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Vertical launch system loadout planner

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MONTEREY, CALIFORNIA

THESIS

VERTICAL LAUNCH SYSTEM LOADOUT PLANNER

by

Michael L. Wiederholt

March 2015

Thesis Advisor: Gerald Brown
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Operational planners strive to find ways to load missiles on Vertical Launch System (VLS) ships to meet mission requirements in their Area of Responsibility (AOR). Requirements are variable: there are missions requiring specific types of missiles; each ship may have distinct capability or capacity to meet every mission; each ship may have a set number of missiles in inventory; and each mission will have a different priority. As a result, the missile-to-ship assignment is labor intensive. Operational planners manually specify the missile loadout, providing recommendations with no assurance that some other plan might not be much better in practice.

This thesis provides operational planners with a programming tool, the VLS Loadout Planner (VLP), to advise the optimal loadout for VLS ships deploying to be ready to execute demanding and high-threat missions. This research employs the VLP model to demonstrate the optimal missile loadout and mission coverage of two fictitious war plans, with 52 missions, on a two-deployment cycle, using 21 VLS-capable ships, and employing a variety of seven types of missiles. The thesis concludes that VLP provides operational planners a recommended loadout for every ship deploying to 7th Fleet (Western Pacific) AOR.

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VERTICAL LAUNCH SYSTEM LOADOUT PLANNER

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Submitted in partial fulfillment of the
requirements for the degree of

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Operational planners strive to find ways to load missiles on Vertical Launch System (VLS) ships to meet mission requirements in their Area of Responsibility (AOR). Requirements are variable: there are missions requiring specific types of missiles; each ship may have distinct capability or capacity to meet every mission; each ship may have a set number of missiles in inventory; and each mission will have a different priority. As a result, the missile-to-ship assignment is labor intensive. Operational planners manually specify the missile loadout, providing recommendations with no assurance that some other plan might not be much better in practice.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
AD	Air Defense
AOR	Area of Responsibility
ASROC	Anti-Submarine Rocket
ASW	Anti-Submarine Warfare
BAE	British Aerospace Engineering
BMD	Ballistic Missile Defense
CAP	Combat Air Patrol
CG	Guided Missile Cruiser
C7F	Commander Seventh Fleet
DDG	Guided Missile Destroyer
DOD	Department of Defense
DON	Department of the Navy
ER	Extended Range
ESSM	Evolved Sea Sparrow Missile
FAS	Federation of America Scientists
FDNF	Forward Deployed Naval Force
GAMS	General Algebraic Modeling System
HVU	High Value Unit
JP	Joint Publication
MR	Medium Range
NMP	Navy Mission Planner
SAG	Surface Action Group
SAM	Surface-to-Air Missile
SM	Standard Missile
SUW	Surface Warfare
TBMD	Theater Ballistic Missile Defense
TLAM	Tomahawk Land Attack Missile
USA	United States of America
US	United States

USN	United States Navy
USS	United States’ Ship
VBA	Visual Basic for Applications
VLP	VLS Loadout Planner
VLS	Vertical Launch System

EXECUTIVE SUMMARY

Commander of Seventh Fleet (C7F) operational planners devote time and resources planning missile loadouts for Vertical Launch System (VLS) ships prior to their deployment in their Area of Responsibility (AOR). C7F has a number of warplans with missions allocated to each one and multiple ships to manage in their AOR. Planners need to consider the mission requirements, ships' missile capability and VLS cells capacity, a limited number of VLS missiles in inventory, certain number of ships available to C7F's AOR, minimal number of missiles on each ship, and missions' risk and priorities.

How do operational planners accomplish this task now, and is there a better way? Operational planners decide missile loading by hand utilizing basic programming software like Excel Spreadsheet (from Microsoft Corporation, 2015) and provide missile loadout recommendations with no idea how much such plans might be improved. Under these circumstances, missile load planning is labor intensive. This thesis provides operational planners with a programming tool, the VLS loadout planner (VLP), to assist them reckon the ships' optimal missile loadouts prior to deployment.

VLP uses optimization software and a mixed-integer linear program to provide the best-achievable missile loadout and ships' assignments to warplan-mission coverage. Each mission has a minimum number of ships required and a penalty if the mission is not completed. The model has the missiles desired for each mission, the minimum number of missiles for each mission, a shortage missile penalty for each mission, and perhaps an alternative missile, a less-effective substitution, to complete a mission but with a penalty assigned for using it. The model considers each ship's missile incompatibilities, VLS cell complements, and minimum missile requirement for each mission. Lastly, a penalty is assigned for adjusting a missile loadout from the pre-existing one to avoid undesirable excessive handling of missiles. The planner has complete control of VLP and can manually override any VLP assignment.

Note that the ideal VLS load considers all ships at once and decides their loads and mission assignments as a unified fighting force. This means that we must deploy our

ships with VLS loads not knowing in advance which of a variety of warplans (and respective mission sets) we might face.

We demonstrate VLP with two fictitious warplans on three main scenarios with 52 missions. We use 23 VLS ships in two-deployment six-month cycles with nine types of missiles. The model adheres to missile and mission restrictions and maximizes all the ships' missile effectiveness. In each scenario, the model suggests a recommended missile loadout for each ship, the missions each of the ships can cover in its respective cycle(s), and the missions not covered. The scenarios range from a completely fixed missile loadout to a non-restricted, optimal missile loadout. As the scenarios become less restricted, VLP optimizes the missile loadout and reduces the missions not covered. Optimization achieves a 49% reduction of missions not covered from most-restricted Scenario I to least-restricted Scenario III. The results reveal VLP's potential for our fleet and can provide a recommendation to operational planners in 10 minutes. This decision tool not only provides missile loadout recommendations, but also reduces the planning time, planning resources, and hazardous missile loading evolutions.

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I would like to acknowledge and express my sincere gratefulness to my advisor, Dr. Gerald Brown. His patience, wisdom, mentoring, and guidance were influential in the completion of this thesis. I would like to give a special thanks to Dr. Emily Craparo for her expertise, helping me initiate the mathematical formulation, and providing sound feedback on this thesis. I would also like to thank Captain Jeffrey Kline for introducing me to the topic and providing the necessary naval guidance throughout the development of this thesis. I would like to acknowledge the US Navy and the Naval Postgraduate School institution for giving me the opportunity to conduct this thesis and graduate with a Master's Degree in Operations Research.

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I. INTRODUCTION

Commander Seventh Fleet (C7F) operational planners face challenges in determining the optimal Vertical Launch System (VLS) missile loadout for U.S. warships in preparation for potential missions in the Western Pacific. This research focuses on reducing the time spent on deciding the complement of missiles for each ship with the objective of maximizing the coverage of missions in C7F's Area of Responsibility (AOR).

Our primary aim is to clearly characterize the missile loadout problem and provide a decision tool for staff members to discover the best missile loadout. A proposed mathematical optimization model can benefit C7F planners by enhancing the deployed fleet's capability to cover both current and potential missions in their AOR.

A. BACKGROUND

1. Problem Statement

With significant tasking in the Western Pacific, C7F operational planners focus on multiple warplans in the region. C7F challenges itself to prepare its warships to counter the threats in their AOR, as shown on the map in Figure 1. Planners face a difficult problem in matching VLS loads with potential missions to counter these threats. This thesis introduces a decision-support tool to determine the best-achievable missile loadout in one of two upcoming deployment cycles. (We understand C7F faces perhaps scores of such plans, and we have taken great care to be able to accommodate this.)

Figure 1. C7F AOR (from U.S. 7th Fleet, 2013)

Planning the best missile loadout on VLS ships for numerous missions in the Western Pacific is complex for operational planners. There is more than one class of ship, each ship has a limited number of missile cells, and ships may have differing capabilities to perform some missions. For instance, all VLS ships are capable of protective escort missions, but some do not have Ballistic Missile Defense (BMD) capability. Second, there are ships permanently deployed in C7F. These forward deployed naval force (FDNF) units operate simultaneously with deployed U.S. mainland warships, and the art of balancing the missile loadout on FDNF and U.S. deployed VLS ships operating in the C7F AOR while preparing the next set of VLS ships from U.S. naval bases is a challenge. The VLS missile inventory may have a lot of older-generation missiles and fewer of the newer, upgraded versions of missiles. This fact complicates the task of determining the missile allocation to ships, as well as determining missile substitutions, where a less-capable missile type, or an over-capable one, may be used instead of a preferred one. Furthermore, each mission requires a certain number of missiles on each ship. This thesis incorporates these complex conditions into one optimization-based decision-support tool for operational planners.

Note that the ideal VLS load considers all ships at once and decides their loads and mission assignments as a unified fighting force. Thus, we are faced with a single set of load decisions for each ship, where the ships may need to face any one of a number of war plan scenarios.

2. Seventh Fleet Missions

The Department of Defense (DOD) uses a variety of military and associated terms to define missions. For the purposes of this thesis, the following terms are identified:

- **Strike**: A land or shore attack to damage to limit or destroy the enemies' ability to operate (Joint Publication [JP] 1–02, 2014).
- **Air Defense (AD)**: A defensive posture to protect friendly or allied units from enemy aircraft or missiles.
- **Theater Ballistic Missile Defense (TBMD)**: An AD posture to protect friendly and allied units and territories from ballistic and cruise missiles in a given theater.
- **Anti-Submarine Warfare (ASW)**: Denying or destroying enemy submarines from conducting missions against friendly or allied units.

- **Protective Escort**: A defensive posture to protect carrier groups, amphibious groups or individual ships from AD, ASW, and surface units' threats.

- **Surface Warfare (SUW)**: Maritime warfare in which naval units are designated to kill or disable enemy surface combatants.

3. Vertical Launch System Missiles

For continuity and clarification in the formulation, the following are descriptions of missiles for this thesis:

- **RGM-109 Tomahawk Land Attack Missile (TLAM)**: Ship-launched land-attack cruise missile with a conventional warhead primarily used in strike missions (DOD 4120.15, 2004).

- **RIM-66 SM2 Medium Range (MR)**: Ship-launched surface-to-air missile with active homing device used to protect ships and protective escorted group's AD against enemy missiles and aircraft.

- **RIM-67 SM2 Extended Range (ER)**: Improved SM2 ship-launched surface-to-air and surface-to-surface missile with semi-active or passive homing device against enemy missiles, aircraft, and surface units.

- **RIM-156 SM2 Block IV**: Ship-launched extended-range guided defense missile used against theater-ballistic missiles in the terminal phase.

- **RIM-161 SM3**: Ship-launched 4-stage missile used in TBMD.

- **RIM-162 Evolved Sea Sparrow Missile (ESSM)**: Ship-launched, 4-missile canister, used primarily for AD against enemy missiles and aircraft.

- **RUM-139 Anti-Submarine Rocket (ASROC)**: Ship-launched rocket used in ASW.

- **RIM-174 SM6**: Advanced version of a ship-launched SM2 missile capable of over-the-horizon engagements used primarily for AD against enemy missiles and aircraft (IWS 3.0, 2011).

4. MK 41 Vertical Launch System (VLS) Description

The MK 41 VLS is a multi-mission module consisting of an 8-cell launcher, as shown in Figure 2, capable of carrying a wide range of missiles on Aegis warships (British Aerospace Engineering [BAE] Systems, 2011). The VLS has been upgraded since the mid-1980s to accommodate new missile technology (Lockheed Martin Corporation, 2013). The MK 41 can perform the following missions: AD, ASW, Surface Action Group (SAG), STRIKE, SUW, and TBMD (BAE Systems, 2011). The system, consisting of some number of these modules, is currently installed on three classes of U.S. warships: Ticonderoga Guided Missile Cruisers, Arleigh Burke Guided Missile Destroyers, and the Zumwalt Guided Missile Destroyer (U.S. Navy Fact File, 2013).

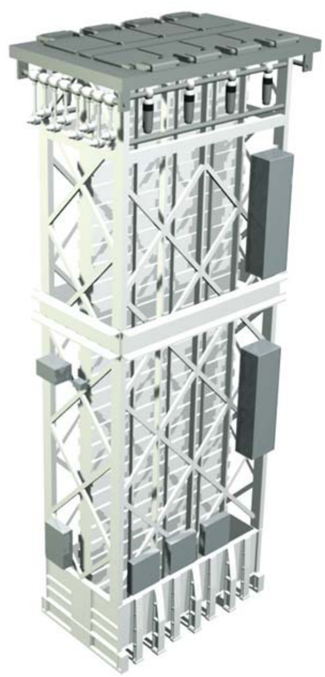

Figure 2. MK 41 VLS 8-Cell Module (from BAE Systems, 2011). VLS is capable of loading SM2 variations, SM3, SM6, ESSM, TLAM variations, and ASROC missiles (from U.S. Navy Fact File, 2013).

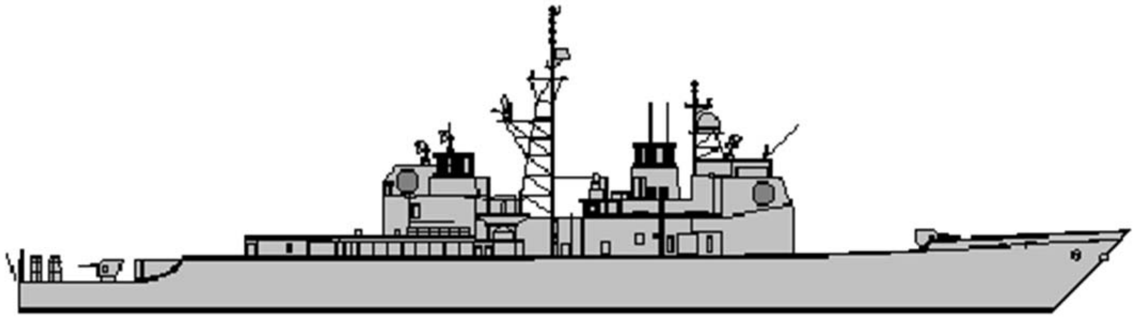

Figure 3. Ticonderoga Guided Missile Cruisers (CG 52–73) (Federation of America Scientists (FAS), 2000). The CG has 15 installed modules. These cruisers are capable of carrying up to 122 missiles (from U.S. Navy Fact File, 2013).

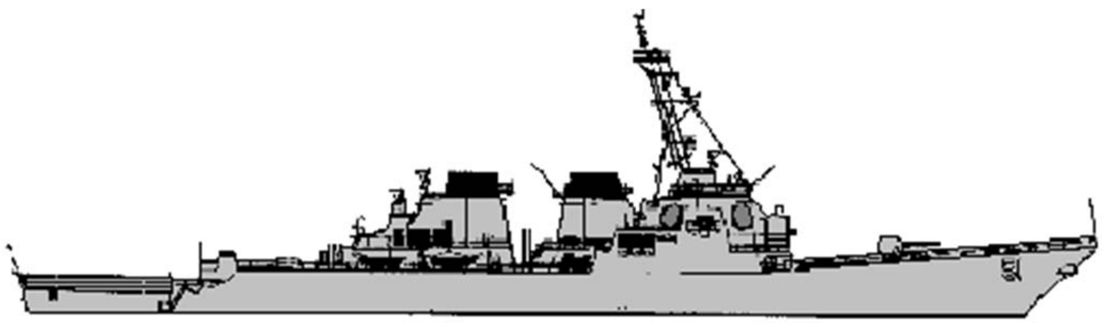

Figure 4. Arleigh Burke Guided Missile Destroyers (DDG 51–115) (FAS, 2014). The DDG has 12 installed modules. These destroyers are capable of carrying up to 96 missiles (from U.S. Navy Fact File, 2013).

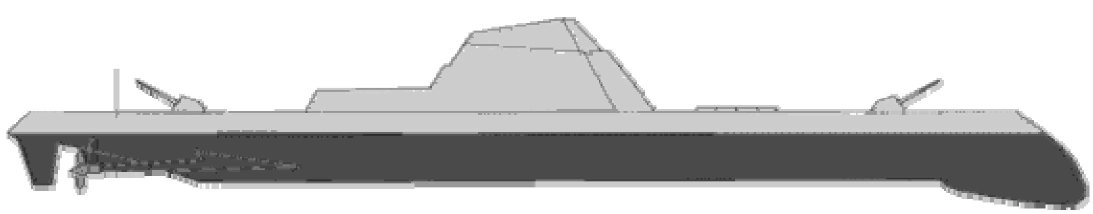

Figure 5. Zumwalt Guided Missile Destroyer (DDG 1000) (FAS, 2000). This DDG 1000 has 10 installed modules. The Zumwalt destroyer is the newest platform to the fleet and is capable of carrying up to 80 missiles (from U.S. Navy Fact File, 2013).

B. SCOPE, LIMITATIONS, AND ASSUMPTIONS

The VLP model is for two successive deployment cycles. The model only recommends the missile loadout for VLS ships and does not provide the exact missile placements in VLS cells.

This is an unclassified thesis with reasonably realistic data about our ships, missiles, inventory, threats and capabilities. Real-world testing with classified data is advisable, though we anticipate no particular problem with this.

C. THESIS ORGANIZATION

Chapter II provides a literature review on previous studies and theses on VLS ships, missile loadouts, and missile-mission assignment models. Chapter III provides the formulation of the MK 41 VLS loadout planner (VLP) model. Chapter IV provides a theoretical version of a VLS loadout plan against adversaries, which provides analysis of the model's results. Chapter V offers recommendations for future development.

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II. LITERATURE REVIEW

A. INTRODUCTION

The Commander of Seventh Fleet (C7F) staff solves the vertical launch system (VLS) loadout problem manually and has been successful in meeting requirements. C7F operational planners could use prior research on missile loadouts or mission planning to decrease workload, but the models we have found are limited in their ability to include all factors involved in mission planning. The following research has discovered simulation scenarios for VLS loadout, optimizing a TLAM variant VLS loadout for a specific mission, and a model designed to schedule warships to meet mission requirements.

B. PREVIOUS RESEARCH

Jarek (1994) develops a simulation to suggest the missile loadout on VLS ships conducting anti-air Warfare (AAW). Jarek's model finds the best number of surface-to-air missiles (SAM) onboard Aegis VLS ships for two main AAW cases in a theater campaign. He uses the probabilities of hard and soft kills in two simulation scenarios to determine the number of missiles required on a VLS ship. One scenario simulates VLS ships with combat air patrol (CAP) coverage and the other scenario simulates VLS ships without CAP in a specific theater. After the completion of the simulation, the model recommends the number of VLS ships with the appropriate number of SAMs assigned to each one.

Kuykendall (1998) builds an optimization model for missile-to-mission matching of the tomahawk land attack missile (TLAM) to TLAM-capable naval assets for strike missions. He uses an integer-programming model to optimize the variations of Tomahawk missiles on ship(s) and submarine(s). His input includes the type of platform (ship, ships in a battle group, or submarines), the loadout of each type of unit, the tasking order in geographic location, and penalties and parameters for the missions that are not met. His outputs include the missile-to-mission assignments, missiles remaining after a mission, and TLAMs that did not fill mission requirements. Kuykendall's model differs from Jarek's model in that it uses optimization versus simulation. Similar to Jarek's model, Kuykendall focuses on one type of mission area, strike missions. Later work by Newman et al. (2011) explains how Kuykendall's work has been extended and deployed by the US navy.

Dugan (2007) constructs the Navy Mission Planner (NMP), an optimization decision-making tool for operational planners to schedule the deployment cycle for ship-to-mission. His thesis focuses on meeting the required missions in a maritime theater, with limited ships available, assigning higher-priority missions over lower-priority missions, and providing a quick recommendation of a deployment schedule for the decision maker. He tests his model on a fictitious scenario on the Korean peninsula over a 15-day period for a ship on a deployment. Table 1 displays a schedule for the *USS John Paul Jones* (DDG 53).

Table 1. *USS John Paul Jones* (DDG 53) mission on a 15-day schedule (from Dugan, 2007). The acronyms correspond to mission tasks, and the coefficients indicate how well this ship can complete each mission, with 1 being perfect, and a fraction less so. For example, on day 10, she can complete TBMD, Strike, and Intel missions, while at once completing half a SUW mission, and 40% of an NSFS one.

DDG53	**Arrives:**	**day 1**									
day 5		**day 6**		**Day 7**		**day 8**		**day 9**		**day 10**	
region 9		**r9**		**r9**		**r9**		**r9**		**r9**	
AD	0	AD	1	AD	0	AD	0	AD	0	AD	0
TBMD	1	TBMD	0	TBMD	1	TBMD	1	TBMD	1	TBMD	1
ASW	0	ASW	0	ASW	0	ASW	0	ASW	0	ASW	0
SUW	0.5	SUW	0	SUW	0.5	SUW	0.5	SUW	0.5	SUW	0.5
Strike	1	Strike	0	Strike	1	Strike	1	Strike	1	Strike	1
NSFS	0.4	NSFS	0	NSFS	0.4	NSFS	0.4	NSFS	0.4	NSFS	0.4
MIO	0	MIO	0	MIO	0	MIO	0	MIO	0	MIO	0
MCM	0	MCM	0	MCM	0	MCM	0	MCM	0	MCM	0
Mine	0	Mine	0	Mine	0	Mine	0	Mine	0	Mine	0
Intel	1	Intel	0	Intel	1	Intel	1	Intel	1	Intel	1
Transit	0	Transit	0	Transit	0	Transit	0	Transit	0	Transit	0
Off	0	Off	1	Off	0	Off	0	Off	0	Off	0
day 11		**day 12**		**day 13**		**day 14**		**day 15**			
r9		**r9**		**r9**		**r9**		**r9**			
AD	0	AD	0	AD	0	AD	0	AD	0		
TBMD	1	TBMD	1	TBMD	1	TBMD	1	TBMD	1		
ASW	0	ASW	0	ASW	0	ASW	0	ASW	0		
SUW	0.5	SUW	0.5	SUW	0.5	SUW	0.5	SUW	0.5		
Strike	1	Strike	1	Strike	1	Strike	1	Strike	1		
NSFS	0.4	NSFS	0.4	NSFS	0.4	NSFS	0.4	NSFS	0.4		
MIO	0	MIO	0	MIO	0	MIO	0	MIO	0		
MCM	0	MCM	0	MCM	0	MCM	0	MCM	0		
Mine	0	Mine	0	Mine	0	Mine	0	Mine	0		
Intel	1	Intel	1	Intel	1	Intel	1	Intel	1		
Transit	0	Transit	0	Transit	0	Transit	0	Transit	0		
Off	0	Off	0	Off	0	Off	0	Off	0		

III. MODEL FORMULATION FOR OPTIMIZING VLS MISSILE LOADOUT

A. INTRODUCTION

This chapter presents the formulation the Vertical Launch System (VLS) Loadout Planner (VLP). This section discusses, in detail, the indexes, data, decision variables, formulation objective function and constraints of VLP.

B. MODEL FORMULATION TO OPTIMIZE THE MK 41 VERTICAL LAUNCH SYSTEM: VLP

1. Index Use [~Cardinality]

$w \in W$	war plan [~10]
$m \in M$	missions (alias m') [~10] (e.g., TBMD station)
$d \in D$	deployment cycles [~2]
$c \in C$	required mission ship classes (includes class "any") [~6]
$s \in S$	individual ships [~25]
$h \in H$	home ports [~2]
$y \in Y$	missile types (alias y', y desired, y' committed)[~8]
$t \in T$	type of mission [~3]
$r \in R$	risk level (including "high") [~2]
c_s	class of ship *s*
t_m	type of mission *m*
r_m	risk of mission

2. Useful Tuples

(Those marked with an asterisk "*" are derived and filtered from the others defined by data.)

$\{w,m\} \in WM$ *	missions of warplan *w* [~10]
$\{w,d,m\} \in WDM$	warplan-mission-cycle triples [10x10x2]
$\{m,c\} \in MC$	mission *m* can be completed by ship class *c*

$\{w,d,m,s\} \in WDMS*$	plan-mission-cycle-ship 4-tuples [10x10x2x25]
$\{s,y\} \in SY$	ship s cannot accommodate missile type y
$\{s,d\} \in SD$	ship s deployment cycles
$\{w,d,m,y\} \in WDMY*$	plan-mission-cycle-missile 4-tuples [10x10x2x10]
$\{m,m'\} \in MM'*$	missions m and m' are mutually exclusive (e.g., $t_m \neq t_{m'}$)
$\{m,y,y'\} \in MYY'*$	missile type y can be substituted for type y'
$\{w,d,m,s,y\} \in WDMSY*$	5-tuple for missile requirements, or loading
$\{w,d,m,s,y,y'\} \in WDMSYY'*$	6-tuple for missile loading with substitutions

3. Given Data [Units]

$priority_m$	priority of mission m [penalty]
$ships\_req_m$	ships required by mission m [ships]
$ships\_short\_pen_m$	ship shortfall penalty for mission m [penalty/ship]
$missiles\_desired_{m,y}$	desired type y missiles on each ship for mission m [missiles]
$missiles\_minimum_{m,y}$	minimum missiles on each ship of type y for mission m [missiles]
$missile\_short\_pen_{m,y}$	missile shortfall penalty for mission m, type y [penalty/missile]
vls_cells_s	number of VLS cells on ship s [cells]
$missile\_inventory_y$	number of type y missiles in inventory [missiles]
$missiles\_per\_cell_y$	number of type y missiles in a VLS cell [missiles per cell]
$risk\_missile\_load_{s,y}$	ship s, type y missiles carried in addition to mission load [missiles]
$under\_pen_y, over\_pen_y$	penalty for disproportionate spread of missile type y among ships carrying these for each mission [penalty]
$min\_missile\_load_{s,y}$	ship s type y missiles carried in addition to mission load [missiles]
$alt\_missile\_pen_{m,y,y'}$	penalty for substituting type y' for y in mission m [penalty/missile]
$loadout_{s,y'}$	ship s load of missile type y' prior to optimization [missiles]
$change\_pen$	penalty for adjusting prior loadout [penalty/missile]

4. Decision Variables [Units]

$ASSIGN_{w,d,m,s}$	assign ship s to war plan w deployment cycle d mission m [binary]
$MISSION_{w,d,m}$	plan w, cycle d, mission m commitment [binary]
$COMMIT_{w,d,m,s,y,y'}$	plan w, cycle d, mission m, want type y, commit type y' [missiles]
$MISSILE\_SLACK_{w,d,m,y}$	plan w, cycle d, mission m, type y missiles short of desired number [missiles]
$SHIPS\_SHORT_{w,d,m}$	plan w, cycle d, mission m, elastic variable for ship shortages on mission [ships]
$MISSILES\_SHORT_{w,d,m,y'}$	plan w, cycle d, mission m, elastic variable for missile shortages on missions [missiles]
$LOAD_{s,y'}$	ship s load of missile type y' [missiles]
$RISK\_MISSILES_{s,y'}$	carried by ship assigned high-risk mission(s) [missiles]
$UNDER_{w,d,m,s,y}, OVER_{w,d,m,s,y}$	elastic variable for inequitable missile loads [fraction]
$CHANGE_{s,y'}$	number of y' missiles changed in VLS cells of ship s [missiles]
$DEPLOY_s$	indicator that ship s is deployed [binary]
$DEPLOY\_WAR_{w,s}$	indicator that ship s is deployed in war plan w [binary]

5. Formulation

$$
\begin{aligned}
\min_{\substack{ASSIGN,\\ MISSION,\\ COMMIT,\\ MISSILE\_SLACK,\\ SHIPS\_SHORT,\\ MISSILES\_SHORT,\\ LOAD,\\ RISK\_MISSILES,\\ UNDER,OVER}} \quad & - \sum_{\{w,d,m\}\in WDM} priority_m MISSION_{w,d,m} \\
& + \sum_{\{w,d,m,s,y,y'\}\in WDMSYY'} alt\_missile\_pen_{m,y,y'} COMMIT_{w,d,m,s,y,y'} \\
& + \sum_{\{w,d,m\}\in WDM} ships\_short\_pen_m SHIPS\_SHORT_{w,d,m} \\
& + \sum_{\{w,d,m,y'\}\in WDMSY} missiles\_short\_pen_{m,y'} MISSILES\_SHORT_{w,d,m,y'} \\
& + \sum_{\{w,d,m,s,y\}\in WDMSY} under\_pen_y UNDER_{w,d,m,s,y} \\
& + \sum_{\{w,d,m,s,y\}\in WDMSY} over\_pen_y OVER_{w,d,m,s,y} \\
& + \sum_{\{s,y'\}\notin SY} change\_pen CHANGE_{s,y'} \qquad \text{(D0)}
\end{aligned}
$$

$$
s.t. \quad ASSIGN_{w,d,m,s} + ASSIGN_{w,d,m',s} \le 1 \qquad \forall \{w,d,m,s\}\in WDMS,\ \{w,d,m',s\}\in WDMS \mid \{m,m'\}\in MM' \qquad \text{(D1)}
$$

$$
MISSION_{w,d,m} \ge ASSIGN_{w,d,m,s} \qquad \forall \{w,d,m,s\}\in WDMS \qquad \text{(D2)}
$$

$$
\sum_{s\mid\{w,d,m,s\}\in WMDS} ASSIGN_{w,d,m,s} + SHIPS\_SHORT_{w,d,m} = ships\_req_m \qquad \forall \{w,d,m\}\in WDM \qquad \text{(D3)}
$$

$$
RISK\_MISSILES_{s,y'} \ge (min\_missile\_load_{s,y'} + risk\_missile\_load_{s,y'} |_{r_m='high'}) ASSIGN_{w,d,m,s} \qquad \forall \{w,d,m,s,y'\}\in WDMSY \qquad \text{(D4)}
$$

$$
\sum_{y'\mid\{w,d,m,s,y,y'\}\in WDMSYY'} COMMIT_{w,d,m,s,y,y'} \le missiles\_desired_{m,y} ASSIGN_{w,d,m,s} \qquad \forall \{w,d,m,s,y\}\in WDMSY \qquad \text{(D5)}
$$

$$
LOAD_{s,y'} \ge \sum_{\{d,m,y\}\mid\{w,d,m,s,y,y'\}\in WDMSYY'} COMMIT_{w,d,m,s,y,y'} + RISK\_MISSILES_{s,y'} \qquad \forall w\in W, \{s,y'\}\notin SY \qquad \text{(D6)}
$$

$$\sum_{\{s,y'\}|\{w,d,m,s,y,y'\}\in WDMSYY'} COMMIT_{w,d,m,s,y,y'}$$

$$+ MISSILES\_SHORT_{w,d,m,y} + MISSILE\_SLACK_{w,d,m,y}$$

$$\geq missiles\_desired_{m,y} MISSION_{w,d,m} \qquad \forall \{w,d,m,y\} \in WDMY \qquad \text{(D7)}$$

$$\sum_{\{s,y'\}\notin SY} \frac{1}{missiles\_per\_cell_{y'}} LOAD_{s,y'} \leq vls\_cells_s \qquad \forall s \in S \qquad \text{(D8)}$$

$$\sum_{\{s\}\notin S} LOAD_{s,y'} \leq missile\_inventory_{y'} \qquad \forall y \in Y \qquad \text{(D9)}$$

$$\sum_{y'|\{w,d,m,s,y,y'\}\in WDMSYY'} COMMIT_{w,d,m,s,y,y'} + UNDER_{w,d,m,s,y} - OVER_{w,d,m,s,y}$$

$$= (missiles\_desired_{m,y} / ships\_req_m) ASSIGN_{w,d,m,s}$$

$$\forall \{w,d,m,s,y\} \in WDMSY \qquad \text{(D10)}$$

$$CHANGE_{s,y'} \geq +(LOAD_{s,y'} - loadout_{s,y'}) \qquad \forall \{s,y\} \notin SY \mid \sum_{y'|\{s,y'\}\notin SY} loadout_{s,y'} > 0 \qquad \text{(D11)}$$

$$CHANGE_{s,y'} \geq -(LOAD_{s,y'} - loadout_{s,y'}) \qquad \forall \{s,y\} \notin SY \mid \sum_{y'|\{s,y'\}\notin SY} loadout_{s,y'} > 0 \qquad \text{(D12)}$$

$$DEPLOY_s \geq ASSIGN_{w,d,m,s} \qquad \forall \{w,d,m,s\} \in WDMS \qquad \text{(D13)}$$

$$DEPLOY_s \leq \sum_{m|\{w,d,m,s\}\in WDMS} ASSIGN_{w,d,m,s} \qquad \forall \{w,d,s\} \in WDS \qquad \text{(D14)}$$

$$DEPLOY\_WAR_{w,s} \geq ASSIGN_{w,d,m,s} \qquad \forall \{w,d,m,s\} \in WDMS \qquad \text{(D15)}$$

$$DEPLOY\_WAR_{w,s} \leq \sum_{m|\{w,d,m,s\}\in WDMS} ASSIGN_{w,d,m,s} \qquad \forall \{w,d,\text{s}\} \in WDS \qquad \text{(D16)}$$

$$ASSIGN_{w,d,m,s} \in \{0,1\} \qquad \forall \{w,d,m,s\} \in WDMS$$

$$MISSION_{w,d,m} \in \{0,1\} \qquad \forall \{w,d,m\} \in WDM$$

$$COMMIT_{w,d,m,s,y,y'} \in Z^+ \qquad \forall \{w,d,m,s,y,y'\}$$

$$\in WDMSYYP$$

$$0 \leq MISSILE\_SLACK_{w,d,m,y}$$

$$\leq missiles\_desired_{m,y} - missiles\_minimum_{m,y} \qquad \forall \{w,d,m,y\} \in WDMY$$

$$SHIPS\_SHORT_{w,d,m} \geq 0 \qquad \forall \{w,d,m\} \in WDM$$

$$MISSILES\_SHORT_{w,d,m,y} \geq 0 \qquad \forall \{w,d,m,y\} \in WDMY$$

$$LOAD_{s,y'} \geq 0 \qquad \forall \{s,y\} \notin SY$$

$$RISK\_MISSILES_{s,y'} \qquad \forall \{s,y\} \notin SY$$

$$UNDER_{w,d,d,s,y'}, OVER_{w,d,m,s,y'} \geq 0 \qquad \forall \{w,d,m,s,y'\}$$

$$\in WDMSY$$

$$CHANGE_{s,y'} \geq 0 \qquad \{s,y'\} \in SY$$

$$DEPLOY_s \geq 0 \qquad \forall s \in S$$

$$DEPLOY\_WAR_{w,s} \geq 0 \qquad \forall w \in W, s \in S \qquad \text{(D17)}$$

6. Discussion

This model advises the best-achievable missile loadouts into vertical launch system cells of a set of combatants, each deploying from one of two home ports, and each participating in one or two upcoming deployment cycles. Each ship is given a single loadout, even if it participates in two deployment cycles, and the inventory of missiles limits the total load-outs. There are a number of alternate war plans, and the loadouts of each ship must accommodate, as best possible, for any one of these. For some ships, the loadout we are given is the one we must use; in other cases, loadouts may be adjusted to our liking. The objective (D0) accounts rewards for prioritized mission accomplishment and deducts penalties for violating policies that cannot be satisfied. A number of these penalties result from optional model features. Each constraint (D1) restricts a ship from performing mutually-exclusive missions. Each constraint (D2) signals a mission accomplishment if any ship is assigned to this mission. Each constraint (D3) provides the required number of ships for a mission, or accounts for any shortfall. Each constraint (D4) reckons whether a ship needs extra defensive missiles due to the risk level of missions assigned to it. Each constraint (D5) commits a number of a required missile type, or an acceptable substitute type to fulfill an assigned mission. Each constraint (D6) reckons the number of missiles of some type that are to be loaded on a ship. Each constraint (D7) reckons whether the required number of missiles has been loaded, or accounts for a shortfall. Each constraint (D8) limits the number of missiles that can be loaded into the vertical launch system of a ship. Each constraint (D9) limits the number of a type of missile to the total in inventory. Each (optional) constraint (D10) requires that a type of missile be loaded proportionately on each ship participating in a mission. Each constraint (D11) and its pair (D12) (optionally) reckon the positive difference between a pre-existing VLS loadout and the one being prescribed by the model. This positive difference is penalized in the objective function in order to reduce unnecessary "turbulence" between legacy loadouts and their optimal revisions, but could just as well be limited numerically by ship and by missile type if it is anticipated that there will be limited pier-side time to make changes. Constraints (D13-14) are, together, optional. Each constraint (D13) sets an indicator that a ship has been assigned a mission in some deployment cycle of some war plan. Each constraint (D14) assures that a deployed ship is assigned at least one mission in each deployment cycle of each war plan. Constraints (D15-16) are, together, optional, and are subsumed if constraints (D13-14) are invoked. Each constraint (D15) sets an indicator that a ship has been assigned a mission in some deployment cycle of some war plan. Each constraint (D16) assures that a deployed ship is assigned at least one mission in each deployment cycle of each war plan to which it has been assigned a mission. (D17) defines decision variable domains.

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IV. ANALYSIS AND RESULTS

A. INTRODUCTION

To verify the Vertical Launch System (VLS) loadout planner (VLP) model, we make a sequence of less and less restricted optimizations evaluated with two fictitious warplans. These warplans are expressed as data about missions and their priorities, ship requirements, and missile-to-mission conditions. The number and designation of forward deployed naval force (FDNF) and West Coast VLS ships remain the same in their respective deployment cycles. Scenario I is tested with the fleet's current VLS missile loadout fixed and evaluated for readiness to complete combat Commander Seventh Fleet's (C7F) present missions. Scenario II allows VLP to choose optimal missile loadouts for West Coast ships while maintaining fixed loadouts for FDNF ships. Scenario III lets VLP choose an optimal missile loadout for all deployed ships in all cycles. Lastly, we run a sensitivity analysis on a modified Scenario III.

B. COMPUTATION PROCESSOR

The integer linear program to plan all of these VLS loadouts has 9,300 constraints and 19,000 variables, 9,000 of which are integers. On a Lenovo W530 laptop with 32 gigabytes of random access memory and eight processors, General Algebraic Modeling System (GAMS) CPLEX version 24 (GAMS, 2015) solves this problem in ten minutes to an integer tolerance of 10%. The GAMS interpreter and CPLEX solver require 75 Megabytes of random access memory for this model.

C. WARPLAN SCENARIO DATA

Our test model has 23 combatants (five CGs, 17 DDGs and one DDG 1000), there are nine missile types, and we consider two warplan scenarios: one with 22 missions, and the other with 30. Table 2 provides a quick reference to designations and abbreviations used hereafter. Table 3 displays a standard missile inventory shared by all ships. Table 4 displays each warplan-mission with a minimum number of ships assigned to each mission, a priority a level assigned to each mission, and a ship shortage penalty. There are currently 106 different missiles-to-missions requirements. Every mission desires a certain number of a specific missile but requires a minimum missile load of the specific missile, with a penalty for every unassigned mission, as shown in Table 5. Table 6 displays the warplan-mission's primary missile, substitutable mission missile, and a penalty for utilizing an alternative missile in a warplan-mission.

Table 2. VLP acronyms and abbreviations.

US Warships	**Designation**	
Ticonderoga Guided Missile Cruiser	CG (52-73)	
Arleigh Burke Guided Missile Destroyer	DDG (51-106)	
Zumwalt Guided Missile Destroyer	DDG 1000	
Missions	**Abbreviation**	
Theater Ballistic Missile Defense	TBMD	
Escort	Escort	
Surface Action Group	SAG	
Strike	STRIKE	
Missiles	**Designation**	**Associated Mission(s)**
Tomahawk (1-3)	TLAM	STRIKE
Standard Missile 2 Medium Range	SM2 MR	Escort/SAG
Standard Missile 2 Extended Range	SM2 ER	Escort/SAG/TBMD
Standard Missile 3	SM3	TBMD
Standard Missile 6	SM6	ESCORT/SAG/TBMD
Anti-Submarine Rocket	ASROC	ESCORT/SAG

Table 3. Initial missile inventory. There are three variants of TLAM.

Missile	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
Inventory	1600	1900	700	500	400	500	400	400	1800

Table 4. Warplan-mission ship requirements, priorities, and ship shortage penalties. There are two warplans, A and B. They have 11 and 15 missions assigned, respectively.

Warplan	Mission	Priorities	Minimum Ships	Ship Shortage Penalty
A	TBMD	Very High	2	100
B	TBMD 1	High	2	100
B	TBMD 2	High	2	100
B	TBMD 3	High	2	100
B	Escort 1	Medium High	3	80
B	Escort 2	Medium High	3	80
B	Escort 3	Medium High	3	80
B	Escort 4	Medium High	2	50
B	Escort 5	Medium High	2	50
B	Escort 6	Medium High	2	50
B	SAG 1	Very High	3	100
B	SAG 2	Medium High	3	100
B	SAG 3	Medium High	3	100
B	SAG 4	Very High	3	50
B	SAG 5	Medium High	2	50
B	SAG 6	Medium High	2	50
A	STRIKE 1	Medium	1	100
A	STRIKE 2	Medium	1	50
A	STRIKE 3	Medium	1	50
A	Escort 1	Medium Low	1	100
A	Escort 2	Medium Low	1	100
A	Escort 3	Medium Low	1	20
A	Escort 4	Medium Low	2	80
A	SAG 1	Very High	3	100
A	SAG 2	Medium high	2	80
A	SAG 3	Medium High	3	80

Table 5. Warplan-mission missile requirements. See Appendix A for more detail.

Warplan	Mission	Missile	Desired Number	Minimum Number	Missile Shortage Penalty
A	TBMD	SM2 ER	40	30	500
A	TBMD	SM3	40	8	1000
B	TBMD 1	SM2 ER	40	30	500
B	TBMD 1	SM3	40	10	1000
A	TBMD	SM2 ER	40	30	500
B	Escort 1	ASROC	30	25	800
B	Escort 2	ESSM	16	16	1000
B	Escort 2	SM3	10	0	1000
B	Escort 2	SM6	20	10	1000
B	Escort 2	ASROC	30	25	1000
B	Escort 1	ASROC	30	25	800
B	SAG 6	SM2 ER	40	20	1000
B	SAG 6	SM2 MR	40	40	1000
B	SAG 6	ESSM	8	8	1000
A	STRIKE 1	ESSM	8	8	1000

Table 6. Primary mission missile, alternative mission missile, and penalty for utilizing a less desirable alternative mission missile.

Warplan	Mission	Desired Missile	Alternative Missile	Alternative Missile Penalty
B	Escort 1	SM2 ER	SM2 MR	5
B	Escort 1	SM6	SM2 MR	8
B	Escort 1	SM6	SM2 ER	7
B	Escort 2	SM2 ER	SM2 MR	5
B	Escort 2	SM6	SM2 MR	8
B	Escort 2	SM6	SM2 ER	7
B	Escort 3	SM2 ER	SM2 MR	5
B	Escort 3	SM6	SM2 MR	8
B	Escort 3	SM6	SM2 ER	7
B	Escort 4	SM2 ER	SM2 MR	5
B	Escort 4	SM6	SM2 MR	8
B	Escort 4	SM6	SM2 ER	7
B	Escort 5	SM2 ER	SM2 MR	5
B	Escort 5	SM6	SM2 MR	8
B	Escort 5	SM6	SM2 ER	7
B	Escort 6	SM2 ER	SM2 MR	5
B	Escort 6	SM6	SM2 MR	8
B	Escort 6	SM6	SM2 ER	7
A	Escort 1	SM2 ER	SM2 MR	5
A	Escort 1	SM6	SM2 MR	9
A	Escort 1	SM6	SM2 ER	7
A	Escort 2	SM2 ER	SM2 MR	5
A	Escort 2	SM6	SM2 MR	9
A	Escort 2	SM6	SM2 ER	7
A	Escort 3	SM2 ER	SM2 MR	5
A	Escort 3	SM6	SM2 MR	9
A	Escort 3	SM6	SM2 ER	7

D. COMPUTATIONAL RESULTS

The VLP model is tested on three main scenarios. Each scenario builds and improves from the previous one and has a short analysis describing the results. In each case, a missile loadout table, visual image of ship assignments by warplan in their respective deployment cycles, and the missions not covered are displayed. In every scenario, VLP optimizes every ship's missile compliment (as allowed) and adheres to the mission and missile restrictions set in the model.

1. Scenario I: Fixed Missile Loadout

This scenario provides the operational planner a view of the current status of each ship. This also offers the operational planner the option to manually fix the missile loadout and evaluate the loadout's readiness to cover warplan missions. We test the VLP model on currently deployed FDNF ships in cycles 1 and 2 and West Coast ships in cycle 1 with their respective missile loadout. In order to prevent the model from reconfiguring the loadout of the ships, we fix the missile loadout for all ships operating in these cycles, as shown in column 3 of Table 7. We do not allow the model to force ships' mission assignments in all cycles but do allow the model to assign ships at least one mission. The assigned missions-to-ship are shown in Figures 6 and 7. The missions not covered are displayed in Table 8.

a. Scenario I Analysis

By fixing the missile loadout on VLS ships, we prevent the model from choosing the best missile loadout and optimizing the warplan-missions requirements in cycle 1 and 2. As displayed in Figure 6, DDG 89 could not meet warplan-mission requirements in cycle 1 due to the fixed missile loadout and could not cover any mission in Table 8: she has no TLAMs to cover STRIKE missions and no SM6s to cover SAG or Escort missions. The fixed missile loadout restricted the model from optimizing ship's coverage in all warplans in their respective cycle(s). The majority of the VLS ships in Figure 6 and 7 are restricted to participate in only one warplan and at most a few missions. Comparable to the DDG 89 situation, most ships cannot cover additional missions due to the fixed missile loadout and restrictions to the requirements placed in the model. Approximately 56% of missions are not covered with the current missile loadout.

Table 7. Scenario I missile loadout. The one in the "Fixed Loadout" column indicates we do not allow any reallocation of missiles.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
CG54	122	1	32	22	18	12	10	8	8	20	16
CG67	122	1	32	0	8	0	1	60	37	0	8
DDG54	96	1	48	22	12	3	12	5	5	5	20
DDG62	96	1	24	22	12	6	10	10	0	0	30
DDG56	96	1	40	2	6	15	27	0	0	0	36
DDG82	96	1	40	0	31	32	0	0	0	0	23
DDG85	96	1	40	0	31	32	0	0	0	0	23
DDG89	96	1	40	0	31	32	0	0	0	0	23
DDG60	96	1	24	20	2	10	20	0	0	0	38
DDG70	96	1	48	13	6	5	14	3	3	4	36
DDG91	96	1	32	28	22	20	4	3	3	4	4
CG65	122	1	32	30	20	30	20	6	0	0	8
CG70	122	1	40	32	16	10	16	10	6	6	16
DDG86	96	1	40	30	20	6	12	6	4	2	6
DDG92	96	1	36	21	18	20	8	4	4	4	8

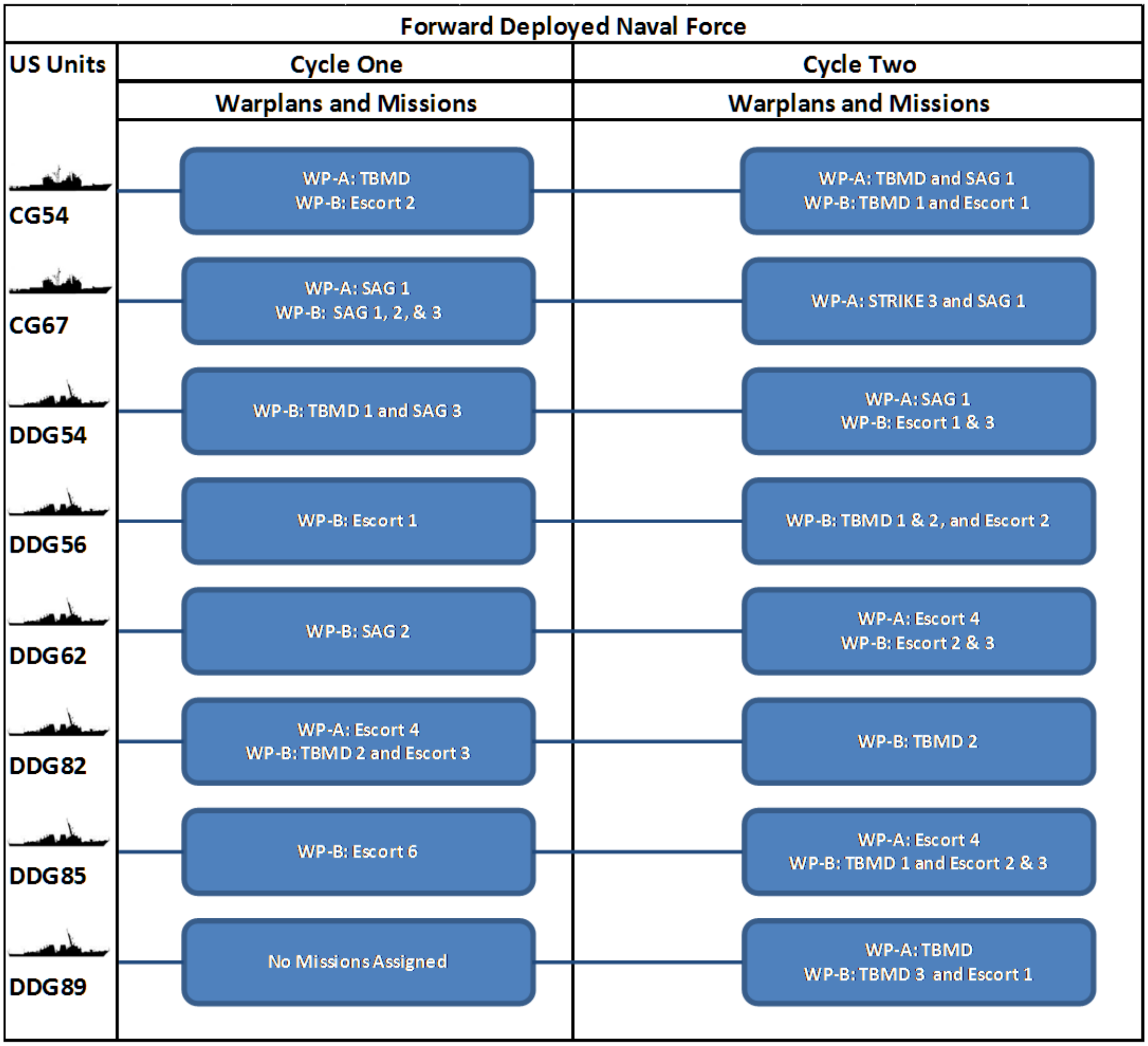

Figure 6. Scenario I warplan-mission coverage in FDNF's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class destroyer (DDG) (from U.S. Navy, 2014).

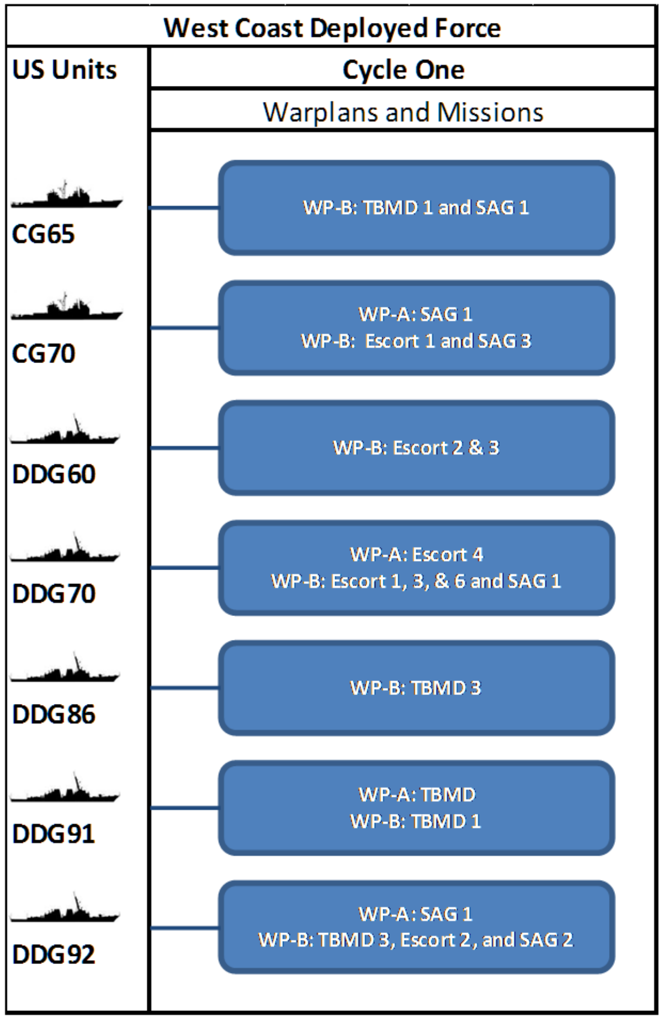

Figure 7. Scenario I warplan-mission coverage in West Coast's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class Destroyer (DDG) (from U.S. Navy, 2014).

Table 8. Missions not covered in Scenario I. 15 in Warplan A and 14 in Warplan B.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 1	Medium
A	1	STRIKE 2	Medium
A	1	STRIKE 3	Medium
A	1	Escort 1	Medium Low
A	1	Escort 2	Medium Low
A	1	Escort 3	Medium Low
A	1	SAG 2	Medium High
A	1	SAG 3	Medium high
A	2	STRIKE 1	Medium
A	2	STRIKE 2	Medium
A	2	Escort 1	Medium Low
A	2	Escort 2	Medium Low
A	2	Escort 3	Medium Low
A	2	SAG 2	Medium High
A	2	SAG 3	Medium high
B	1	Escort 4	Medium
B	1	Escort 5	Medium
B	1	SAG 4	Very High
B	1	SAG 5	Medium
B	1	SAG 6	Medium
B	2	Escort 4	Medium
B	2	Escort 5	Medium
B	2	Escort 6	Medium
B	2	SAG 1	Very High
B	2	SAG 2	Medium
B	2	SAG 3	Medium
B	2	SAG 4	Very High
B	2	SAG 5	Medium
B	2	SAG 6	Medium

2. Scenario II: Fixed and Flexible Missile Loadout

This scenario adds eight West Coast VLS ships in cycle 2. This provides recommended missile loadout for pre-deploy ships and an insight of the warplan mission coverage for all deployed ships. FDNF ships in cycle 1 and 2 and West Coast ships in cycle 1 missile loadouts will remain fixed, but the West Coast ships' missile loadout in cycle 2 are optimized, as shown in column 3 in Table 9. For the same reasons as in Scenario I, we did not allow the model to force ships' mission assignments in all cycles but did allow the model to assign ships at least one mission.. VLP provides the recommended missile loadout for each new ship and assigns every ship to warplan missions.

a. Scenario II Analysis

VLP has more flexibility in meeting warplan missions when optimizing the missile loadout for the West Coast ships in cycle 2. Even though there are additional ships to reduce the missions not covered in cycle 2, VLP has increased the coverage of warplan missions and assigns each ship more missions than in Scenario I, as displayed in Figure 8 and 9. The model's optimization of the additional eight VLS ships has reduced the missions not covered to approximately 25%, as shown in Table 10. The ships' fixed missile loadout limit VLP's effectiveness in decreasing the missions not covered. For example, CG 67 has only 37 TLAM2s but requires at least 50 TLAM2s to cover the STRIKE 2 mission in cycle 2 and has only one SM6 but requires at least six SM6s to cover SAG 5 and SAG 6 missions in cycle 2. This is inefficient employment of CG 67 in cycle 2.

Table 9. Scenario II missile loadout. The zeros in the "Fixed Loadout" column signify eight West Coast ships deployed for cycle 2 of the scenario for which we can specify an optimal VLS loadout. All other ships have the same fixed loadout as in Scenario I.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
DDG1000	80	0	24	18	7	0	10	0	21	0	18
CG54	122	1	32	22	18	12	10	8	8	20	16
CG67	122	1	32	0	8	0	1	60	37	0	8
DDG54	96	1	48	22	12	3	12	5	5	5	20
DDG62	96	1	24	22	12	6	10	10	0	0	30
DDG56	96	1	40	2	6	15	27	0	0	0	36
DDG82	96	1	40	0	31	32	0	0	0	0	23
DDG85	96	1	40	0	31	32	0	0	0	0	23
DDG89	96	1	40	0	31	32	0	0	0	0	23
DDG60	96	1	24	20	2	10	20	0	0	0	38
DDG70	96	1	48	13	6	5	14	3	3	4	36
DDG91	96	1	32	28	22	20	4	3	3	4	4
CG65	122	1	32	30	20	30	20	6	0	0	8
CG70	122	1	40	32	16	10	16	10	6	6	16
DDG86	96	1	40	30	20	6	12	6	4	2	6
DDG92	96	1	36	21	18	20	8	4	4	4	8
DDG77	96	0	16	23	13	0	10	5	15	0	26
DDG90	96	0	32	20	13	0	6	23	15	10	1
DDG76	96	0	32	28	18	0	9	5	12	0	16
DDG93	96	0	40	1	30	4	13	0	0	0	38
CG73	122	0	24	18	8	0	6	12	22	50	0
DDG59	96	0	24	7	0	0	3	50	0	0	30
DDG69	96	0	24	8	30	0	12	4	5	0	31

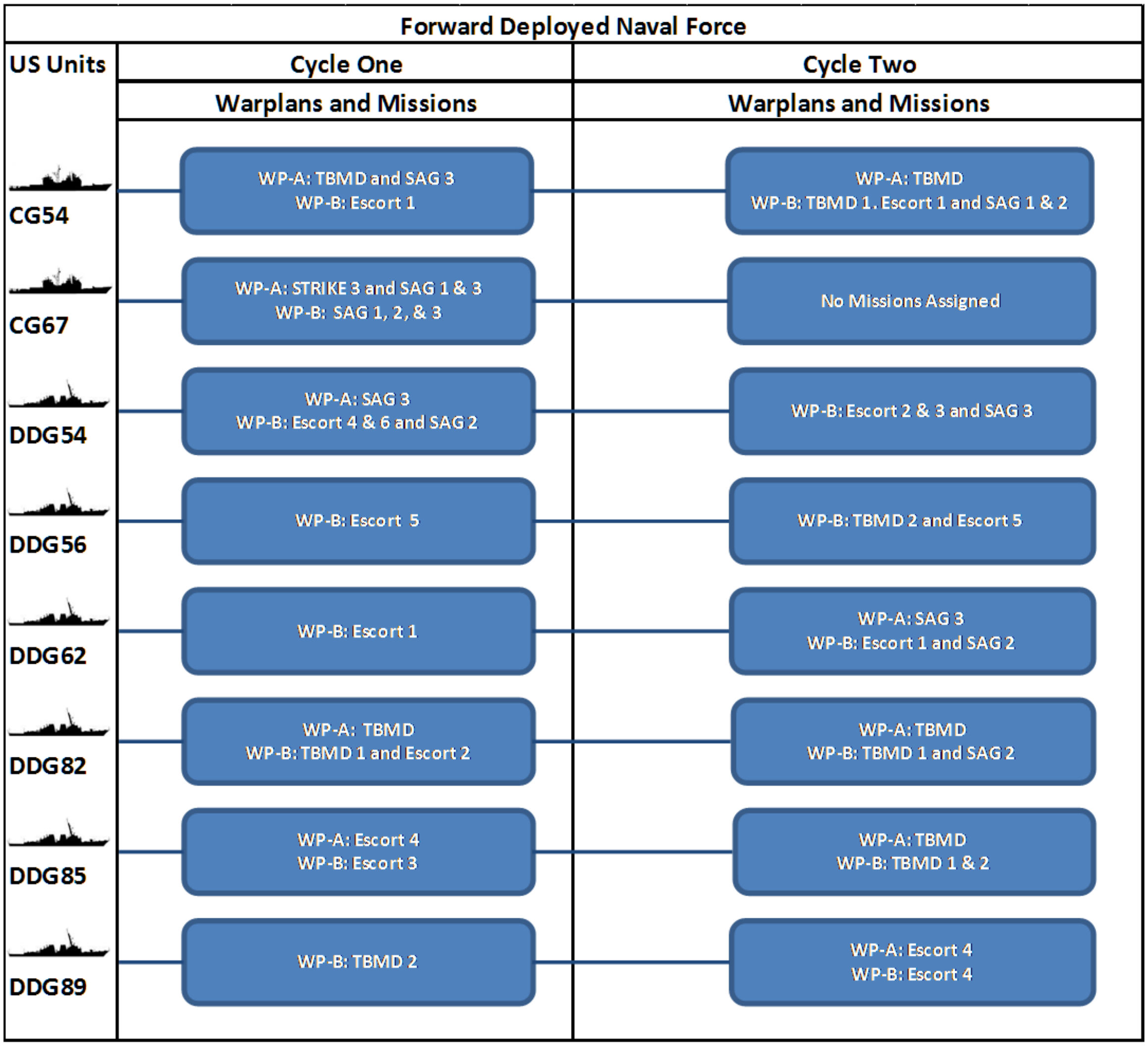

Figure 8. Scenario II warplan-mission coverage in FDNF's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class destroyer (DDG) (from U.S. Navy, 2014).

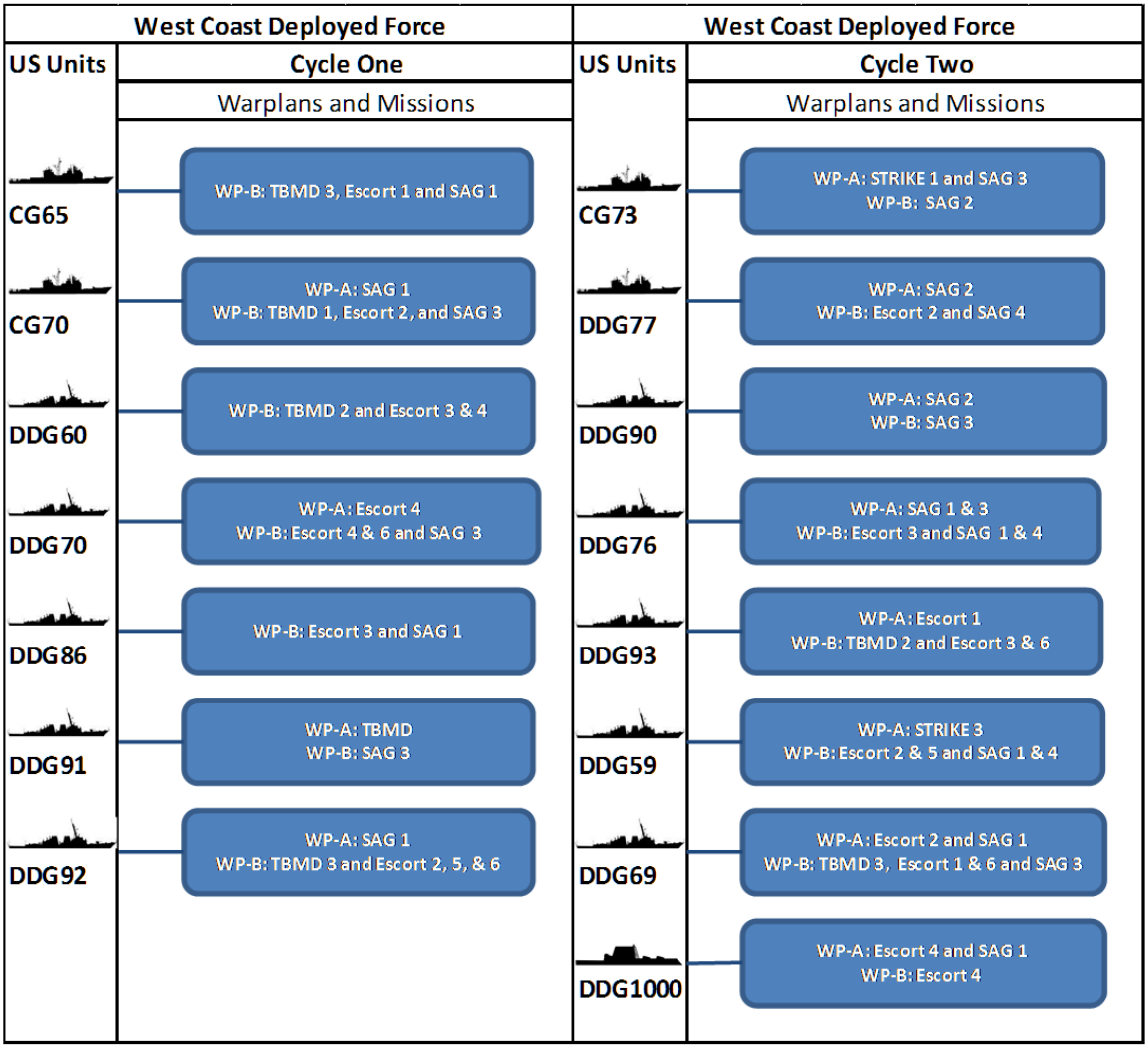

Figure 9. Scenario II warplan-mission coverage in West Coast's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class destroyer (DDG) (from U.S. Navy, 2014) and Zumwalt-Class destroyer (DDG 1000) (from Global Security, 2015).

Table 10. Missions not covered in Scenario II. There are eight missions not covered in Warplan A and five in Warplan B. The eight new West Coast ships with their optimized VLS loadouts have reduced uncovered missions from 18 to 11 in Warplan A and from 17 to six in Warplan B.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 1	Medium
A	1	STRIKE 2	Medium
A	1	Escort 1	Medium Low
A	1	Escort 2	Medium Low
A	1	Escort 3	Medium Low
A	1	SAG 2	Medium High
A	2	STRIKE 2	Medium
A	2	Escort 3	Medium Low
B	1	SAG 4	Very High
B	1	SAG 5	Medium High
B	1	SAG 6	Medium High
B	2	SAG 5	Medium High
B	2	SAG 6	Medium High

3. Scenario III: Flexible Missile Loadout for All Ships in All Cycles

This scenario replicates Scenario II, and we allow the missile loadout of each ship to be adjusted to better serve the missions at hand. Additionally, we allow the model to force all ships to be assigned all warplans in all cycles because the model has more flexibility in missile loadouts. This scenario would present itself in the planning of future deployments. Table 11 displays the optimal missile loadout for each ship. Figures 10 and 11 display the ship's warplan-mission assignments in each cycle. Table 10 reveals the missions still not covered.

a. Scenario III Analysis

VLP is able to optimize the missile loadout on each ship, as shown in Table 11. VLP assigns the ships to the best warplan mission coverage in each deployment cycle, as displayed in Figures 10 and 11. Lastly, there are just two missions not covered in each warplan over both deployment cycles, displayed in Table 12. This is approximately 7% of missions. This is an 18% decrease of missions not covered from Scenario II and a 49% decrease of missions not covered from Scenario I.

Table 11. Scenario III missile loadout. The zeroes in the "Fixed Loadout" column indicate VLP is able to adjust loadouts optimally to complete assigned missions.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
DDG1000	80	0	24	12	18	0	16	0	0	0	28
CG54	122	0	32	25	20	1	8	10	0	50	0
CG67	122	0	32	48	23	0	1	17	25	0	0
DDG54	96	0	32	22	10	0	1	50	5	0	0
DDG62	96	0	24	28	10	0	10	6	15	0	21
DDG56	96	0	32	10	30	0	13	0	0	0	35
DDG82	96	0	36	13	27	4	0	10	10	0	23
DDG85	96	0	40	0	30	0	13	0	8	0	35
DDG89	96	0	40	0	30	22	11	0	0	0	23
DDG60	96	0	24	20	3	0	16	15	10	0	26
DDG70	96	0	48	13	6	0	14	5	10	0	36
DDG91	96	0	32	27	14	0	4	13	30	0	0
CG65	122	0	24	30	20	7	9	50	0	0	0
CG70	122	0	40	13	30	10	18	10	0	0	31
DDG86	96	0	40	30	11	6	12	17	10	0	0
DDG92	96	0	36	14	13	0	13	10	15	0	22
DDG77	96	0	24	14	25	0	10	10	0	0	31
DDG90	96	0	28	26	14	0	6	27	16	0	0
DDG76	96	0	32	20	12	0	14	21	0	0	21
DDG93	96	0	24	7	30	1	12	9	0	0	31
CG73	122	0	24	13	8	9	12	10	14	50	0
DDG59	96	0	36	0	30	8	18	0	0	0	31
DDG69	96	0	32	27	13	0	10	10	12	0	16

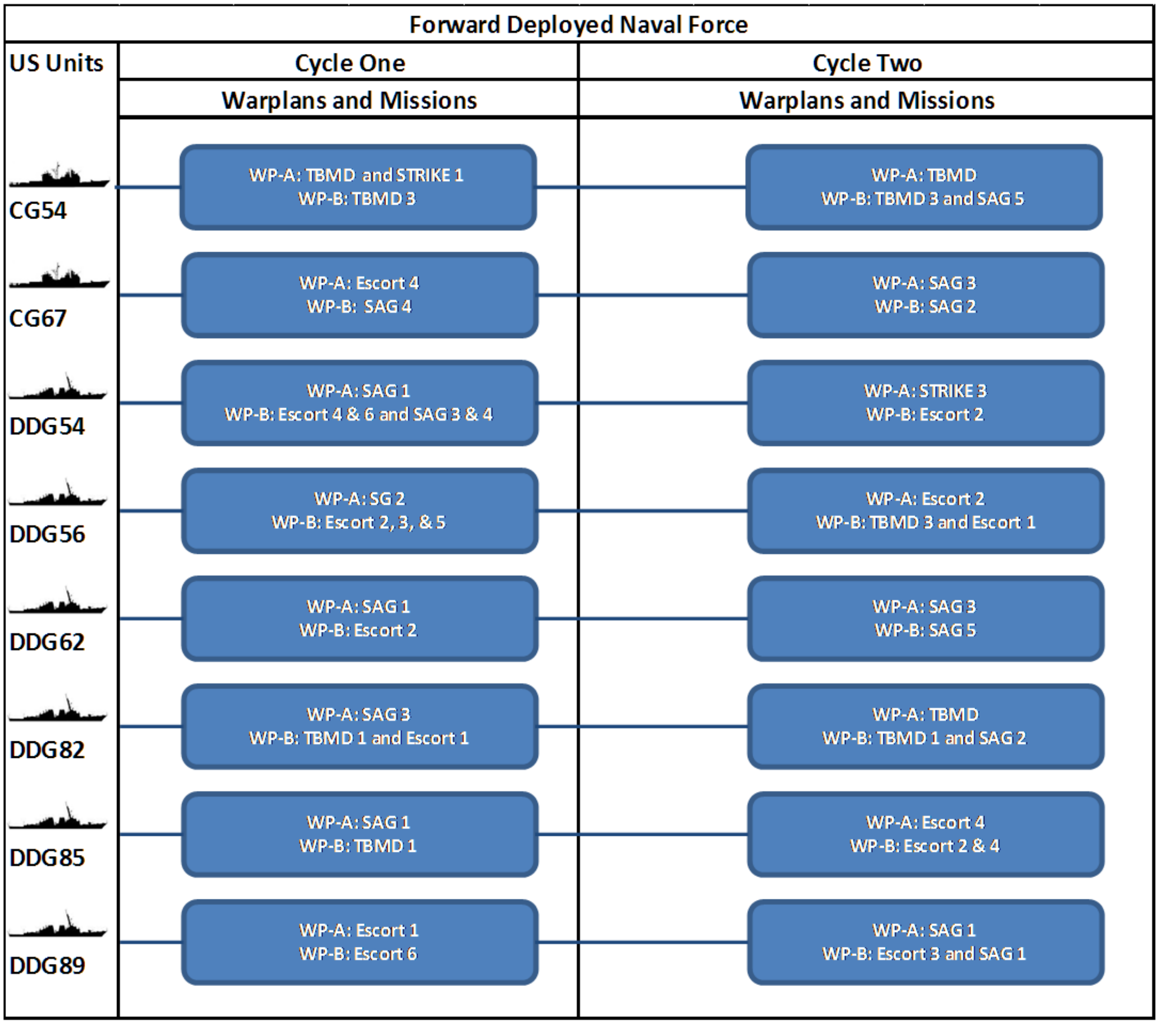

Figure 10. Scenario III warplan-mission coverage in FDNF's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class destroyer (DDG) (from U.S. Navy, 2014).

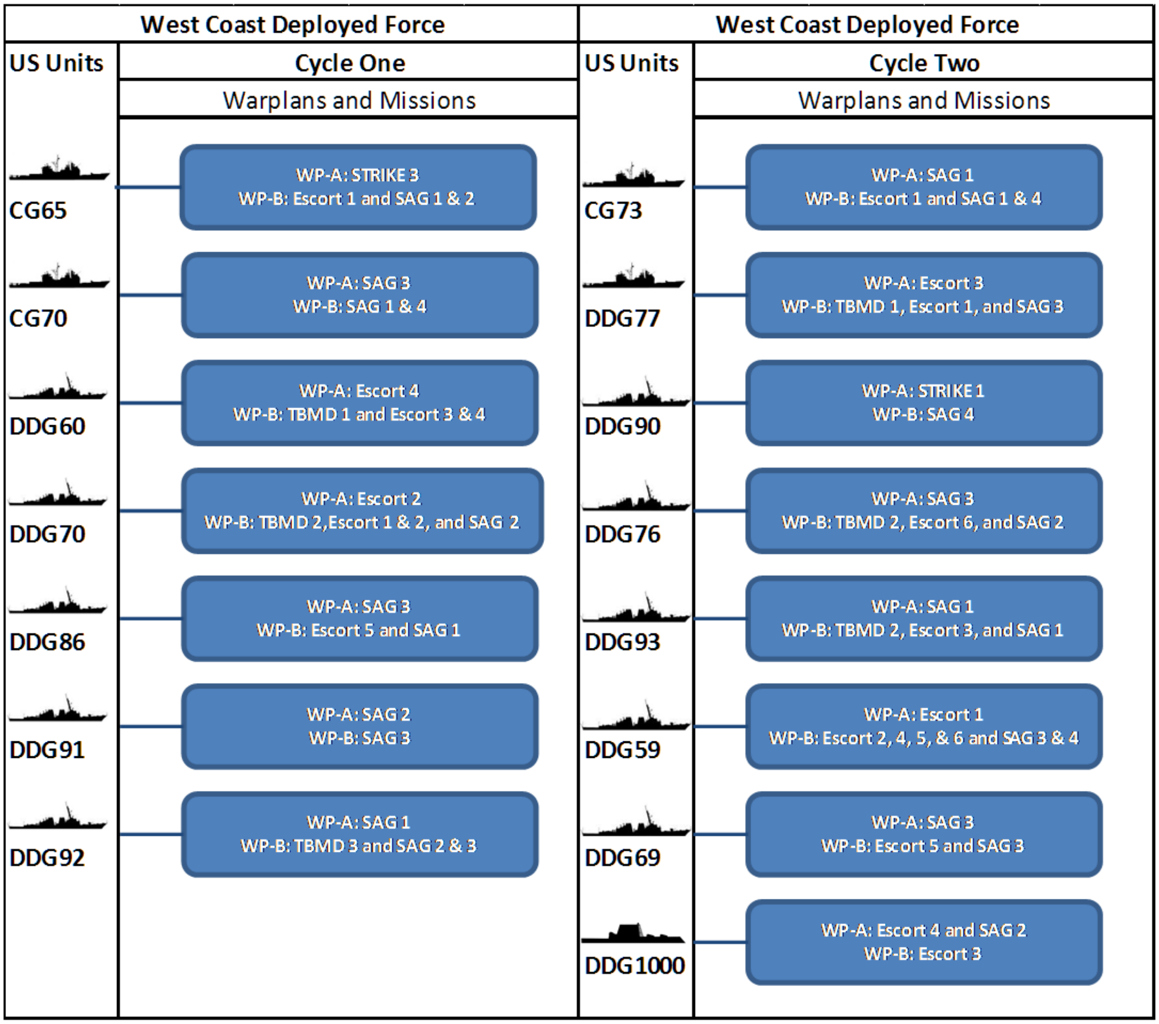

Figure 11. Scenario III warplan-mission coverage in West Coast's deployment cycle 1 and cycle 2. Ship images of Ticonderoga-Class cruiser (CG) and Arleigh Burke-Class destroyer (DDG) (from U.S. Navy, 2014) and Zumwalt-Class destroyer (DDG 1000) (from Global Security, 2015).).

Table 12. Missions not covered in Scenario III. Optimizing the VLS loadouts has reduced the unfilled missions in Warplan A from 18 to two, and in Warplan B from 17 to two.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 2	Medium
A	2	STRIKE 2	Medium
B	1	SAG 6	Medium
B	2	SAG 5	Medium

E. SENSITIVITY ANALYSIS

Following is sensitivity analysis conducted on the model. We are conducting this extra step to see how the missile loadout and warplan-missions react to changes in the data. We change Warplan B priorities, increase the number of ships with missile incompatibilities, and limit the missile inventory. In every scenario, VLP maximizes every ship's missile complement and adheres to the mission and missile restrictions set in the model.

1. Scenario IV: Changing Warplan Preferences

We increase the importance of Warplan B priorities and ship shortage penalties from Table 4. This might occur if a certain crisis in the world arises and operational planners need to concentrate on one warplan more than any other. Using Scenario III, we modify the model by increasing all Warplan B mission priorities to Very High and ship shortage penalties from 50 and 80 to 100. We reduce the bulk of the Warplan A mission priorities to Medium or Medium Low and ship shortage penalties from 100, 80, and 50 to 20.

a. Scenario IV Analysis

By increasing Warplan B mission priorities and ship shortage penalties, and reducing Warplan A mission priorities and ship shortage penalties, displayed in Table 13, the model is able to cover all Warplan B missions. In this scenario run, Table 14 displays the recommended missile loadout for each ship. Given the focus on Warplan B, Table 15 displays Warplan A missions not covered.

Table 13. Warplan-mission ship requirements and priorities in Scenario IV. All Warplan B missions' priorities and ship shortage penalties are increased to Very High and to a penalty of 100, respectively. All Warplan A missions' priorities and ship shortage penalties are decreased to Medium or Medium Low and to a penalty of 20, respectively, with the exception of TBMD missions.

Warplan	Mission	Priorities	Minimum Ships	Ship Shortage Penalty
A	TBMD	Very High	2	100
B	TBMD 1	Very High	2	100
B	TBMD 2	Very High	2	100
B	TBMD 3	Very High	2	100
B	Escort 1	Very High	3	100
B	Escort 2	Very High	3	100
B	Escort 3	Very High	3	100
B	Escort 4	Very High	2	100
B	Escort 5	Very High	2	100
B	Escort 6	Very High	2	100
B	SAG 1	Very High	3	100
B	SAG 2	Very High	3	100
B	SAG 3	Very High	3	100
B	SAG 4	Very High	3	100
B	SAG 5	Very High	2	100
B	SAG 6	Very High	2	100
A	STRIKE 1	Medium	1	20
A	STRIKE 2	Medium	1	20
A	STRIKE 3	Medium	1	20
A	Escort 1	Medium Low	1	20
A	Escort 2	Medium Low	1	20
A	Escort 3	Medium Low	1	20
A	Escort 4	Medium Low	2	20
A	SAG 1	Medium Low	3	20
A	SAG 2	Medium Low	2	20
A	SAG 3	Medium Low	3	20

Table 14. Ships' missile loadout display in Scenario IV.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
DDG1000	80	0	24	8	10	0	17	8	0	0	31
CG54	122	0	32	26	20	0	10	50	8	0	0
CG67	122	0	32	65	29	0	0	20	0	0	0
DDG54	96	0	48	22	12	0	4	16	10	0	20
DDG62	96	0	24	27	7	0	10	21	0	0	25
DDG56	96	0	40	0	19	0	22	1	0	0	44
DDG82	96	0	32	22	35	10	0	21	0	0	0
DDG85	96	0	32	0	32	10	13	0	10	0	23
DDG89	96	0	40	10	28	0	10	3	0	0	35
DDG60	96	0	24	20	20	0	10	9	0	0	31
DDG70	96	0	48	4	0	0	16	0	10	0	54
DDG91	96	0	32	26	20	8	4	30	0	0	0
CG65	122	0	32	30	20	10	17	27	0	0	10
CG70	122	0	40	32	16	4	16	18	10	0	16
DDG86	96	0	16	30	24	6	12	10	10	0	0
DDG92	96	0	24	22	19	10	9	10	20	0	0
DDG77	96	0	16	20	20	0	16	10	0	0	26
DDG90	96	0	24	40	13	0	6	19	12	0	0
DDG76	96	0	32	20	12	0	12	15	9	0	20
DDG93	96	0	40	18	17	0	13	10	0	0	28
CG73	122	0	24	30	15	0	11	50	10	0	0
DDG59	96	0	40	0	30	10	15	0	0	0	31
DDG69	96	0	32	20	12	0	9	20	11	0	16

Table 15. Missions not covered in Scenario IV. Every Warplan B mission is covered.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 1	Medium
A	1	STRIKE 2	Medium
A	1	Escort 3	Medium Low
A	1	SAG 2	Medium
A	2	STRIKE 1	Medium
A	2	STRIKE 2	Medium
A	2	Escort 1	Medium Low
A	2	Escort 3	Medium Low
A	2	SAG 2	Medium

2. Scenario V: Ships Unable to Accommodate Certain Missiles

There are VLS ships not capable of carrying certain missile types, and operational planners need to account for this missile incompatibility. Taking this into consideration, we modify Scenario III by restricting six VLS ships (CG67, CG73, DDG82, DDG77, DDG76, and DDG70) from carrying SM6 missiles.

a. Scenario V Analysis

The VLP model restricts six VLS ships from carrying SM6 missiles, as highlighted in the SM6 column in Table 16, and still optimizes the missile loadout. Very similar to Scenario III, the majority of warplan-missions are fulfilled. Similar to Scenario III, about 7% of warplan-missions are not covered, as shown in Table 17.

Table 16. Scenario V missile loadout. The highlighted zeroes identify ships now restricted from carrying the SM6 missile.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
DDG1000	80	0	24	0	7	0	10	0	26	0	31
CG54	122	0	32	2	18	10	10	0	8	50	16
CG67	122	0	32	36	30	0	0	33	15	0	0
DDG54	96	0	32	18	12	0	3	50	5	0	0
DDG62	96	0	32	13	20	0	10	10	0	0	35
DDG56	96	0	32	12	0	0	6	50	0	0	20
DDG82	96	0	32	0	12	6	0	0	50	0	20
DDG85	96	0	40	0	29	4	16	0	12	0	25
DDG89	96	0	40	0	30	0	19	0	2	0	35
DDG60	96	0	16	11	9	0	16	30	0	0	26
DDG70	96	0	48	13	6	0	0	10	10	0	45
DDG91	96	0	24	38	20	8	4	10	10	0	0
CG65	122	0	32	32	21	10	20	16	15	0	0
CG70	122	0	40	31	20	10	16	20	15	0	0
DDG86	96	0	40	26	21	2	15	6	0	0	16
DDG92	96	0	32	21	20	0	12	4	0	0	31
DDG77	96	0	16	40	20	0	0	4	28	0	0
DDG90	96	0	32	20	0	0	12	6	0	50	0
DDG76	96	0	32	20	7	0	0	16	0	0	45
DDG93	96	0	24	37	20	9	17	3	4	0	0
CG73	122	0	16	27	17	0	0	27	30	1	16
DDG59	96	0	40	0	30	1	23	0	0	0	32
DDG69	96	0	32	5	25	0	22	5	0	0	31

Table 17. Missions not covered in Scenario V.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 2	Medium
A	2	Escort 3	Medium Low
B	1	SAG 5	Medium
B	2	SAG 6	Medium

3. Scenario VI: Reduced Missile Inventory

We now significantly reduce the missile inventory from Table 3. The US Navy may have missile shortages in inventory or may allocate some missiles to another theater of operation that may limit operational planner's options in missile loadout of VLS ships. We modify the new missile inventory in Table 18. We display the reduced missile loadout in Table 19 and missions not covered in Table 20.

a. Scenario VI Analysis

The missile inventory reduction limits the ships' coverage warplan-missions. As shown in Table 19, 19 warplan-missions, approximately 30%, are not covered. The model optimizes the new missile loadout, shown in Table 18, given the reduced missile inventory.

Table 18. Reduced missile inventory in Scenario VI

Missile	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
Inventory	1000	800	200	300	100	200	200	200	1900

Table 19. Scenario VI missile loadout.

Ship	VLS Cells	Fixed Loadout	ESSM	SM2 MR	SM2 ER	SM3	SM6	TLAM1	TLAM2	TLAM3	ASROC
DDG1000	80	0	24	24	3	0	7	0	10	4	26
CG54	122	0	32	13	11	12	2	0	10	50	16
CG67	122	0	32	51	20	0	3	10	20	0	10
DDG54	96	0	48	22	7	3	4	10	10	5	23
DDG62	96	0	24	20	7	0	3	10	15	5	30
DDG56	96	0	40	0	0	15	27	0	0	0	44
DDG82	96	0	40	12	19	32	0	0	0	0	23
DDG85	96	0	40	0	30	32	0	0	0	0	24
DDG89	96	0	40	0	27	32	3	0	0	0	24
DDG60	96	0	24	20	0	10	0	0	0	0	60
DDG70	96	0	48	13	3	5	8	3	0	4	48
DDG91	96	0	32	24	13	20	3	10	10	4	4
CG65	122	0	32	30	0	30	0	10	0	0	44
CG70	122	0	40	30	0	3	3	50	10	0	16
DDG86	96	0	40	30	13	6	3	10	10	2	12
DDG92	96	0	36	21	7	20	3	4	10	4	18
DDG77	96	0	24	20	0	0	0	50	0	0	20
DDG90	96	0	32	21	13	0	5	8	15	10	16
DDG76	96	0	32	13	0	0	0	0	5	50	20
DDG93	96	0	40	20	14	4	3	5	10	3	27
CG73	122	0	24	27	6	0	6	10	50	1	16
DDG59	96	0	40	0	0	15	11	0	0	0	60
DDG69	96	0	32	20	7	3	6	10	15	5	22

Table 20. Missions not covered in Scenario VI.

Warplan	Cycle	Mission	Priority
A	1	STRIKE 2	Medium
A	1	Escort 1	Medium Low
A	1	Escort 2	Medium Low
A	1	Escort 3	Medium Low
A	1	Escort 4	Medium Low
A	1	SAG 2	High
A	2	Escort 1	Medium Low
A	2	Escort 2	Medium Low
A	2	Escort 3	Medium Low
B	1	TBMD 2	High
B	1	TBMD 3	High
B	1	SAG 4	Very High
B	1	SAG 5	Medium High
B	1	SAG 6	Medium High
B	2	TBMD 2	High
B	2	TBMD 3	High
B	2	SAG 4	Very High
B	2	SAG 5	Medium High
B	2	SAG 6	Medium High

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V. RECOMMENDATIONS AND FUTURE DEVELOPMENT

A. SUMMARY

In this thesis, we develop the vertical launch system (VLS) loadout planner (VLP), a mixed-integer linear program designed to optimally load missiles on ships to cover missions in a multi-threat fleet area. There may be multiple warplans, and we must plan missile loads to be prepared to meet any one of these: we seek a robust missile allocation to our ships regardless of the war plan we turn out to face. There are numerous considerations in missile loading: mission requirements and restrictions, missile inventory limitations, and individual ships' missile compatibilities and VLS cell capacities. The actual missile loading and unloading process for a ship is time consuming, expensive, and a hazardous evolution. With the assistance of VLP, missile loading and unloading can be reduced by providing the operational planners with accurate missile loadout recommendations.

B. RECOMMENDATIONS

The operational planner has multiple options to employ VLP to recommend the missile loadout on ships. We have demonstrated VLP's effectiveness in six different scenarios in Chapter III; three were sensitivity analyses. We hope VLP can plan future deployments without fixing the missile loadout on ships; this would allow the model to optimally choose the ships' missile loadout to face any of the warplan mission scenarios. Realistically, operational planners desire more control in missile loading inputs. VLP permits the planner to control all aspects of loadout decisions. VLP can still assist, rather than replace, with planners' inputs and provide a recommended missile loadout.

C. FUTURE DEVELOPMENT

VLP is the first model of its kind, and future development may expand the model's potential. We suggest the following to improve VLP's performance and operational planners' management.

1. Real-World Data

VLP requires testing on real-world data. This thesis is based on two fictitious warplan scenarios. We may learn more about how to improve the model by testing with classified material. We hope to analyze the model in Commander Seventh Fleet (C7F) Area of Responsibility (AOR), which has multiple warplan missions with requirements, multiple threats, and several restrictions. The model is already set up to accommodate forward deployed naval forces (FDNF) and West Coast ships in two deployment cycles. Classified scenarios may provide further insight and improve the model's accuracy.

2. Python Programs

There are alternative and free software programs to create the same optimization capabilities to solve the missile loadout model. We use the General Algebraic Modeling System (GAMS) CPLEX version 24.3 (GAMS, 2015), an optimization package, to solve the VLP model, but this program requires a license with an annual fee. An alternative program is Enthought Canopy Version: 1.0 (Enthought Inc., 2012), free Python software that performs multiple analyses, including optimization. Future research may develop a VLP model with Python-like capabilities, which could operate on any computer system.

3. Excel Interface

Operational planners can benefit from an Excel interface to operate GAMS or Enthought Canopy. Both programs are powerful optimization tools but are mathematically complex and require training to operate the software. A Visual Basic for Applications (VBA) Excel (Microsoft Corporation, 2015) spreadsheet, can remotely operate GAMS or Python. From Excel, VLP-software could import forms of data: ship names, updated missile inventory count, ability to add or delete warplan-missions, change penalties, and other pertinent data-inputs. Then, VLP would output the results back into Excel for the operational planners' review.

APPENDIX. A COMPLETE LIST OF WARPLAN MISSION REQUIREMENTS

Warplan	Mission	Missile	Desired Number	Minimum Number	Missile Shortage Penalty
A	TBMD	SM2 ER	40	30	500
A	TBMD	SM3	40	8	1000
B	TBMD 1	SM2 ER	40	30	500
B	TBMD 1	SM3	40	10	1000
B	TBMD 1	SM6	15	10	500
B	TBMD 2	SM2 ER	40	30	500
B	TBMD 2	SM3	40	10	1000
B	TBMD 2	SM6	15	10	500
B	TBMD 3	SM2 ER	40	30	500
B	TBMD 3	SM3	40	10	1000
B	TBMD 3	SM6	15	10	500
B	Escort 1	ESSM	16	16	800
B	Escort 1	SM3	10	0	800
B	Escort 1	SM6	20	10	800
B	Escort 1	ASROC	30	25	800
B	Escort 2	ESSM	16	16	1000
B	Escort 2	SM3	10	0	1000
B	Escort 2	SM6	20	10	1000
B	Escort 2	ASROC	30	25	1000
B	Escort 3	ESSM	16	16	1000
B	Escort 3	SM3	10	0	1000
B	Escort 3	SM6	20	10	1000
B	Escort 3	ASROC	30	25	1000
B	Escort 4	ESSM	16	16	1000
B	Escort 4	SM3	10	0	1000
B	Escort 4	SM6	20	10	1000
B	Escort 4	ASROC	30	25	1000
B	Escort 5	ESSM	16	16	1000
B	Escort 5	SM3	10	0	1000
B	Escort 5	SM6	20	10	1000
B	Escort 5	ASROC	30	25	1000
B	Escort 6	ESSM	16	16	1000
B	Escort 6	SM3	10	0	1000
B	Escort 6	SM6	20	10	1000
B	Escort 6	ASROC	40	25	1000
B	SAG 1	SM6	10	6	600
B	SAG 1	TLAM1	30	30	800
B	SAG 1	SM2 ER	40	20	1000

B	SAG 1	SM2 MR	40	40	1000
B	SAG 1	ESSM	8	8	1000
B	SAG 2	SM6	10	6	1000
B	SAG 2	TLAM1	30	30	1000
B	SAG 2	SM2 ER	40	20	1000
B	SAG 2	SM2 MR	40	40	1000
B	SAG 2	ESSM	8	8	1000
B	SAG 3	SM6	10	6	1000
B	SAG 3	TLAM1	30	30	1000
B	SAG 3	SM2 ER	40	20	1000
B	SAG 3	SM2 MR	40	40	1000
B	SAG 3	ESSM	8	8	1000
B	SAG 4	SM6	10	6	1000
B	SAG 4	TLAM1	30	30	1000
B	SAG 4	SM2 ER	40	20	1000
B	SAG 4	SM2 MR	40	40	1000
B	SAG 4	ESSM	8	8	1000
B	SAG 5	SM6	10	6	1000
B	SAG 5	TLAM1	30	30	1000
B	SAG 5	SM2 ER	40	20	1000
B	SAG 5	SM2 MR	40	40	1000
B	SAG 5	ESSM	8	8	1000
B	SAG 6	SM6	10	6	1000
B	SAG 6	TLAM1	30	30	1000
B	SAG 6	SM2 ER	40	20	1000
B	SAG 6	SM2 MR	40	40	1000
B	SAG 6	ESSM	8	8	1000
A	STRIKE 1	ESSM	8	8	1000
A	STRIKE 1	TLAM3	50	50	1000
A	STRIKE 2	ESSM	8	8	1000
A	STRIKE 2	TLAM2	50	50	1000
A	STRIKE 3	ESSM	8	8	1000
A	STRIKE 3	TLAM1	50	50	1000
A	Escort 1	ESSM	8	8	1000
A	Escort 1	SM2 ER	40	30	1000
A	Escort 1	SM6	20	10	1000
A	Escort 1	ASROC	30	25	1000
A	Escort 2	ESSM	8	8	1000
A	Escort 2	SM2 ER	40	30	1000
A	Escort 2	SM6	20	10	1000
A	Escort 2	ASROC	30	25	1000
A	Escort 3	ESSM	8	8	1000
A	Escort 3	SM2 ER	40	30	1000
A	Escort 3	SM6	20	10	1000

A	Escort 3	ASROC	30	25	1000
A	Escort 4	ESSM	8	8	1000
A	Escort 4	SM2 ER	40	30	1000
A	Escort 4	SM6	20	10	1000
A	Escort 4	ASROC	30	25	1000
A	SAG 1	SM6	10	6	1000
A	SAG 1	TLAM2	30	30	1000
A	SAG 1	SM2 ER	40	20	1000
A	SAG 1	SM2 MR	40	40	1000
A	SAG 1	ESSM	8	8	1000
A	SAG 2	SM6	10	6	1000
A	SAG 2	TLAM2	30	30	1000
A	SAG 2	SM2 ER	40	20	1000
A	SAG 2	SM2 MR	40	40	1000
A	SAG 2	ESSM	8	8	1000
A	SAG 3	SM6	10	6	1000
A	SAG 3	TLAM2	30	30	1000
A	SAG 3	SM2 ER	40	20	1000
A	SAG 3	SM2 MR	40	40	1000
A	SAG 3	ESSM	8	8	1000

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