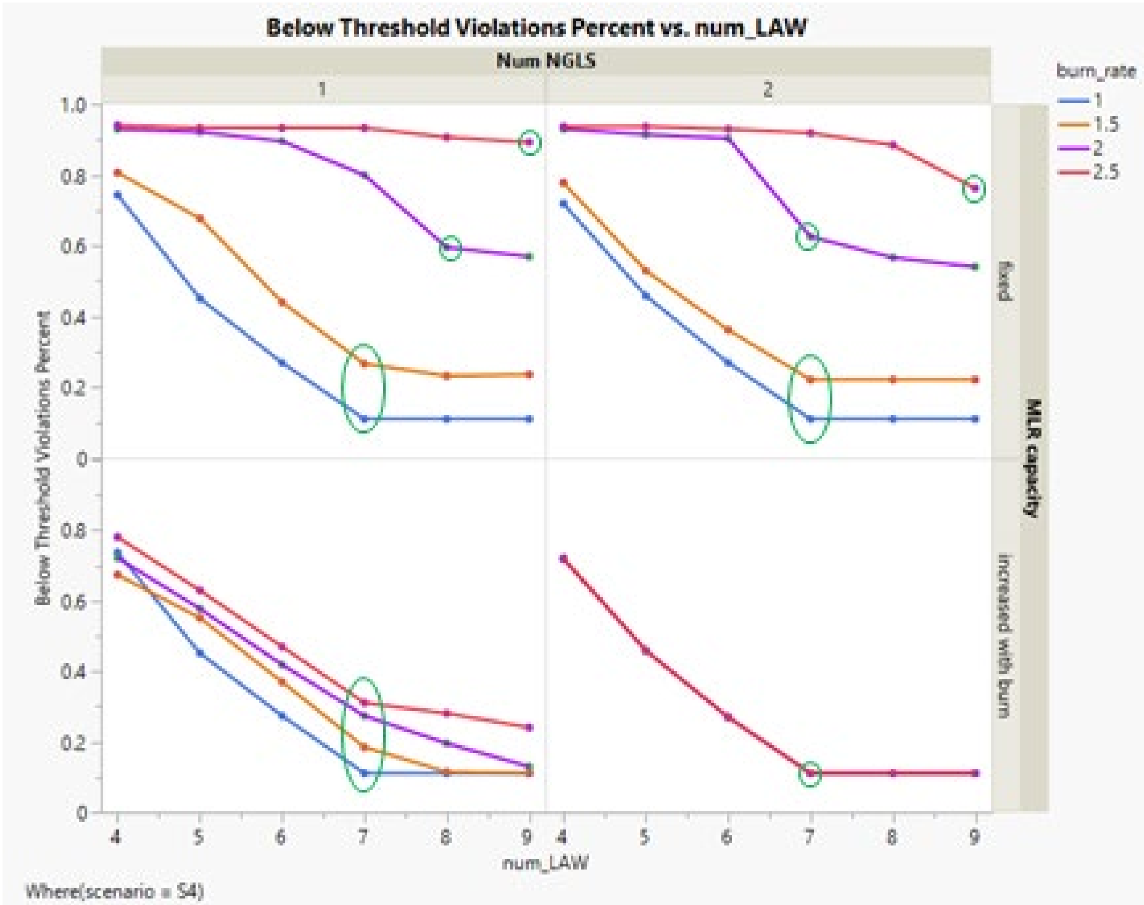

Figure 17. Scenario 4 BTV Results

Figure 17 displays the BTV results for scenario 4. With a single NGLS and fixed MLR capacity, the 100% and 150% burn rates were best supported with 7 or more LAWs, with time spent below trigger level values increased considerably if less LAWs were employed. The 200% burn rate was best supported by 9 LAWs but demonstrated a knee in the curve when 8 LAWs were utilized with only a 3% higher BTV. The 250% burn rate was best supported by 9 or more LAWs, however at 9, the MLR was poorly supported with it spending 89% of the time below its 34% fuel trigger value. When MLR capacity was allowed to increase with burn rate, all burn rates saw much improvement with up to 7 LAWs, with the burn rates showing only minor increases with any additional LAWs employed. Allowing MLR fuel capacity to increase greatly improved the ability to support the MLR at higher burn rates. For example, with 7 LAWs employed, the 150%, 200%, and 250% burn rates had BTVs drop by 8%, 60%, and 62% respectively when capacity was allowed to increase. When a second NGLS was added with fixed MLR capacity, the 100%, 150%, and 200% burn rates demonstrated knees in the curve at 7 LAWs. At the 250% burn rate, any less than 9 LAWs resulted in much reduced supportability, with 9 LAWs leaving the MLR spending 76% of the time below the trigger value.

With 2 NGLSs and MLR capacity allowed to increase, all burn rates saw the best results with all best supported by 7 LAWs at a BTV value of 11%. These results assert that the employment of 7 LAWs proved most successful in supporting a MLR in scenario 4.

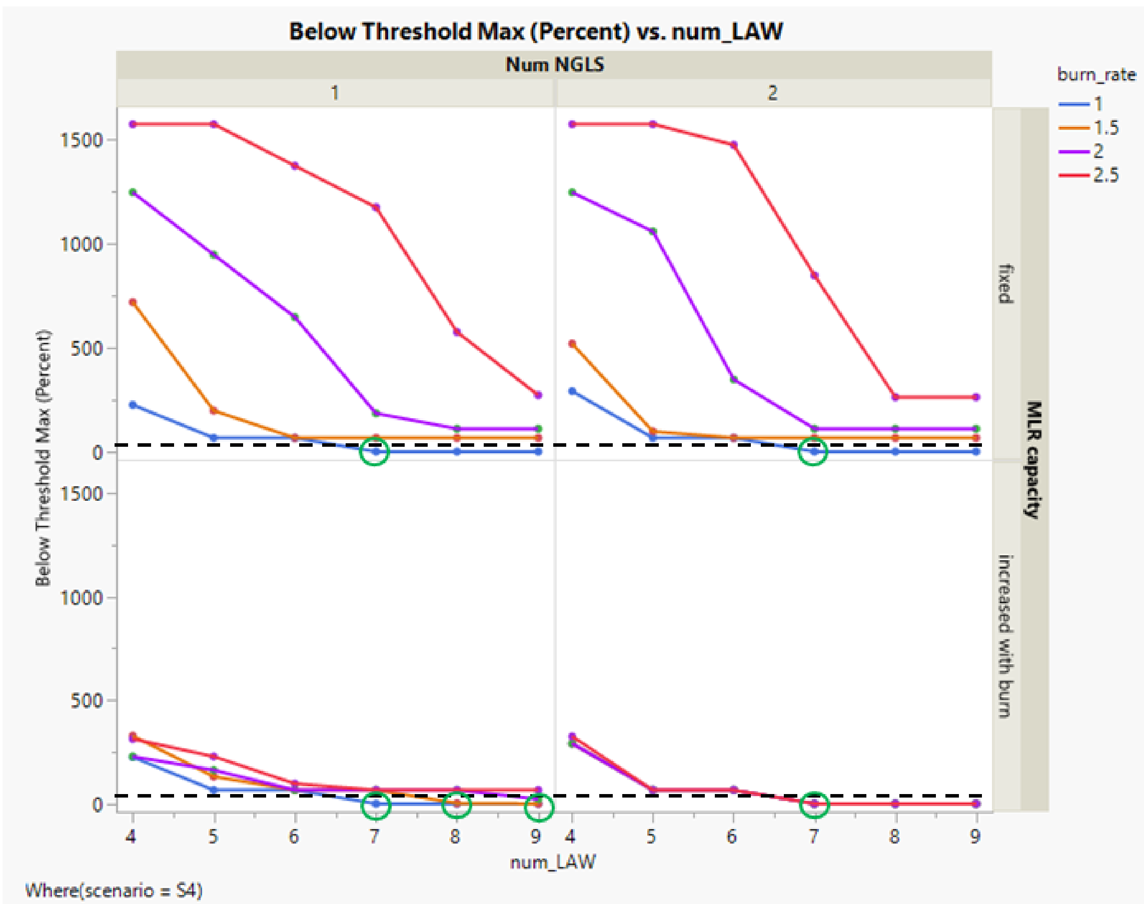

Figure 18. Scenario 4 BTM Results

Figure 18 displays the BTM results for Scenario 4 with the trigger value of 34% represented by the black dashed line. With one NGLS and fixed MLR capacity, only the

100% burn rate with 7 or more LAWs resulted in the MLR not exhausting their stored fuel prior to replenishment. Adding more LAWs did not improve the 100% burn rate's supportability. When MLR capacity was allowed to increase, the 100% burn rate saw the same results, while the 150% and 200% burn rates were able to be supported by 8 LAWs and 9 LAWs respectively, without fully exhausting fuel stores prior to replenishment. The 250% burn rate remained unsupportable with 9 or less LAWs, however, there was considerable improvement. When a second NGLS was added with fixed MLR fuel capacity, the MLR was only fully supported at a 100% burn rate with 7 or more LAWs utilized, with no improvement adding any additional LAWs. All other burn rates resulted in the MLR fully exhausting all stored fuel prior to replenishment. When considering 2 NGLSs and increased capacity at the MLR site, all burn rates were fully supported by 7 LAWs, with a BTM value of 0%, and no improved supportability from any greater number of LAWs. This meant that the MLR, at all burn rates, only ever reached the fuel replenishment trigger value of 34% stored fuel by the time replenishment arrived.

The results of Scenario 4 were similar to Scenario 3 in demonstrating the greater effectiveness of 7 LAWs and 2 NGLSs to successfully support a MLR under a more complex location distribution. More specifically, Scenario 4 was the greatest stressor on the examined combinations of LAWs and NGLSs, thus the success of 7 LAWs and 2 NGLSs under these conditions further reinforces the potential of this combination of platforms in supporting a MLR. Furthermore, these results demonstrate that unless MLR capacity is allowed to increase with demand, only the baseline 100% demand can be fully supported without the MLR completely exhausting fuel prior to replenishment, regardless of the number of supporting LAWs and NGLSs.

B. FUSED RESULTS

The purpose of the FUSED modeling was to answer the second research question, which sought to compare the logistical and readiness measures between a dual-fuel concept and a single-fuel concept in sustaining a MLR operating in a contested environment in the

INDOPACOM AOR. For the purposes of this modeling, we applied the most complex scenario, Scenario 4, which was composed of a 9 MLR location distribution and a second RP within the WEZ (RP-3). This was selected because it was observed from the RASP results that the 9-island distribution placed the most strain on the overall system and gave greater insights to the most complex operating scenario. Additionally, modeling Scenario 4 with the second RP within the WEZ provided more insight into the scenario that gives the most flexibility in scheduling and less overall predictability. The results for the dual fuel scenario are referred to as case 1 in the model and the results for the single fuel scenario are referred to as case 2 in the model.

1. INPUT DATA AND PARAMETER SETTINGS

The inputs for the FUSED model used many of the same inputs that were used for RASP in that it factored distances between the rendezvous points (Table 1), capacities (Table 4), and burn rates (Table 4) of the MLR locations and capacities (Table 3) and burn rates (Table 3) of the LAWs and NGLSs. The trigger levels of the LAWs and NGLSs remain constant for case 1 at 60% each however, the trigger level was lowered to a 50% threshold for these platforms in case 2 due to the pooling effect of combining F-76 and JP-5 tank capacities into one single capacity. These inputs were used along with the RASP outputs of the most successful combination of LAWs and NGLSs and the ideal schedule that sustains the MLR with that combination of platforms. To conduct the FUSED modeling, we used the most successful combination of 7 LAWs and 2 NGLSs for scenario 4 indicated in the RASP results from the previous subchapter. Since this combination was shown to support the MLR best in this type of distribution, choosing this combination provided the best insight. Additionally, FUSED requires a schedule as an input to calculate its outputs. One of the functions of RASP is to create an ideal schedule output which was able to be used as an input for the FUSED modeling. This schedule is shown in Tables 5 and 6. The FUSED outputs analyzed from this modeling were the number of RASs required, total fuel burned by the LAWs, and total fuel delivered to the MLRs.

The upper section of the table shows respective MLR locations on each row and days of operations on the columns. Replenishment days and the providing ship are indicated under the respective columns. The lower section of the table shows the providing ships on the rows and the replenishment schedule at the RP in the columns.

Table 5. Scenario 4 Schedule (Jan 1–15)

MLR	Jan1	Jan2	Jan3	Jan4	Jan5	Jan6	Jan7	Jan8	Jan9	Jan10	Jan11	Jan12	Jan13	Jan14	Jan15
MLR1 (MLR-1)	MLR LOC 1		LAW5	MLR LOC 1		LAW4	MLR LOC 1		LAW3	MLR LOC 1		LAW4	MLR LOC 1		LAW2
MLR2 (MLR-2)	MLR LOC 2		LAW3	MLR LOC 2		LAW1	MLR LOC 2		LAW2	MLR LOC 2		LAW1	MLR LOC 2		LAW3
MLR3 (MLR-3)	MLR LOC 3		LAW6	MLR LOC 3		LAW5	MLR LOC 3		LAW5	MLR LOC 3		LAW3	MLR LOC 3		LAW5
MLR4 (MLR-4)	MLR AREA 4		LAW2	MLR AREA 4		LAW7	MLR AREA 4		LAW6	MLR AREA 4		LAW7	MLR AREA 4		LAW6
MLR5 (MLR-5)	MLR AREA 4		LAW2	MLR AREA 4		LAW7	MLR AREA 4		LAW6	MLR AREA 4		LAW7	MLR AREA 4		LAW6
MLR6 (MLR-6)	MLR AREA 6		LAW4	MLR AREA 6		LAW3	MLR AREA 6		LAW7	MLR AREA 6		LAW6	MLR AREA 6		LAW1
MLR7 (MLR-7)	MLR AREA 6		LAW4	MLR AREA 6		LAW3	MLR AREA 6		LAW7	MLR AREA 6		LAW6	MLR AREA 6		LAW1
MLR8 (MLR-8)	MLR LOC 8		LAW1	MLR LOC 8		LAW2	MLR LOC 8		LAW1	MLR LOC 8		LAW2	MLR LOC 8		LAW7
MLR9 (MLR-9)	MLR LOC 9		LAW7	MLR LOC 9		LAW6	MLR LOC 9		LAW4	MLR LOC 9		LAW5	MLR LOC 9		LAW4
PROVIDER															
LAW	Jan1	Jan2	Jan3	Jan4	Jan5	Jan6	Jan7	Jan8	Jan9	Jan10	Jan11	Jan12	Jan13	Jan14	Jan15
LAW1 (LAW-1)	RP 2		MLR8	RP 3		MLR2		RP 3	MLR8	RP 3		MLR2		RP 3	MLR6/
LAW2 (LAW-2)	RP 2		MLR4/MLR5		RP 3	MLR8	RP 3		MLR2		RP 3	MLR8	RP 3		MLR1
LAW3 (LAW-3)	RP 2		MLR2		RP 3	MLR6/	RP 3		MLR1		RP 2	MLR3	RP 2		MLR2
LAW4 (LAW-4)	RP 2		MLR6/	RP 3		MLR1		RP 2	MLR9	RP 2		MLR1		RP 2	MLR9
LAW5 (LAW-5)	RP 2		MLR1		RP 2	MLR3		RP 2	MLR3		RP 2	MLR9	RP 2		MLR3
LAW6 (LAW-6)	RP 2		MLR3		RP 2	MLR9	RP 2		MLR4/MLR5		RP 3	MLR6/	RP 3		MLR4/
LAW7 (LAW-7)	RP 2		MLR9	RP 2		MLR4/MLR5		RP 3	MLR6/	RP 3		MLR4/MLR5		RP 3	MLR8

This table shows the schedule for the MLR and LAW replenishments Jan. 1st-15th. Note that each MLR is replenished every third day and each LAW is replenished every 3–4 days. Days spent underway are colored in light blue.

Table 6. Scenario 4 Schedule (Jan 16–30)

MLR	Jan16	Jan17	Jan18	Jan19	Jan20	Jan21	Jan22	Jan23	Jan24	Jan25	Jan26	Jan27	Jan28	Jan29	Jan30
MLR1 (MLR-1)	MLR LOC 1		LAW7	MLR LOC 1		LAW3	MLR LOC 1		LAW7	MLR LOC 1		LAW6	MLR LOC 1		
MLR2 (MLR-2)	MLR LOC 2		LAW5	MLR LOC 2		LAW6	MLR LOC 2		LAW1	MLR LOC 2		LAW2	MLR LOC 2		
MLR3 (MLR-3)	MLR LOC 3		LAW4	MLR LOC 3		LAW4	MLR LOC 3		LAW3	MLR LOC 3		LAW7	MLR LOC 3		
MLR4 (MLR-4)	MLR AREA 4		LAW1	MLR AREA 4		LAW2	MLR AREA 4		LAW5	MLR AREA 4		LAW4	MLR AREA 4 5		
MLR5 (MLR-5)	MLR AREA 4		LAW1	MLR AREA 4		LAW2	MLR AREA 4		LAW5	MLR AREA 4		LAW4	MLR AREA 4 5		
MLR6 (MLR-6)	MLR AREA 6		LAW3	MLR AREA 6		LAW1	MLR AREA 6		LAW2	MLR AREA 6		LAW5	MLR AREA 6 7		
MLR7 (MLR-7)	MLR AREA 6		LAW3	MLR AREA 6		LAW1	MLR AREA 6		LAW2	MLR AREA 6		LAW5	MLR AREA 6 7		
MLR8 (MLR-8)	MLR LOC 8		LAW6	MLR LOC 8		LAW5	MLR LOC 8		LAW6	MLR LOC 8		LAW1	MLR LOC 8		
MLR9 (MLR-9)	MLR LOC 9		LAW2	MLR LOC 9		LAW7	MLR LOC 9		LAW4	MLR LOC 9		LAW3	MLR LOC 9		
PROVIDER															
LAW	Jan16	Jan17	Jan18	Jan19	Jan20	Jan21	Jan22	Jan23	Jan24	Jan25	Jan26	Jan27	Jan28	Jan29	Jan30
LAW1 (LAW-1)	RP 3		MLR4/MLR5		RP 3	MLR6/	RP 3		MLR2		RP 3	MLR8		RP 2	
LAW2 (LAW-2)		RP 2	MLR9	RP 2		MLR4/MLR5		RP 3	MLR6/	RP 3		MLR2		RP 2	
LAW3 (LAW-3)		RP 3	MLR6/	RP 3		MLR1		RP 2	MLR3		RP 2	MLR9	RP 2		
LAW4 (LAW-4)	RP 2		MLR3		RP 2	MLR3		RP 2	MLR9	RP 2		MLR4/MLR5		RP 2	
LAW5 (LAW-5)	RP 2		MLR2		RP 3	MLR8	RP 3		MLR4/MLR5		RP 3	MLR6/MLR7		RP 2	
LAW6 (LAW-6)	MLR5	RP 3	MLR8	RP 3		MLR2		RP 3	MLR8	RP 3		MLR1		RP 2	
LAW7 (LAW-7)	RP 3		MLR1		RP 2	MLR9	RP 2		MLR1		RP 2	MLR3		RP 2	

This table shows the schedule for the MLR and LAW replenishments Jan. 16th-30th. Note that each MLR is replenished every third day and each LAW is replenished every 3–4 days. Days spent underway are colored in light blue.

2. DUAL FUEL RESULTS

In case 1, dual fuel concept, the LAWs and the NGLSs utilize F-76 fuel for their propulsion and the MLRs use JP-5. The results from case 1 yielded that the total F-76 consumption over the thirty-day time-period totals to 2,642,951 gallons of fuel burned by the LAWs. The total fuel delivered across the MLR locations over this period was 423,000 gallons. To meet these overall fuel demand requirements, the total number of RASs conducted amongst all the LAWs from the NGLSs at RP-2 and RP-3 was 49. Additionally, the total number of RASs that the NGLSs needed to conduct at RP-1 to sustain its operations was 8.

3. SINGLE FUEL RESULTS

In case 2, single fuel concept, the LAWs, NGLSs, and the MLRs all utilize JP-5. Therefore, the previous F-76 and JP-5 carrying capacities of the LAWs and NGLSs are combined so that their new carrying capacities for solely JP-5 were 195,840 gallons and 1,722,000 gallons respectively. Due to the slight inefficiencies of operating the LAWs on JP-5 fuel, an assumed 3% efficiency loss was factored in when calculating the amount of fuel burned. This 3% efficiency loss is meant to align with the 2.6% loss estimated by the Single Fuel at Sea study (Giannini et al. 2002). The results from case 2 yielded that the total JP-5 consumption over the thirty-day period was 2,724,692 gallons for the LAWs. The total amount of fuel delivered across the MLR locations over this time-period remained constant at 423,000 gallons because the MLR demand and the schedule at which the LAWs visited the MLR locations and responded to their demand remained the same in both cases. To meet these overall fuel demand requirements, the total number of RASs that needed to be conducted by the LAWs with the NGLSs at RP-2 and RP-3 was 28 (19 fewer than in the dual fuel concept). Additionally, the total number of RASs that the NGLS needed to conduct at RP-1 to sustain its operations was 6 (2 fewer than in the dual fuel concept).

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VI. CONCLUSIONS AND RECOMMENDATIONS

From the results of both models, several conclusions and recommendations can be made. Additionally, limitations and recommendations for further research are all listed in the following subchapters.

A. RESEARCH QUESTION 1: RASP MODELING

1. CONCLUSIONS

The results from the RASP modeling provide valuable insight into the first research question regarding the most successful combination of LAWs and NGLSs to support a MLR operating in a contested environment in the INDOPACOM AOR. The results indicate that if a MLR ran out of fuel between refueling (a BTM of 34% or greater), the MLR was unsupported. When examining the baseline anticipated operational case of MLR expected fuel demand at 100% burn rate and fixed MLR capacity, the MLR could be supported in every scenario examined with a single NGLS. With simpler geometry, such as in Scenario 1, the MLR was fully supported at 100% burn rate with 4 or more LAWs employed. There is potential that the MLR could be supported in the simplest geometry with less than 4 LAWs, but this data point was not considered in this study due to its oversimplification and lack of redundancy contrary to the fundamentals required in the concept of EABO operations (ability to sustain operations and lethality for prolonged periods). The MLR is expected to be able to perform its range of mission capabilities for as long as needed. As geometry became more complex, more LAWs were required to fully support the MLR with 6 or more LAWs required for Scenario 2 and 7 or more LAWs required for Scenarios 3 and 4.

There were improvements in supportability of the 100% fuel demand and fixed fuel capacity case when a second NGLS was utilized. The MLR in Scenario 1 retained more fuel on hand between refuels, still fully supported by 4 or more LAWs. The MLR in Scenario 2 was fully supported by 5 or more LAWs, versus the required 6 LAWs when a single NGLS was employed. The MLR in Scenario 3 was fully supported with 7 or more LAWs just as with the single NGLS, but retained more fuel on hand between refuels with the second NGLS included when 7 LAWs were employed. The MLR in Scenario 4 was the only scenario that saw the same support with both 1 and 2 NGLSs for the 100% fuel demand and fixed fuel capacity case. In addition to the previously stated improvements, a second NGLS provides greater redundancy in fuel supportability of the MLR. While supportability was possible with a single NGLS, loss of the single asset would prove extremely detrimental to the MLR's mission. If two NGLSs were employed and one was lost to mechanical issues or kinetic attack, there is still a single NGLS to provide fuel support.

When increased MLR fuel demand levels were considered (all burn rates greater than 100%), supportability of the MLR in each scenario was not possible with fixed capacity, regardless of the number of LAWs and NGLSs utilized. However, there were significant improvements in supportability when MLR capacity was allowed to increase in lockstep with demand. For example, the MLR subject to the most complex geometry considered, Scenario 4, was fully supported at all burn rates considered with 7 or more LAWs and 2 NGLSs employed.

The scenarios that proved most difficult to sustain were the cases where higher burn rates were used for scenarios 3 and 4 which both consisted of 9 island distributions. The only difference between scenarios 3 and 4 was the added RP within the WEZ where the NGLSs could alternately replenish the LAWs. This additional RP provides little additional logistical support in terms of improved OV, BTV, or BTM metrics. However, an operational or fleet planner may wish to have this additional RP for schedule flexibility and to maintain a level of unpredictability. These results show that to best sustain these cases of higher burn rates in a 9-island distribution, the MLR needs to be able to increase its organic capacity to store fuel, multiple NGLSs need to be used, and a minimum of 7 LAWs must be employed.

By considering all above conclusions, we determined the most successful combination of surface platforms to provide fuel support to a MLR operating in a contested environment in the INDOPACOM AOR varied based on the complexity of the island distribution and whether capacity could be increased at the MLR. For a simpler island distribution, such as what was demonstrated in scenario 1, 4 LAWs and 2 NGLSs was the best combination in most conditions. For a slightly more complex island distribution, such as what was demonstrated in scenario 2, 6 LAWs and 2 NGLSs proved to be the best combination in most conditions. In the most complex island distributions, such as what was demonstrated in scenarios 3 and 4, 7 LAWs and 2 NGLSs proved to be the best combination. These combinations of platforms not only proved successful in the 100% fuel demand and fixed fuel capacity cases when subject to the most complex geometry considered in the study, but also provided the greatest supportability across all considered burn rates when MLR capacity was allowed to increase. A summary of the most successful combinations of LAWs and NGLSs for each Scenario is shown in Table 7.

Table 7. Summary of Most Successful Combinations of LAWs and NGLSs

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
LAW	4	6	7	7
NGLS	2	2	2	2

With 7 LAWs and 2 NGLSs successfully supporting the most complex MLR distribution scenario examined (Scenario 4), and exceeding the numbers of platforms required to successfully support all other scenarios considered, this combination of LAWs can be considered the most successful overall at supporting MLR operating in a contested environment in the INDOPACOM AOR.

2. RECOMMENDATIONS

The greatest increases in MLR fuel supportability were due to the ability to increase MLR fuel capacity. Though increased fuel supportability is provided to the MLR when fuel capacity is allowed to increase, there is potential for the method of capacity increase to prove detrimental to the MLR's ability to be mobile. Additionally, more fuel storage gives the MLR a larger footprint which could make the MLR easier to identify and potentially a larger target. With this understanding, it is recommended that a method for MLR fuel capacity to increase in line with burn rate, such as additional fuel bladders that the MLR sites can fill, be established for employment in theater, with consideration given to the potential detrimental effects to the MLR's mission associated with such an increase.

All conclusions established through this research are subject to the MLR's fuel safety trigger value being set to 34%. This rate could be considered low for real world applications. If this fuel safety trigger value were increased, fuel supportability for the MLR becomes more complex as MLR locations will need to be refueled more frequently and thus require more replenishment visits. It is recommended that planners take this into consideration as any increase in this safety trigger value could require employment of greater numbers of support assets.

B. RESEARCH QUESTION 2: SINGLE FUEL CONCEPT

1. CONCLUSIONS

The results from the FUSED modeling provided some insight into answering the second research question seeking the logistical and readiness benefits of a dual fuel concept versus a SFC. The greatest differential output in comparing the results from case 1 and case 2 was the reduction in the number of RASs that were required for the LAWs and the NGLSs to continue their operations and support the MLR. In analyzing the number of RASs required for the LAWs from the NGLSs at RP-2 and RP-3, there was a nearly 40% reduction in the number of RASs required for the LAWs to complete their assigned operations. In analyzing the number of RASs required for the NGLSs at RP-1, there was a 25% reduction in the number of RASs required.

There are several logistical and readiness implications that can be derived from a reduction in the frequency of required RASs by switching to a JP-5 SFC. An LAW or NGLS would be able to spend more (or less time if desired) in the operating area and less time traveling back and forth between rendezvous points. With fewer trips back and forth there are potential savings in the amount of fuel burned by the LAW and NGLS transiting back and forth, and there is the potential for faster response times by the LAW to the MLR if they can spend that time saved in the operating area rather than refueling. Faster response times to the MLR could potentially lead to the MLR fuel levels spending less time below the threshold value and reduce the overall magnitude the fuel levels drop below the threshold value. This could reduce the likelihood of any single MLR location exhausting all fuel stores, resulting in greater overall MLR sustainability. The results of these gained efficiencies could have been explored and analyzed further by modifying the scenario schedule input into FUSED to calculate the reduction in total fuel burned by the LAWs with fewer trips back and forth to the rendezvous points however, this further exploration was not conducted in this study.

2. RECOMMENDATIONS

There are tangible benefits demonstrated through various studies regarding the logistical benefits and efficiencies gained from the pooling effects that occur in the implementation of a JP-5 SFC. Even when considering the slight inefficiency of running ship propulsion engines on JP-5, our study shows that a JP-5 SFC proves to have potential in reducing the number of RASs and extending operational reach when operating abroad. While this study bolsters the body of knowledge regarding JP-5 SFC benefits, further studies should be considered to weigh the costs of implementation of a JP-5 SFC with the estimated benefits.

C. LIMITATIONS

The best effort was made to conduct comprehensive and insightful research that could inform decision making at the appropriate level. However, certain limitations were encountered that affected the scope and relevance of the analysis. The limitations below can guide further research into the logistics and operational benefits of supporting warfighters in any operational environment.

1. The full implementation of the EABO concept is limited by the availability (lack of) of the naval platforms and capabilities required for its execution. The LAWs and NGLSs are currently in design and development phase at the time of this research. It is recommended that the USN expedite the building of the LAWs and NGLSs to support timely availability of the platforms to support USMC operations. The USMC initiated the implementation of the EABO concept with the creation of the 3rd MLR (Feichert, 2023). The other essential factor is the availability of LAWs and NGLSs to enable full scale adoption. The Navy's

current 379 shipbuilding plan includes LAWs and NGLSs, but the actual procurement of LAWs has been delayed to FY2025 (O'Rourke, 2022a) and NGLS to FY2026 (O'Rourke, 2022b) in the final budget. This delay will further push back the availability and utilization of the new platforms for training and experimentation to fine-tune war fighting concepts.

2. The RASP run time for each simulation to find the most successful combination of LAWs and NGLS to support the MLR was limited to 3 hours. To allow for a timely analysis of the results of the modeling and simulation, the run time was interrupted when an optimal schedule for the number of each type of platform considered in a specific run was established. Potential scheduling solutions that could have been identified by expanding the 3-hour limit were not factored into this research. To further explore the full range of potential solutions from RASP, it is recommended to allow the simulation to run for as long as necessary to generate the optimal schedule for each combination of LAWs and NGLSs under all other variable conditions.
3. The research is limited by its utilization of estimated typical fuel demand data and not from real life experimentation. Data from typical fuel demand was provided by the USMC OAD to be used as the baseline demand for projected MLR equipment as input for simulating operational demand data from MLR units. The data provided is a projection based on the typical equipment fuel consumption from a non-MLR operation. This projection was done due to the absence of MLR specific data since EABO is a recent operational concept that is in its initial stages. It is recommended that future research utilizes actual MLR data performing full ranges of assigned mission tasks. This will give a more realistic operational picture of demand and other requirements.
4. The research utilizes notional demand rates of 100%, 150%, 200%, and 250% to simulate increases in demand as a limitation to allow objective analysis and comparison. In real life situations, fluctuations in demand will not be exact as depicted in this research. It is recommended to utilize average demand data to

ascertain the potential increases in demand as a better measure of understanding the real operational impacts of such changes.

D. FUTURE WORK

It is recommended that further research be conducted to explore the resource availability at the wholesale level that could impact the adoption of a JP-5 SFC for use by USN afloat units. Considerations should be made for potential interruption of the supply chain and actions to mitigate the attendant impact to U.S. military global operations.

It is also recommended that subsequent research be conducted to re-run RASP with all afloat units using JP-5 as the single fuel while supporting a MLR conducting the full range of mission capabilities in a contested environment or similar situation to simulate real life scenario. This research did not utilize real life consumption data due to lack of available information, and instead used estimated consumption data.

Additional research is required to identify the cost-benefit analysis of the full implementation of JP-5 SFC compared to the legacy dual fuel approach in use. It stands to be discovered if there are tangible financial benefits to be derived from the adoption of JP-5 as the primary fuel. This could be especially relevant considering the increasingly limited availability of fiscal funds and the increasing cost of conducting operations.

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