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THESIS

**OPTIMIZING SELECTION
OF
TOMAHAWK CRUISE MISSILES**

by

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March, 1998

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REPORT DOCUMENTATION PAGE			Form Approved OMB No. 0704-0188	
Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instruction, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188) Washington DC 20503.				
1. AGENCY USE ONLY (Leave blank)		2. REPORT DATE March 1998		3. REPORT TYPE AND DATES COVERED Master's Thesis
4. TITLE AND SUBTITLE OPTIMIZING SELECTION OF TOMAHAWK CRUISE MISSILES				5. FUNDING NUMBERS
6. AUTHOR(S) Kuykendall, Scott D.				
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) Naval Postgraduate School Monterey, CA 93943-5000				8. PERFORMING ORGANIZATION REPORT NUMBER
9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)				10. SPONSORING / MONITORING AGENCY REPORT NUMBER
11. SUPPLEMENTARY NOTES The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.				
12a. DISTRIBUTION / AVAILABILITY STATEMENT Approved for public release; distribution is unlimited.				12b. DISTRIBUTION CODE
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14. SUBJECT TERMS Tomahawk Land Attack Cruise Missiles (TLAM), Vertical Launch System (VLS), Missile Selection, Missile-to-Mission Matching (M3)				15. NUMBER OF PAGES 59
				16. PRICE CODE
17. SECURITY CLASSIFICATION OF REPORT Unclassified		18. SECURITY CLASSIFICATION OF THIS PAGE Unclassified		19. SECURITY CLASSIFICATION OF ABSTRACT Unclassified
				20. LIMITATION OF ABSTRACT UL

NSN 7540-01-280-5500

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. Z39-18

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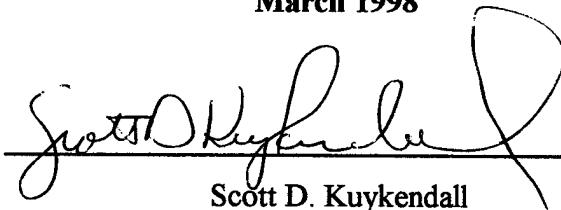
Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

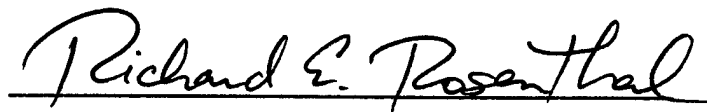
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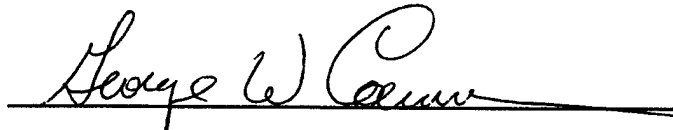
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March 1998**

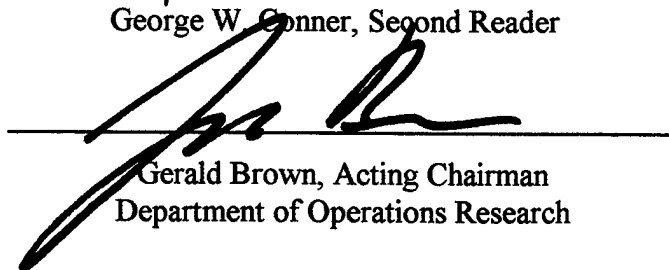
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ABSTRACT

The Tomahawk Land Attack Cruise Missile (TLAM), launched from surface ships and submarines, has become the weapon of choice for the United States in many situations. In an era of high-precision, fast-delivery weapons, the method currently used for assigning TLAM engagements is out of step with the development of the weapons themselves. Missile assignment today is manual, with the potential consequences of inefficient missile-to-mission matching and unnecessary delay.

This thesis develops a new optimizing approach to missile-to-mission matching, using integer programming. In a matter of seconds for a single ship or a matter of minutes for a battle group, the optimization model determines which missile to select for each tasking order and provides back-up assignments if requested. The objective of the model is to ensure the correct weapon is applied against each target while maximizing the potential of the firing unit(s) to perform future taskings.

The new missile-to-mission matching model is better than current methods and performs robustly in extensive sensitivity analyses. The optimization model is currently being considered for shipboard implementation by the Naval Surface Warfare Center. At the very least, the model can be used to independently assess the performance of any new missile-to-mission matching decision support considered by the Navy.

DISCLAIMER

The data incorporated in this thesis is unclassified; classified data may be required for the best results.

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LIST OF SYMBOLS, ACRONYMS AND/OR ABBREVIATIONS

ADCAP	Advanced Capability
ASROC	Anti-submarine Rocket
ATWCS	Advanced Tomahawk Weapons Control System
BIT	Built-In-Test
CONOPS	Concept of Operations
CG-47	Ticonderoga Class Guided Missile Cruiser
CII	Tomahawk with Conventional Warhead, Block II
CIII	Tomahawk with Conventional Warhead, Block III
DD-963	Spruance Class Destroyer
DDG-51	Arleigh Burke Class Guided Missile Destroyer
DII	Tomahawk with Sub-munition Warhead, Block II
DIII	Tomahawk with Sub-munition Warhead, Block III
ECO	Engagement Control Officer
EP	Engagement Planner
ER	Extended Range
FCTC	Fleet Combat Training Center
FPPWP	First Pre-planned Waypoint
GAMS	General Algebraic Modeling System
GPS	Global Positioning System
LC	Launch Controller
LCC	Launch Control Console
M3	Missile to Mission Matching

MR	Medium Range
NSWCDD	Naval Surface Warfare Center Dahlgren Division
RIM-7P	Vertical Launch Seasparrow
SC-21	Surface Combatant for the Twenty-first Century
SM	Standard Missile
SSN-688	Los Angeles Class Nuclear Attack Submarine
TERCOM	Terrain Contour Matching
TLAM	Tomahawk Land Attack Missile
TLAM-C	Tomahawk Land Attack Missile-Conventional Warhead
TLAM-D	Tomahawk Land Attack Missile-Submunition Variant
TSOM	Tomahawk Selection Optimization Model
TWCS	Tomahawk Weapons Control System
VGAS	Vertical Launch Gun Advanced System
VLA	Vertically Launched Anti-submarine Rocket
VLS	Vertical Launching System

ACKNOWLEDGEMENT

The author would like to thank Mr. Charles Fennemore of Naval Surface Warfare Center, Dahlgren Division for his support in this project. Also, I would like to thank Professor Rosenthal and Captain Conner for their dedication and support. Most of all, I would like to thank my wife Melissa, and my daughter Lindsay, who got to spend a lot of extra "quality" time together while I was locked in the den typing away.

EXECUTIVE SUMMARY

Precision strike, real-time targeting and fast response are all attributes used to describe necessities for the battlefield of the future. The Tomahawk Land Attack Missile (TLAM) is a proven precision strike weapon. Real-time targeting continues to be improved, and with Block IV and Block V TLAM under development, real-time targeting will soon be realized. Fast response will continue to be a problem for TLAM without new enhancements. This thesis explores changes sufficient to make TLAM a fast response weapon.

A TLAM engagement takes hours to complete. Once orders are received by a ship, several hours pass before a TLAM can be on target. Real-time targeting and the shipboard ability to write and modify plans would eliminate some of this unnecessary delay. However, the problem of selecting the correct missile for a given mission remains. The Tomahawk Weapon Control System (TWCS) provides an option for automatic missile selection that can decrease planning time. The problem with TWCS is that although the correct type of missile is assigned to a mission, the missile is often assigned from a sub-optimal location. Because TWCS does not select missiles optimally, current practice is to manually select missiles.

Optimal, efficient allocation of missiles to missions could reduce planning time, and provide the maximum remaining capability for the ship(s) to conduct future strikes. Because the Vertical Launching System (VLS) is limited to firing one missile per half-module (set of four launch cells), the selection of missile location within the launcher is very important. The Tomahawk Selection Optimization Model (TSOM) developed here

will select the correct type of missile for the assigned mission, and leave the firing platform(s) with maximum flexibility for the performance of future strikes.

The decision support model can be applied in two ways: single-platform and battlegroup. The single-platform application allows an individual shooter to optimally assign his missiles to missions in a tasking order, based only on his loadout. Task planning that could take upwards of fifteen minutes manually can be completed in less than one second with TSOM. On the battlegroup scale, application of TSOM can provide the entire battlegroup with a method for increasing residual firepower after firing and flexibility in fulfilling future tasking orders. The Strike Warfare Coordinator SWC can use TSOM after tasking has been received, or TSOM can be applied before writing the tasking orders. If applied prior to writing such orders, missile-to-mission assignments could include the actual location from which to fire that mission, and the time spent performing missile-to-matching by individual shooters could be saved.

The outputs of TSOM are the missile-to-mission, the remaining loadouts of each ship, and any mission not assigned due to lack of a required type of missile.

The new missile-to-mission matching model is better than current methods and performs robustly in extensive sensitivity analyses. The optimization model is currently being considered for shipboard implementation by the Naval Surface Warfare Center. At the very least, the model can be used to independently assess the performance of any new missile-to-mission matching decision support considered by the Navy.

I. INTRODUCTION

A. BACKGROUND

In 1972, a program was initiated to develop a subsonic anti-ship cruise missile launched from a torpedo tube. It was an all-Navy project until 1977, when it became a joint Navy and Air Force project with the Navy as the lead service. Soon after initial developments, a multitude of possible missile configurations and missions were explored, including land attack, air and ground launching, vertical launching system (VLS), nuclear and sub-munition warheads and armored-box launchers. The program led to the development of the Navy's current premier weapon: the Tomahawk Land Attack Missile (TLAM).

Since Tomahawk's first wartime use in 1991 in the Persian Gulf War, the missile and most aspects of its associated weapon control systems have undergone continual improvement and modification. However, the automatic missile selection algorithm in the Tomahawk Weapon Control System (TWCS) often does not select missiles from the correct locations, as will be explained later in this chapter. As a result, the Engagement Control Officer (ECO) and Launch Controller (LC) are well-advised to ignore the automatic solution and select missiles manually, with the potential consequences of inefficient missile-to-mission matching (M3) and a critical loss of time.

This thesis suggests a replacement automatic selection algorithm based on integer programming. The algorithm in TWCS, which is to be replaced, is a myopic heuristic that selects the correct type of missile for each mission but fails to consider the consequences of its choices on future launches. The resultant, often poor, missile selection can cause mission degradation in ensuing salvos by creating an inability to

complete tasking due to lack of required missile types. As evidence of the fleet's dissatisfaction with the current system, consider the following quote from a sailor who is a Tomahawk specialist:

The program we received to help with missile selection is horrible. Any one of us can do a better job than it can...so...we will continue to do it the old [manual] way. Fire Controlman First Class (SW) Robert Pratt, U.S. Navy [Pratt, 1996]

B. THE TOMAHAWK CRUISE MISSILE

The large number of Tomahawk missile variants makes missile selection difficult, and as more variants are developed and introduced into the fleet, the problem of selecting the correct missile for a given mission will become more complicated. There are currently three basic types of TLAM warheads: nuclear, conventional and sub-munition. The conventional (TLAM-C) contains 1,000-pound bullpup warheads, and the sub-munition (TLAM-D) has several possible warhead configurations. Within each warhead type, missiles are further differentiated based upon engine type, guidance, and other discriminating factors. The selection of the correct missile type is paramount to mission success. Here, only four missile types will be considered: TLAM-C Block III (CIII), CII, DIII and DII. Additional missile types can be added.

The CIII variant of TLAM is the most capable missile in the current inventory. It is guided by a Global Positioning System (GPS), and has an improved accuracy and range over previous versions of the missile. Since most TLAM missions are planned for conventional warheads, the majority of a ship's loadout will be CII and CIII missiles.

C. THE VERTICAL LAUNCHING SYSTEM

Tomahawk missiles are launched from the Mk 41 Vertical Launching System (Figure 1). The VLS serves both as the magazine for storing the missiles and as the

launcher. It consists of eight modules, each with eight cells for carrying and launching missiles, with the exception of "module five". Module five has a strike-down crane in cells six, seven, and eight, which is used to assist in loading and unloading missiles. Each of the eight cell modules is divided into two *half-modules*. Due to launcher configuration and wiring constraints, only one missile at a time may be fired from each half-module. This creates a maximum salvo capability of 16 missiles per launcher, with a total possible loadout of 61 missiles. Because of the half-module launching constraint, choosing which missile to launch, and which cell to launch it from, needs careful consideration. The selection of a missile in a sub-optimal location for a current mission can result in an inability to complete later missions due to the unavailability of the required missile.

Missile locations on submarines are different from surface ships. Submarines have twelve vertical launch cells, all of which may fire simultaneously. In addition, submarines can launch TLAMs from the torpedo tubes. There are four such tubes, each of which can have one pre-loaded TLAM, with three more for future loading. Thus, a submarine can fire a single salvo of up to 16 missiles, with a total possible loadout of 28 missiles. Because of the different restrictions, the missile selection problem is more difficult for surface ships than for submarines.

D. MISSILE SELECTION

While fulfilling a mission, the highest priority is to try to maintain a single salvo capability of 16 CIII missiles from each launcher for future missions. If possible, the capability of 16 CIII and/or CII missiles should also be preserved.

For example, if an order calls for a CIII missile, it should be selected if possible from a half-module containing two or more CIII missiles. This ensures that a CIII will

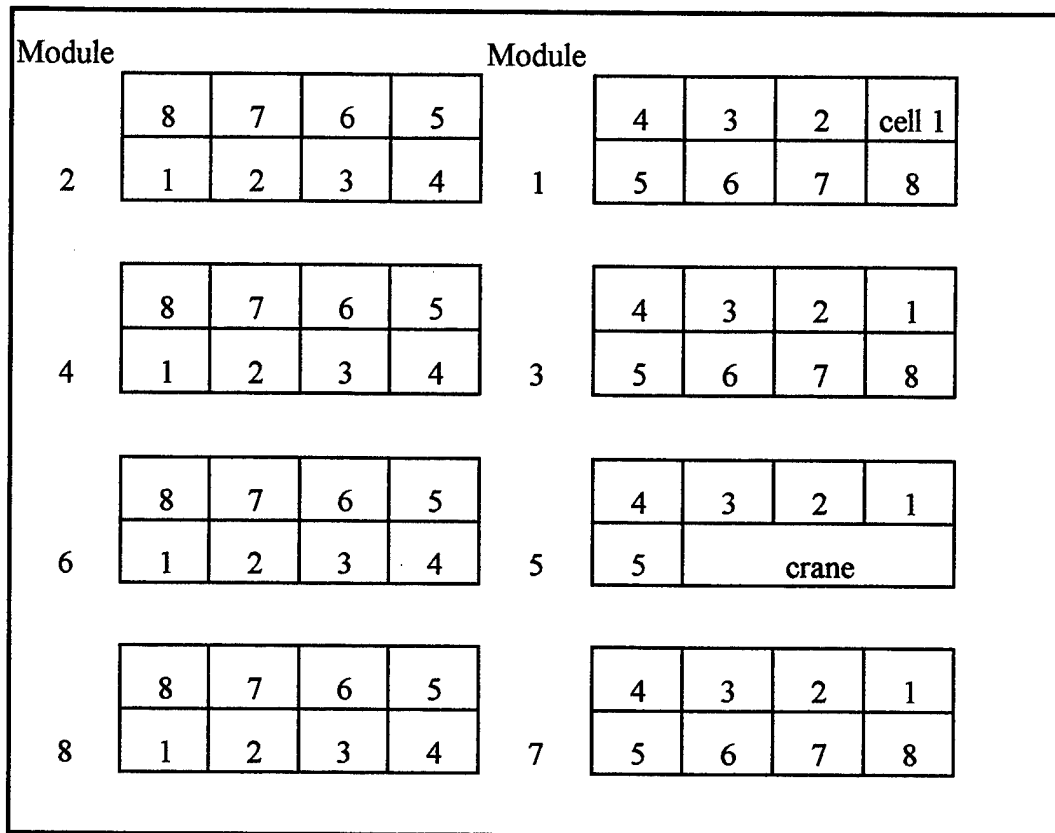


Figure 1. Mk 41 Vertical Launching System Containing 61 Cells. Each of the eight modules has two half-modules. Cells 1-4 are in the first half-module, and cells 5-8 are in the second, except for half-module 5, which contains a crane. A key constraint of the missile selection problem is that only one missile can be launched at a time from each half-module.

still be available from that half-module for any ensuing orders. If there are no half-modules with more than one CIII, then the missile is selected from a half-module with a total of two or more CIII and CII missiles.

The remaining mission capability of the Tomahawk shooter can be dramatically reduced by poor missile selection. This degrades the overall effectiveness of the current and ensuing strikes, and is especially important when a ship is operating independently.

1. An Illustrative Example with Two Half-modules

To illustrate the difference between optimal and sub-optimal selection, we consider an example with only two half-modules (Figure 2). With the given loadout, it is

	cell 1	2	3	4
Half-module 1	CIII	CII	CII	DIII
Half-module 2	CIII	CIII	CII	DIII
	8	7	6	5

Figure 2. Loadout for Two Half-Module Example.

possible to fulfill any of the following tasking orders: $\{(CIII, CIII), (CIII, CII), (CII, CII), (CIII, DIII), (CII, DIII), (DIII, DIII)\}$. The problem lies in choosing the correct locations from which to fulfill the given missions. Suppose the assigned tasking order is $(CIII, CII)$. There are several possible combinations of cells that could fulfill that order. One possible solution is to assign cell 1 to the first mission and cell 6 to the second mission (Fig. 3). This is a solution that the myopic procedure in TWCS would produce.¹ Beginning at half-module 1, cells would be searched until a missile is found that can fulfill the required mission. Using this procedure, the first CIII (the missile required by mission 1) discovered is in half-module 1, cell1, and it is assigned to mission 1. Then, since half-module 1 is no longer available, the search would begin at half-module 2 for a CII missile to fulfill mission 2, and cell 6 would be assigned.

After the missiles in cells 1 and 6 are fired, the tasking orders that can still be fulfilled are: $[(CIII, CII), (CII, DIII), (DIII, DIII), (CIII, DIII)]$, and the maximum future CIII salvo is one. By this missile selection, the set of possible future orders that can still

¹ The author does not have access to TWCS code or documentation. The characterization of the algorithm as myopic is based on many observations, and was confirmed in discussions with Charles Fennemore, Head, Estimation and Control Team, and others at Naval Surface Warfare Center, Dahlgren Division, on 03 March, 1998.

be fulfilled is only two-thirds as large as what was possible with the initial loadout, and the maximum remaining CIII salvo capability is halved.

Half-module 1	mission 1	CII	CII	DIII
Half-module 2	CIII	CIII	mission 2	DIII

Figure 3. Poor Solution to Two Half-module Example. Starting with the original loadout in Figure 2 and a tasking order consisting of one CIII and one CII missile, this assignment would be undesirable. Mission capability is degraded by one third and the maximum CIII salvo is one.

The solution shown in Figure 4 is much better. By assigning cell 8 to mission one and cell 2 to mission two, the ship maintains the capability to execute all the same tasking orders after launch as were possible before, and the preserved maximum CIII salvo is still two. This simple example illustrates that there is a lot to gain (in addition to valuable time) from optimization.

Half-module 1	CIII	mission 2	CII	DIII
Half-module 2	mission 1	CIII	CII	DIII

Figure 4. Better Solution to Two Half-module Example. Starting with the original loadout in Figure 2 and a tasking order consisting of one CIII and one CII missile, this assignment is better than that shown in Figure 3. The capability to perform six separate tasking order combinations remains and the maximum CIII salvo is two.

2. Mission Planning

In some cases, a ship will have approximately one hour to select missiles, write flight plans, and initialize the missiles. Flight plans are written by the Engagement Planner (EP), and consist of launch times, flight times, and over-water flight paths for the missiles to the First Pre-planned Waypoint (FPPWP). The FPPWP is the point at which

the missile reaches landfall. All land overflight paths are pre-programmed on a mission disk and are downloaded to the missile during the initialization process. Missile initialization consists of applying power to the missile, loading the operational flight software, loading mission data from the mission disk, conducting built-in-tests (BIT) for missile degradation, and conducting navigation alignment. The initialization can occur only after missile selection and takes from 25 minutes (for a single missile) to 40 minutes (for multiple missiles). TWCS assumes a worst-case scenario and begins initialization 40 minutes prior to the planned launch time. Any mistakes or failures of the BITs can result in mission abort.

The first step in manual missile selection is to place the Launch Control Console (LCC) in manual mode to prevent the automatic selection of missiles by TWCS. By carefully verifying mission requirements and missile capabilities, the LC and ECO match missile identification numbers to missions. This process is called Missile-to-Mission Matching (M3). Once matched, the ECO and LC select the missiles from the ship's loadout that will be fired.

The ship's primary concern while conducting TLAM launches is to meet the tasking as efficiently as possible. The ECO and LC must be careful to select the proper missiles, and leave the ship with as much residual firepower as possible.

Once all missiles are selected, the Tactical Action Officer and the Commanding Officer approve them. Once approved, the missile locations are manually fed into the LCC while the EP completes the flight plans. The entire M3 and data entry process can take upwards of twenty minutes.

E. THESIS GOAL

The goal of this thesis is to develop, implement and test an optimization model that performs M3 functions. The program must select the correct types of missiles from feasible launching locations, while maximizing the ship's remaining ability to perform future strikes. Two models are developed: one for a single ship and one for an entire battlegroup. Inputs for the program are the ship types and their loadouts, and the known tasking orders. The program outputs the missile-to-mission assignments, remaining ship's loadout, and a list of any missions that were unable to be completed due to launching or loadout limitations.

II. SHIP CONFIGURATIONS AND WEAPONS

The Vertical Launch System, introduced in 1985, is a versatile tool for the United States Navy. Incorporated into the design of three current classes of surface combatants and one attack submarine class, the Mk 41 VLS is the worldwide standard in shipborne missile launching systems. By eliminating time-consuming training and slewing requirements and firing restrictions faced by other missile launching systems, VLS increases firing rates considerably. The VLS minimizes required deck space for separate systems, allows mounting of missile launchers on all types of ships, and yields higher firepower and battle availability. The VLS simultaneously supports multiple warfighting capabilities, including anti-air warfare, anti-submarine warfare, ship self-defense, and strike warfare. In support of these roles, the VLS currently can be loaded with three different missiles: the TLAM, SM-2, and VLA. [Raytheon, 1997]

A. SHIP AND LAUNCHER LAYOUTS

1. Spruance Class Destroyer (DD-963)

Spruance Class Destroyers were designed as replacements for the aging Allen M. Sumner (DD-962) and Gearing (DD-710) class ships. The ships are designed with the intention of installing future weapon systems and sensors, such as VLS. There are thirty-one ships in the class, twenty-four of which have been backfitted with one VLS launcher each (Figure 5). From the VLS, Spruance Class ships can launch Tomahawks and Vertically Launched Anti-submarine Rockets (VLA). One launcher provides the capability to load up to 61 missiles and fire a single salvo of up to 16 TLAMs.

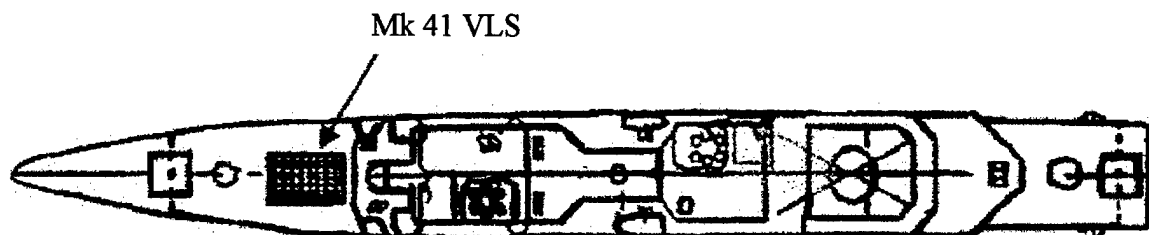


Figure 5. Location of VLS on Spruance Class Destroyer. The VLS is located forward of the superstructure, and is capable of being loaded with 61 TLAM and/or VLA.

2. Arleigh Burke Class Guided Missile Destroyer (DDG-51)

The Arleigh Burke Class Guided Missile Destroyers were authorized for construction in 1985, with the first ship of the class commissioned in 1991. The ships are constructed entirely of steel, with several stealth features incorporated into the design. The ships are smaller, faster and more stable than the Ticonderoga Class Cruisers.

The Arleigh Burke is equipped with 2 VLS launchers (Figure 6). The forward launcher is composed of 32 cells, 29 for carrying TLAMs, Standard Surface-to-Air Missiles (SM-2), or VLA. The aft launcher consists of 64 cells, 61 for carrying TLAMs, SM-2, or VLA. The ships are capable of firing a salvo of up to 24 TLAMs.

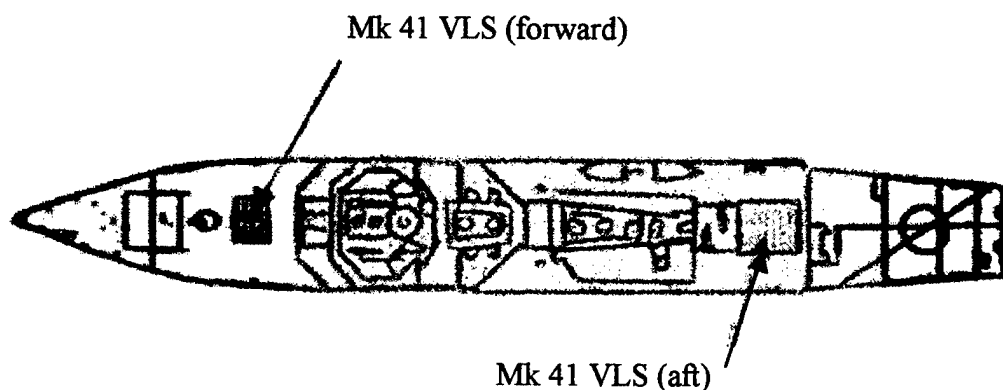


Figure 6. Location of VLS on Arleigh Burke Class Guided Missile Destroyer. The forward VLS is forward of the superstructure and contains 29 cells. The aft launcher is aft of the superstructure and contains 61 cells. A total of 90 TLAM, SM-2 and/or VLA may be loaded.

3. Ticonderoga Class Guided Missile Cruiser (CG-47)

Originally built as the DDG 47 Class, the Ticonderoga Class Aegis Cruisers are the most lethal air defense units in military service anywhere in the world [Ticonderoga, 1997]. The lead ship of the class entered service in 1983, and the final ship was commissioned in 1994. The first five ships of the class were built to the configuration of Aegis Baseline 1, with two Mk 26 missile launchers, and no VLS. The final 22 cruisers were built with two VLS launchers. One VLS is located forward of the superstructure and the second is aft of the helo deck (Figure 7). Both launchers contain 61 cells for loading any variant of Tomahawk, SM-2 (Medium Range), or VLA, providing the capability to launch a salvo of up to 32 missiles.

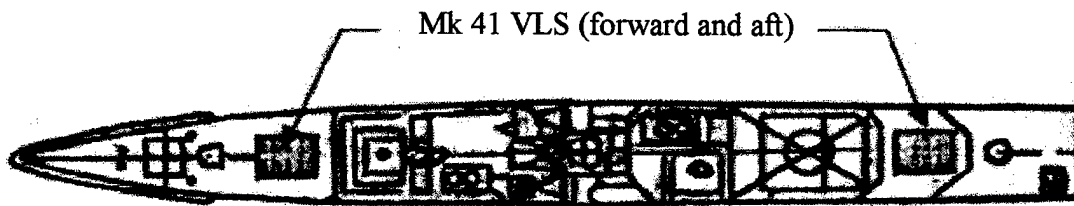


Figure 7. Location of VLS on Ticonderoga Class Cruiser. The forward and aft launchers contain 61 cells each, for a total of 122 cells capable of launching TLAM, SM-2, and VLA.

4. Future Surface Combatant

Both the Arleigh Burke and Ticonderoga class ships are scheduled for future replacement by the multi-mission Surface Combatant for the 21-st Century (SC-21). The SC-21 is scheduled to begin construction in 2004 and will be equipped with 128 VLS cells for launching TLAMs, SM-2, VLA, and additional future weapons under development. [Wright, 1997]

5. Los Angeles Class Attack Submarine (SSN-688)

Originally designed for carrier escort duties, the Los Angeles Class submarine combines the most desired qualities for an attack submarine: silence, speed, and powerful weaponry [Los Angeles Class Submarine, 1997]. The submarines can be armed with Mk 48 and Advanced Capability (ADCAP) torpedoes, the Harpoon anti-ship missile, and Tomahawk missiles. The first 31 submarines in the class can fire the Tomahawk using the standard 21 inch torpedo tubes, while the remaining members of the class can use the torpedo tubes and any of twelve vertical launch tubes located forward of the sail. Tomahawk missiles are launched while the sub is submerged, and rise to the surface. Once surfaced, the wings and fins extend and a solid propellant booster ignites, accelerating the missile until the turbofan engine starts.

B. MISSILE VARIANTS

1. Tomahawk Land Attack Cruise Missile (TLAM)

The Tomahawk Cruise Missile can be launched by ship, submarine, or aircraft. It has a cruise speed of about 550 miles per hour and a range of up to 1350 miles, depending on the variant. The missile is propelled from the launcher by a solid rocket booster, before eventually being driven by a small turbofan engine for the cruise portion of the flight. TLAM is guided by terrain contour matching (TERCOM) and GPS. TERCOM uses a stored reference map to compare with actual terrain. If necessary, a course correction is made by the missile to regain course to the target. With a small radar cross section and low altitude flight profile, TLAM is a highly survivable weapon against predicted hostile defense systems. [Navy Fact File, 1997]

2. Vertically Launched Anti-submarine Rocket (VLA)

The Anti-submarine Rocket (ASROC) has been used by the U.S. Navy since 1950, and became a standard loadout on all surface ship in the 1960's. Originally configured for launch from its own unique launcher, the ASROC's first operational launch from the VLS was in the early 1990's. With a range of 17,200 yards, the VLS extends the weapon's original range by almost 5,000 yards. From the VLS, ASROC can be launched much quicker and in greater numbers, an important advantage in defense against submarines.

3. Standard Missile

The SM-2 is the Navy's most widely used surface-to-air missile. Originally designed for launch from the Mk 26 and Mk 13 guided missile launchers, it was modernized for launching from the VLS. The first operational VLS launch of an SM-2 was in 1986. Both Ticonderoga Class Cruisers and Arleigh Burke Destroyers are capable of firing and guiding the SM-2. The Spruance Class Destroyer is not equipped to guide the SM-2, but it can be launched from a Spruance, and guided by a nearby Arleigh Burke or Ticonderoga class ship.

The Standard Missile has medium range (SM-2 MR) and extended range (SM-2 ER) versions. The SM-2 ER is only fired from Arleigh Burke Class ships with hull numbers DDG-72 and beyond.

The ship configuration and missile variant data described in this chapter are summarized in Tables 1 and 2.

Class	Ship Type	Commissioned	Max Loadout	Max Salvo	Missile Types
Spruance	Destroyer	1975	61	16	TLAM, VLA
Arleigh Burke	Guided Missile Destroyer	1991	90	24	TLAM, VLA, SM-2
Ticonderoga	Guided Missile Cruiser	1983	122	32	TLAM, VLA, SM-2

Table 1. Ships Containing Vertical Launching System.

Missile	Variants	Mission	Range (miles)	Operational from VLS
Tomahawk	CIII, CII, DIII, DII	Strike	700-1350	1985
VLA	N/A	Ant-submarine	8.6	Early 1990's
SM-2	MR, ER	Anti-air	90(MR), 100(ER)	1986

Table 2. Missile Variant Data

III. TOMAHAWK SELECTION OPTIMIZATION MODEL (TSOM)

A. DEVELOPMENT

This chapter presents the mathematical development of the integer programming model for optimizing Tomahawk missile selection. Values are assigned to each missile type, and the primary objective is to maximize the value of the missiles available for the next salvo after completing current tasking order requirements. The missile values are designed to first maximize the residual CIII salvo, then maximize the residual CII salvo, then DIII, and finally DII. Some elastic penalties are included in the objective function to give the Tomahawk shooter flexibility in cases when not all missions can be completed.

There are three types of missions possible in a tasking order: primary, ready-spare, and back-up. The *primary missions* are the main missile firings to be executed. *Ready-spare* and *back-up missions* are assignments of missiles to be available to fire in case of primary mission failure. They differ in the following way: a ready-spare mission, if requested, must be assigned to the same ship as the primary mission, whereas a back-up mission, if requested, must be assigned to a different ship.

B. INPUTS AND OUPUTS

The model inputs, in general terms, are as follows:

1. Configuration: identification of the ship or battlegroup needing missile-to-mission assignments and of the cells from which the missiles can be fired.
2. Loadouts: the type of missile loaded in each cell of each ship.
3. Tasking Orders: for each firing mission, specification of the missile type called for and whether a ready-spare or back-up is also required.

4. Command Judgment: relative values for missile types, and penalty parameters for missions that cannot be filled due to missile shortages or inefficient loadouts.

C. FORMULATION

Indices:

s	ships {e.g., DD-987, DDG-53, CG-54, SSN-720}
i	half-module, dependent on type of ship {e.g., h1-h16 for DD-987}
j	cell, each half-module contains four cells {c1-c4} or {c5-c8}

Note: the valid (s,i,j) tuples are called *missile locations*.

m	missile type loaded in cell, {e.g., CIII, DII, ASROC, etc...}
n	mission number, total missions known to require tasking {e.g., n1, n2, n3, ...} Each mission corresponds to a single requested missile firing.

Given Data:

$load_{sijm}$	equals 1 if initial loadout in location (s,i,j) is a missile of type m, 0 otherwise
$order_{nm}$	equals 1 if mission n calls for missile m, 0 otherwise
rs_n	equals 1 if mission n calls for a ready-spares, 0 otherwise
$bkup_n$	equals 1 if mission n calls for a back-up, 0 otherwise
val_m	relative value for missile m
$primepen$	elastic penalty for not completing a primary mission
$rspen$	elastic penalty for not completing a ready-spares mission
$bkpen$	elastic penalty for not completing a back-up mission

torppen elastic penalty for assigning a missile not currently loaded
 in torpedo tubes (refers only to submarine assignments)

notintube_{sij} equals 1 if location (s,i,j) is not in torpedo tubes, 0
 otherwise (refers only to submarines)

Derived Data:

ok_{sijn} equals 1 if missile in location (s,i,j) can be assigned as a
 primary, ready-spare or back-up for mission n;

$$ok_{sijn} = \sum_m load_{sijm} * order_{nm}$$

Variables:

Missile Firing and Assignment

X_{sijn} equals 1 if missile in location (s,i,j) is fired for primary mission n,
 0 otherwise

W_{sijn} equals 1 if missile in location (s,i,j) is assigned as ready-spare for
 mission n, 0 otherwise

Z_{sijn} equals 1 if missile in location (s,i,j) is assigned as back-up for
 mission n, 0 otherwise

Y_{sij} equals 1 if missile in location (s,i,j) is fired for a primary mission,
 0 otherwise

V_{sij} equals 1 if missile in location (s,i,j) is assigned for a ready-spare or
 back-up mission, 0 otherwise

Missile Counting

HMOD_{sim} residual number of missile m on ship s, in half-module i after firing

$SALVO_{sim}$ equals 1 if ship s , half-module i contains one or more missiles of type m after firing, 0 otherwise

Incomplete Missions

$UNABLE_n$ equals 1 if no missile is selected for primary mission n , 0 otherwise

$RSUNABLE_n$ equals 1 if no missile is assigned as ready-spare for mission n , 0 otherwise

$BKUNABLE_n$ equals 1 if no missile is assigned as back-up for mission n , 0 otherwise

Notes on Variable Definitions:

- 1) X_{sijn} , W_{sijn} , and Z_{sijn} are not defined if $ok_{sijn} = 0$.
- 2) Y_{sij} and V_{sij} are not defined if $\sum_m load_{sijm} = 0$.
- 3) $HMOD_{sim}$ is meant to be general integer, but can be treated as continuous since it must equal the sum of binary variables in Constraint (3).
- 4) $HMOD_{sim}$ and $SALVO_{sim}$ are not defined if $\sum_j load_{sijm} = 0$.
- 5) $UNABLE_n$, $RSUNABLE_n$, and $BKUNABLE_n$ are meant to be binary variables, but are treated as continuous since they must equal 1 minus the sum of binary variables in Constraints (6) – (8).

Formulation:

- 1a) $MAXIMIZE \quad \sum_s \sum_i \sum_m val_m * SALVO_{sim}$
- 1b) $- primepen * \sum_n UNABLE_n$
- 1c) $- rspen * \sum_n rs_n * RSUNABLE_n$
- 1d) $- bkpen * \sum_n bkup_n * BKUNABLE_n$
- 1e) $- torppen * \sum_{sij} notintube_{sij} * (Y_{sij} + V_{sij})$

$$1f) \quad + \sum_s \sum_i \text{HMOD}_{s,i,\text{CIII}}$$

Subject to:

- 2) $\sum_j (Y_{sij} + V_{sij}) \leq 1$ $\forall s,i$
- 3) $\sum_j \text{load}_{sijm} - \sum_j \text{load}_{sijm} * Y_{sij} = \text{HMOD}_{sim}$ $\forall s,i,m$
- 4) $\text{HMOD}_{sim} \geq \text{SALVO}_{sim}$ $\forall s,i,m$
- 5) $\sum_m \text{SALVO}_{sim} \leq 1$ $\forall s,i$
- 6) $\sum_s \sum_i \sum_j X_{sijn} + \text{UNABLE}_n = 1$ $\forall n$
- 7) $\sum_s \sum_i \sum_j W_{sijn} + \text{RSUNABLE}_n = 1$ $\forall n \text{ s.t. } rs_n=1$
- 8) $\sum_s \sum_i \sum_j Z_{sijn} + \text{BUNABLE}_n = 1$ $\forall n \text{ s.t. } bk_n=1$
- 9) $\sum_i \sum_j X_{sijn} \geq \sum_i \sum_j W_{sijn}$ $\forall s,n \text{ s.t. } rs_n=1$
- 10) $\sum_i \sum_j (X_{sijn} + Z_{sijn}) \leq 1$ $\forall s,n \text{ s.t. } bk_n=1$
- 11) $Y_{sij} = \sum_n X_{sijn}$ $\forall s,i,j$
- 12) $V_{sij} = \sum_n (rs_n * W_{sijn} + bk_n * Z_{sijn})$ $\forall s,i,j$

Objective function explanation:

- 1a) Maximize the value of future potential salvos,
- 1b-1d) minus elastic penalties for unfulfilled primary, ready-spare and back-up missions,
- 1e) minus a penalty for using a missile on a submarine that was not previously loaded into the torpedo tube,
- 1f) plus the sum of all CIII missiles remaining.

Constraint explanations:

- 2) Fire or assign at most one missile out of each half-module during a tasking.

This is a design limitation of the launching system.

- 3) The residual missile count after tasking equals the pre-launch loadout minus the missiles launched. (This assumes missiles assigned to primary missions are fired, but ready-spare and back-up missiles are not fired.)
- 4) The number of residual missiles in each half-module after tasking is greater than or equal to the number that can be fired from that half-module in the next tasking.
- 5) In conjunction with objective function term (1a) and Constraint (4), this constraint sets $SALVO_{sim} = 1$ for the single most valuable missile type remaining in half-module i of ship s after firing.
- 6) There can be at most one missile fired per primary mission, and if none are fired the elastic variable is set to one.
- 7-8) Similar to (6) for ready-spare and back-up missions.
- 9) If a ready-spare is requested for mission n , assign it to the same ship that fires the primary mission.
- 10) If a back-up is requested for mission n , assign it to a different ship than the one that fires the primary mission.
- 11) Establish logical relationship among firing variables for primary missions.
- 12) Establish logical relationship among assignment variables for ready-spare and back-up missions.

The single-ship version of this model is a simplification of the above in which index s is suppressed, variables Z_{sijn} and $BKUNABLE_n$ are deleted, and constraints (8) and (10) are omitted.

IV. IMPLEMENTATION AND TESTING

The integer programming model described in the previous chapter for optimizing missile-to-mission assignments was implemented and tested with GAMS [Brooke, Kendrick and Meeraus, 1996]. This chapter discusses the model's inputs and outputs, and then reports the results of base-case runs and sensitivity analyses with both the single-ship and multi-ship versions of the optimization model.

A. INPUTS

The prototypic model inputs are contained in separate data files, which can be modified to accommodate a variety of scenarios. Mandatory inputs include ship or battlegroup cell configuration, loadouts, tasking orders, and command guidance (missile values and penalty parameters). With the exception of the tasking orders, these data can be prepared ahead of time, so no time is lost when a tasking order is received.

1. Battlegroup Configuration

Any combination of one or more VLS-equipped ships and submarines can be modeled. Each ship class has been tested in single-ship program runs, and various battlegroup configurations have been tested in the multi-ship runs.

2. Loadouts

Loadouts vary for each type of ship. Due to operational considerations and ship capabilities, DD-963 class destroyers normally carry a significantly greater percentage of TLAMs than do CG-47 class cruisers and DDG-51 class destroyers. CG-47s and DDG-51s carry a high number of SM-2s for air defense, limiting the number of TLAMs. The loadouts used for the CG-47 class when testing the model are similar to the loadouts used by NSWCCD [Allewelt, Fennemore, Makarowski and Shea, 1997]. Loadouts for DDG-

51 and DD-963 classes are much like the CG-47 loadout, and are based upon operational experience. Because operational loadouts may vary greatly, even between ships of the same class, it is impossible to test the model with all possible loadouts, but those used are certainly typical.

3. Tasking Order

Because any specific geographic area can be modeled, there is no one representative sample tasking order for the model. Guidance in preparing tasking orders varies with operational circumstances and objectives. In the single-ship runs reported later in this chapter, each ship is tested with five different tasking orders. In the multi-ship runs, each battlegroup configuration is tested with four tasking orders.

4. Command Guidance

The amount of data in the command guidance section is so small that it can be entered at any time the user desires. It is shown in the sensitivity analysis section that the absolute values of the command inputs are not crucial, as long as the values are ordinally consistent with preferences.

B. OUTPUTS

The model outputs are missile-to-mission assignments, the remaining loadouts in each ship after firing, and a list of unfulfilled missions. These results are reported in output files that the user can print, read, and manipulate. Possible manipulations include sending the results to other software, such as a spreadsheet, or using the outcome of one run as the input for another. For example, the residual loadouts are printed in a format that can be used as input to the model.

As noted, it is possible that some mission(s) cannot be fulfilled due to missile shortages or inefficient placement of missiles in cells relative to tasking orders. In a single-ship application, it is important to notify the proper authorities of the unfulfilled missions, so they can adjust tasking appropriately. In the case of a battlegroup planning application, the unfulfilled mission list helps the planner determine what kinds of taskings are feasible.

C. RESULTS OF SINGLE-SHIP RUNS

All classes of ships were tested in the single-ship runs of the program. Figure 8 shows the original loadout used for the base-case single ship run with the DD-963. The computing time of the program was less than 0.5 seconds using a Pentium II 200 MHz personal computer with 64 MB of RAM. There were 273 constraints and 699 variables, of which 636 were integer variables.

The tasking order for the base-case DD-963 single-ship run is shown in Table 3. The optimal assignments are shown in Figure 9. The optimal objective function value is 82 and, if ready-spares are assumed not to be expended, the maximum resulting preserved future CIII salvo is 16.

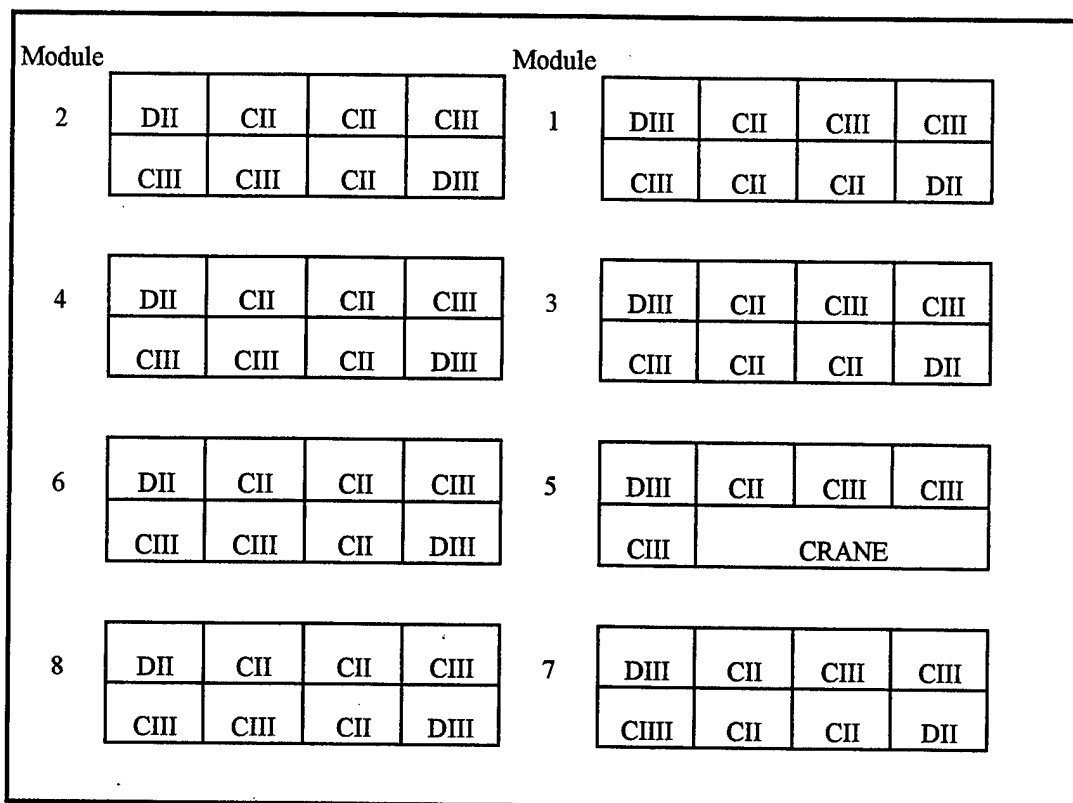


Figure 8. Loadout for DD-963 Single-ship Program Example. (See Figure 1 for legend.)

Order Number	Mission Type	Missile Type
1	Primary	CII
2	Primary	CII
3	Primary	DII
4	Primary	DII
5	Primary	DIII
6	Primary	DIII
7	Primary	CIII
8	Primary	CIII
9	Primary	CIII
10	Primary	CIII
11	Primary	CIII
12	Primary	CIII
RS1	Ready Spare	CII
RS2	Ready Spare	CII
RS11	Ready Spare	CIII
RS12	Ready Spare	CIII

Table 3. Tasking Order for DD-963 Single-ship Example. For example, mission number 1 is a primary mission and requires a CII missile. Ready-spares are required for mission numbers 1, 2, 11, and 12.

Module					Module				
2	DIII	CII	1	CIII	1	1	CII	CIII	CIII
	1	CIII	CII	DIII		CIII	2	CII	DII
4	1	CII	CII	CIII	3	DIII	CII	CIII	10
	1	CIII	CII	DIII		CIII	1	CII	DII
6	1	CII	CII	CIII	5	DIII	CII	CIII	1
	CIII	CIII	CII	1		1	CRANE		
8	DII	CII	2	CIII	7	DIII	CII	CIII	1
	1	CIII	CII	DIII		CIII	1	CII	DII

Figure 9. Optimal Assignments for DD-963 Single-ship Example. Shaded cells indicate the cells that are assigned to the corresponding missions from Table 3. Unshaded cells are the residual loadout after all required assignments have been made. In addition to the unshaded cells, the cells assigned to ready-spare missions are also residual loadout, given the primary mission is fired successfully. For example, mission 1 required a CII missile and is assigned to be fired from module 2, cell 6, and ready-spare mission 1 is assigned to module 7, cell 6.

D. SENSITIVITY ANALYSIS FOR SINGLE-SHIP VERSION

The numbers and types of missions have been varied to check the sensitivity of the single-ship version of the model to tasking order variations (Table 4). As the number of missions tasked increases, the generation and solution times of the model increase slightly but total computing times are always under two seconds. Each ship class has been given maximum tasking for its capabilities.

Single-ship Program Runs							
Case Number	Ship Class	Tasking Order				Generation Time (sec)	Solution Time (sec)
		CIII	CII	DIII	DII		
1	CG-47	32	0	0	0	0.77	0.93
2		24	8	0	0	0.74	0.61
3		20	8	4	0	0.84	0.67
4		14	10	4	4	0.76	0.5
5		8	8	8	8	0.58	0.44
6	DDG-51	24	0	0	0	0.56	0.42
7		18	6	0	0	0.39	0.34
8		15	6	3	0	0.37	0.34
9		10	8	3	3	0.33	0.36
10		6	6	6	6	0.31	0.33
11	DD-963	16	0	0	0	0.29	0.3
12		12	4	0	0	0.29	0.3
13		10	4	2	0	0.3	0.32
14		7	5	2	2	0.27	0.3
15		4	4	4	4	0.23	0.31
16	SSN-688	16	0	0	0	0.19	0.2
17		12	4	0	0	0.18	0.2
18		10	4	2	0	0.19	0.21
19		7	5	2	2	0.18	0.22
20		4	4	4	4	0.17	0.24

Table 4. Solution Times for Single-ship Version with Varying Tasking Orders on Pentium II 200 MHz Personal Computer.

The model has also been checked for sensitivity to the missile values. The relative order of the values must be maintained, since this is the basis of the objective function, but the actual values used are arbitrary. Table 5 shows the values used in the single-ship DD-963 model runs and the associated solution times. In all cases the model obtains the same optimal solution. This indicates empirically that the absolute missile values are incidental. It only matters that they are ordinally consistent with preferences.

Missile Values				Solution time (sec)
CIII	CII	DIII	DII	
4	3	2	1	0.5
40	30	20	10	0.56
140	130	120	110	0.59
14	13	12	11	0.54
1000	100	10	1	0.55
9999	999	99	9	0.55

Table 5. Solution times for Single-ship DD-963 with Varying Missile Values

E. MULTI-SHIP RUNS

Various battlegroup configurations have been tested in the multi-ship runs of the model. Table 6 shows the battlegroup compositions, tasking orders, and computing times associated with these various runs. The times shown in Table 6 represent the optimal solution in all cases. For larger problems, allowing some small tolerances in optimality (using the GAMS *optcr* parameter) can reduce the amount of solution time required. Table 7 gives a comparison of computing time and solution quality as a function of optimality tolerance for the first case listed in Table 6. This case is the largest problem considered to date and takes the longest time to solve. The experiment of relaxing the optimality tolerance cuts the solution time by a third with a negligible decrement to the objective function. Of course, such outcomes are not guaranteed.

Multi-ship Program Runs							
Battlegroup Composition	Tasking Order (Primary\Ready Spare\Backup)				Generation Time (sec)	Solution Time (sec)	Variables
	CIII	CII	DIII	DII			
2 CG, 2 DD, 2 DDG, 2 SS	75\15\15	20\10\5	10\5\3	10\2\5	5.64	1855.46	31151
	50\10\10	10\5\5	5\2\2	5\2\2	3.39	241.53	20533
	40\15\10	15\5\5	5\2\2	5\3\3	3.42	711.62	20342
	25\10\10	10\3\3	5\1\1	5\1\1	2.36	141.09	14426
1 CG, 1 DD, 1 DDG, 1 SS	37\8\8	10\5\2	5\3\1	5\1\2	3.28	105.91	8623
	25\5\5	5\3\2	3\1\1	2\1\1	2.48	18.47	5951
	20\7\5	8\3\2	3\1\1	2\2\1	2.5	21.92	5873
	13\5\5	10\5\5	5\3\2	5\2\3	2.55	28.98	5753
2 CG, 2 DD 2 DDG	50\10\10	15\4\4	8\2\1	4\3\2	3.14	222.79	19107
	40\5\5	10\3\2	6\1\1	3\2\2	2.19	65.95	13938
	30\3\2	5\2\1	4\1\1	2\1\1	3.53	17.56	10124
	20\5\5	5\1\1	2\1\1	2\1\1	1.37	17.75	8681
2 CG, 2DDG	50\10\10	10\5\5	5\2\2	5\2\2	4.82	250.25	13887
	40\8\8	8\3\3	4\2\2	4\2\2	4.16	87.5	11251
	30\6\6	6\2\2	3\1\1	3\1\1	3.49	50.03	8749
	20\5\5	5\1\1	2\1\1	2\1\1	2.82	3.91	6629
2 CG, 1 DD, 2 DDG, 1 SS	50\10\10	15\4\4	8\2\1	4\3\2	2.91	497.31	17691
	40\5\5	10\3\2	6\1\1	3\2\2	4.42	298.97	12927
	30\3\2	5\2\1	4\1\1	2\1\1	3.58	24.14	9423
	20\5\5	5\1\1	2\1\1	2\1\1	1.31	63.03	8084

Table 6. Solution Times for Multi-ship Battlegroup Runs with Varying Tasking Orders. Times shown are for optimal solutions

Requested Optimality Tolerance	Achieved Optimality Tolerance	Objective Function Value	Residual CIII Salvo	Solution Time (seconds)
0 (optimal)	0	638	105	1855.5
0.05	0.00784	633	105	1223.8
0.1	0.00784	633	105	1219.3
0.2	0.00784	633	105	1207.6

Table 7. Solution Times and Values for the Largest Multi-ship Problem with Varying Optimality Tolerance Settings. With an optimality tolerance setting of 0.1, solution time was cut by over ten minutes, and the residual CIII salvo remained the same.

F. IS IT WORTH OPTIMIZING?

After developing an optimization model, it is a good idea to assess its value by asking whether or not it yields sufficient improvement over current practice to justify its adoption. This question has been addressed by re-solving the 20 single-ship problems of Table 5 using three different approaches and comparing the results in terms of residual CIII salvo capacity. The competing approaches are:

1. Find the optimal solution using TSOM.
2. Find a feasible solution myopically, similar to the selection method in the current TWCS program.
3. Find the worst possible solution by minimizing rather than maximizing the optimization model.

The results of this experiment are shown in Table 8. On average, the optimal solution is 16% better than the myopic solution and 45% better than the worst case. Looking at these cases more closely, the benefits of optimization come into clearer focus and are in fact more dramatic than the averages.

In 7 of the 20 cases the optimal solution is no better than the myopic and worst-case solutions. This finding would be disappointing to a modeler except for the fact that these examples correspond to predictable situations. In cases 1, 6, 11 and 16, the tasking order calls for 100% CIII missiles. Optimization is pointless in these cases because all feasible solutions will necessarily consume the same number of CIIIs and leave the same residual salvo. Furthermore, in all but one of the submarine cases (16-20), optimization yields no improvement because of the limited number of possibilities in a submarine's launching configuration. Therefore, if we exclude all cases that call for 100% CIII

missiles or are restricted to submarines, then on average the optimal solution is 25% better than the myopic solution and 73% better than the worst case solution.

This comparison was performed only for the single-ship version of the model because TWCS does not attempt to solve the multi-ship problem.

Residual CIII Salvo Capability					
Case Nr	Optimal	Myopic	Worst	Opt/Myopic	Opt/Worst
1	16	16	16	1	1
2	24	20	16	1.2	1.5
3	28	22	16	1.27	1.75
4	32	25	18	1.28	1.78
5	32	28	24	1.14	1.33
6	11	11	11	1	1
7	17	13	11	1.31	1.55
8	20	16	9	1.25	2.22
9	24	15	14	1.6	1.71
10	24	20	18	1.2	1.33
11	8	8	8	1	1
12	12	10	4	1.2	3
13	13	11	8	1.18	1.63
14	15	12	9	1.25	1.67
15	15	14	12	1.07	1.25
16	1	1	1	1	1
17	1	1	1	1	1
18	1	1	1	1	1
19	1	1	1	1	1
20	6	5	5	1.2	1.2

Table 8. Comparison of Optimal, Myopic, and Worst-Case Solutions to Single-ship Tomahawk Assignment Problems. The optimal solution yields no improvement in cases 1, 6, 11, and 16, because their tasking orders call for 100% CIII missiles, and little or no improvement in cases 17-20 because of the limitations in submarine launching configuration. The average improvement in the other cases is 25% over the myopic solution and 73% over the worst case.

V. FUTURE TOMAHAWK DEVELOPMENTS

The strategic employment and National Command Authority-controlled role of the Tomahawk cruise missile has served the United States well, but the dynamics of the modern, joint battlefield of the future will demand increasingly responsive and flexible weapons.

There is an immediate operational requirement to expand the Tomahawk's capability to react to time-sensitive emerging and relocatable targets. CAPT Denis V. Army, USN [Army, 1997]

The model presented in this thesis is current with today's Navy. All ship types with VLS and all weapons that can be loaded into VLS are modeled and optimally selected. Any combination of battlegroup configuration, loadout, and tasking order can be used. However, as the Navy continues to modify existing systems and create new ones in response to newly defined objectives, additions and modifications to the Concept of Operations (CONOPS) for TLAM will have to be developed. The missile selection program of this thesis can support these developments. Four weapons programs are given as examples.

A. WEAPONS

1. Surface Combatant for the 21st Century

Through rapid response, volume fire and accurate targeting, the Navy's new surface ships were to include capabilities to conduct precision strike, interdiction and fire support missions to support ground and expeditionary forces in the littoral and engage enemy targets ashore. CAPT Richard L. Wright, USN [Wright, 1997]

In response to the above requirements, the navy has begun to develop the SC-21. In addition to many other warfare advancements, the SC-21 will be equipped with 128 vertical launch cells. The VLS will support launching of a supersonic land attack missile currently under development and the vertically launched gun system (VGAS), as well as

all previously discussed missile types. With more missions to perform than previously required of a surface ship, and a greater variety of loadout in the VLS, missile selection will become a more challenging key to the success of the SC-21.

2. Tomahawk Block IV

The Navy's premier strike weapon for the next generation is the Block IV Phase I Tomahawk. Block IV Tomahawk will be equipped with more memory and processing capability, increased accuracy and stability, two-way communications for receipt of mission modification messages and transmission of missile status reports, and GPS anti-jamming upgrades. Additional variants include an anti-armor round with a real-time targeting system for moving targets and a Block V missile that use modular design and construction technology to dramatically lower costs. [Townes, 1997]

3. Fasthawk

Based on a new set of Defense Planning Guidance, the Director of Defense Research and Engineering identified seven thrusts upon which to base its science and technology programs. One of these thrusts is precision strike against targets such as missile launchers, buried munitions factories, buried and hardened command and control sites, and munitions sheltered in tunnels.

The technology drivers required to counter these threats include: reduced time to target; warhead penetration against buried and hardened targets; low observable weapons systems; standoff range to increase platform survivability; and affordability. LT Steven C. Sparling, USN, Steve Lyda, and Tim Riffel [Sparling, Lyda, and Riffel, 1997]

Designed to travel at Mach 4, the Fasthawk missile meets the necessary requirements described above. Based upon the concept of the Tomahawk missile, Fasthawk is designed for launch from the VLS. It is 21.2 inches in diameter and 256 inches long. With the addition of another missile type into the inventory of the VLS,

missile selection becomes more complicated. Bearing in mind that the fasthawk will be targeted more quickly, speedy and accurate missile selection is paramount.

4. Vertical Launch Seasparrow

Another addition to the future VLS inventory is the Vertical Launch Seasparrow (RIM-7P). Currently deployed on surface ships for firing from its own trainable launcher, the RIM-7P will use the same missile design as the surface-to-air missile in use today. The missile has been fully integrated with the MK 41 VLS, and provides quick-reaction, 360-degree defense against anti-ship missiles, aircraft, and surface targets. Using vertical launch, the missile is able to be fired much more quickly by the elimination of training and slew requirements of the launcher. [Raytheon, 1997]

VI. CONCLUSIONS

A. THE NAVY NEEDS TO OPTIMIZE TOMAHAWK SELECTION

Current missile selection techniques are not standardized. There is no direct guidance regarding how to properly select missiles to meet mission requirements, except that current practice dictates that missiles are selected manually. Manual missile selection is often slow, tedious, and sub-optimal. The ship's (or battlegroup's) ability to meet future tasking can be degraded by improper selection.

B. THE TSOM OPTIMIZATION MODEL

The optimization model presented in this thesis is a very versatile tool. The model can be used on board ships for individual ship missile selection or it can be applied to an entire battlegroup. It can easily be modified to adapt to changing battle environments. New weapons and platforms can be introduced without affecting model speed or accuracy. If command guidance and the objective for missile selection change, the model can be adjusted accordingly by changing penalty and parameter values. Lastly, if the user has a large number of missions to task in a very limited amount of time, the optimality tolerance of the model can be loosened to allow for the possibility of a quicker solution.

C. POTENTIAL USERS OF THIS RESEARCH

The optimization program was developed in cooperation with the Naval Surface Warfare Center, Dahlgren Division (NSWCDD). They are currently working on a similar program that will be integrated into the Advanced Tomahawk Weapons Control System (ATWCS), and have shown great interest in this thesis [Allewelt, Fennemore, Makarowski, and Shea, 1997]. The model of this thesis is implemented in a stand-alone

General Algebraic Modeling System (GAMS) [Brooke, Kendrick, and Meeraus, 1996] program, but the model formulation and solution procedure are generic and can be adapted for use within ATWCS or any other program.

Fleet Combat Training Center (FCTC), Dam Neck, Virginia is also interested in the thesis. FCTC Dam Neck provides all of the training for Tomahawk personnel, both officer and enlisted.

D. RECOMMENDATIONS

With this model, the Navy has a tool to assign missiles to missions efficiently and quickly for a time-constrained TLAM launch. It is a robustly performing model that has proven effective regardless of tasking order content and battlegroup configuration and loadouts. Unless the tasking order consists of 100% CIII missions or is restricted only to submarines, optimization provides a much better solution to the missile-to-mission assignment problem. If the Navy continues to field heuristics rather than an optimization for missile selection, then at the very least, TSOM can be used to test heuristics under development.

By providing launch platforms with an additional ten to fifteen minutes formerly needed for manual missile selection, launch failures can be minimized. Extra time for refinement of launch plans and troubleshooting missile or launcher failures could allow more missions to be completed successfully. In addition, if a missile were to fail BIT tests, a replacement missile could be selected and powered-up in time to meet the original launch order.

As our Armed Forces move toward a faster paced, highly technical battlefield, it will become increasingly important to respond to orders to fire as quickly as possible. By

selecting missiles automatically and maximizing ensuing salvo capabilities, this model enables the United States Navy not only to respond quicker, but also to respond more often and with more force.

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