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ASSESSMENT OF A HEURISTIC ALGORITHM FOR SCHEDULING THEATER SECURITY COOPERATION NAVAL MISSIONS

by

Michael R. Rodman

March 2009

Thesis Advisor:	Javier Salmeron
Thesis Co-Advisor:	W. Matthew Carlyle
Second Reader:	Jeff E. Kline

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13. ABSTRACT (maximum 200 words)

Theater Security Cooperation (TSC) is a U.S. strategy for improving multi-national relationships through cooperative efforts. Spitz develops the Central-West Africa Resource and Mission Allocation (CARMA) optimization model, which posits a naval vessel carrying various expeditionary partnership teams to transit an area of responsibility and conduct missions garnering the maximum amount of TSC value. CARMA can be solved with formal, mixed-integer optimization, at the expense of computational time. This thesis modifies the original Spitz's scenarios to test H-CARMA, a fast heuristic algorithm developed by Dwyer, and its performance under shorter planning horizons, multiple budget constraints and different distribution of missions and TSC value across countries. Most of the scenarios evidence shortcomings of H-CARMA that were not apparent in the earlier scenarios tested by Dwyer. In all but one of the reviewed cases, H-CARMA generates solutions with total TSC value less than 81% of those using Spitz's algorithms, and, in the worst of these cases, the solution only achieves 51 percent. When there is no slack in terms of time and budget, MIP solutions outperform those of H-CARMA by more than 25% in most cases examined. We identify sources for some of these deficiencies and recommend changes to address them.

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ASSESSMENT OF A HEURISTIC ALGORITHM FOR SCHEDULING THEATER SECURITY COOPERATION NAVAL MISSIONS

Michael R. Rodman
Lieutenant Commander, United States Navy
B.A., Boston College, 1995

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March 2009

Author: Michael R. Rodman

Approved by: Javier Salmeron
Thesis Advisor

W. Matthew Carlyle
Co-Advisor

Jeff E. Kline
Second Reader

Robert F. Dell
Chairman, Department of Operations Research

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Theater Security Cooperation (TSC) is a U.S. strategy for improving multi-national relationships through cooperative efforts. Spitz develops the Central-West Africa Resource and Mission Allocation (CARMA) optimization model, which posits a naval vessel carrying various expeditionary partnership teams to transit an area of responsibility and conduct missions garnering the maximum amount of TSC value. CARMA can be solved with formal, mixed-integer optimization, at the expense of computational time. This thesis modifies the original Spitz's scenarios to test H-CARMA, a fast heuristic algorithm developed by Dwyer, and its performance under shorter planning horizons, multiple budget constraints and different distribution of missions and TSC value across countries. Most of the scenarios evidence shortcomings of H-CARMA that were not apparent in the earlier scenarios tested by Dwyer. In all but one of the reviewed cases, H-CARMA generates solutions with total TSC value less than 81% of those using Spitz's algorithms, and, in the worst of these cases, the solution only achieves 51 percent. When there is no slack in terms of time and budget, MIP solutions outperform those of H-CARMA by more than 25% in most cases examined. We identify sources for some of these deficiencies and recommend changes to address them.

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LIST OF ACRONYMS

CARMA	Central-West Africa Resource and Mission Allocation
CMC	Commandant of the Marine Corps
CNO	Chief of Naval Operations
EPT	Expeditionary Partnership Team
GAMS	General Algebraic Modeling System
GFS	Global Fleet Station
GoG	Gulf of Guinea.
H-CARMA	Central-West Africa Resource and Mission Allocation Heuristic (algorithm)
HSV	High Speed Vessel
LSD	Landing Ship Dock
MIP	Mixed Integer Program
MIP-CARMA	Central-West Africa Resource and Mission Allocation Mixed Integer Programming (algorithm)
RH-CARMA	Central-West Africa Resource and Mission Allocation Rolling Horizon (algorithm)
SSTR	Stability, Security, Transition and Reconstruction
STP	Sao Tome and Principe
TSC	Theater Security Cooperation
VBA	Visual Basic for Applications

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EXECUTIVE SUMMARY

Theater Security Cooperation (TSC) is a United States strategy for improving multi-national relationships through cooperative efforts. These efforts include military training, medical assistance, and infrastructure building to aid foreign countries in developing sustainable indigenous processes. The wide spectrum of missions, countries involved, budget and logistical constraints, and the length of the planning horizon make it challenging for planners to determine an optimal use of resources in support of this endeavor.

Recent studies by Spitz and Dwyer have developed mathematical optimization approaches to solving this resource allocation problem for scenarios pertaining to the Gulf of Guinea region of Africa using a Landing Ship Dock and a High Speed Vessel as the transiting platforms. Spitz develops the Central-West Africa Resource and Mission Allocation (CARMA), which models a naval vessel carrying various expeditionary partnership teams to transit the area while garnering the maximum amount of TSC value while minimizing cost. CARMA can be solved as a mixed-integer program (MIP) or by a rolling-horizon (RH) heuristic algorithm. Both MIP- and RH-CARMA are computationally challenging and require commercial optimization software not readily available to most Navy end-users. Dwyer develops a license-free, heuristic (H-CARMA) algorithm. In his analysis, H-CARMA solutions lie within 7% of optimal, taking only a fraction of the time spent by MIP- and RH-CARMA, for 90- and 180-day scenarios.

This thesis modifies existing scenarios to test H-CARMA's performance for shorter time horizons, under differing budget constraints and distributions of missions and TSC values across countries. Most of the scenarios evidence shortcomings of H-CARMA that were not apparent in the earlier scenarios tested by Dwyer.

In all but one of the reviewed cases, H-CARMA generates solutions with total TSC value less than 81% of those using Spitz's algorithms, and, in the worst of these |

cases, the solution only achieves 51 percent. When there is no slack in terms of time and budget, MIP- and RH- CARMA give significantly better solutions than H-CARMA, by more than 25% in most cases examined.

Dwyer acknowledges the requirement for a ship to remain in port during ongoing missions as a shortcoming of H-CARMA, which limits feasible solutions more significantly than MIP-CARMA and RH-CARMA. It is not evident that this assumption is the only cause for the solution gaps previously mentioned: Our test cases show H-CARMA's solutions may still be of relative low quality compared to those generated by MIP-CARMA even when all missions are required to be in-port. Thus, other aspects of H-CARMA's routing and scheduling logic may be preventing it from achieving better results. For example, competition among high-TSC-value countries creates a problem for H-CARMA in short time periods. When multiple countries have similar total TSC values within only a few points of each other, H-CARMA chooses the one with the highest value regardless of distances or costs.

We recommend revising H-CARMA to account for deficiencies discovered in this thesis. These include removing the requirement for the ship to remain in-port while EPTs conduct missions, not only because it hinders opportunities to perform missions in other countries but also because it makes the ship incur additional in-port costs. H-CARMA must also adjust for its tendency to implement a "packing routine" based first on maximum TSC available and second on the length of the longest mission. This prevents the algorithm from finding alternatives that support the overall TSC value goal. Changes in how the algorithm prioritizes missions having the same length need further review as well. Finally, H-CARMA should seek to minimize cost as a secondary goal, just as the CARMA model states.

I. INTRODUCTION

A. OVERVIEW

Theater Security Cooperation (TSC) is a United States strategy for improving multi-national relationships through cooperative efforts. These efforts include military training, medical assistance, and infrastructure building to aid foreign countries in developing sustainable indigenous processes. According to the Chief of Naval Operations (CNO), the Commandant of the Marine Corps (CMC) and the Commandant of the Coast Guard, "building and reinvigorating … relationships through Theater Security Cooperation requires an increased focus on capacity-building, humanitarian assistance, regional frameworks for improving maritime governance, and cooperation in enforcing the rule of law in the maritime domain" (CNO et al. 2007).

Recently, greater emphasis has been placed on the importance of the Navy's Global Maritime Partnership initiative, more commonly referred to as the "1000 Ship Navy." Expanding the use of national and multi-national forces shapes cooperative relationships in times of peace. This creates a foundation that enables collaborative efforts in the event of international security threats and disasters requiring humanitarian assistance. Deciding how to employ limited resources to support these missions remains a challenge. Directives explain the level and types of cooperation needed to support Stability, Security, Transition and Reconstruction (SSTR) operations by teams of civilian, military and international personnel (Department of Defense 2005).

This thesis explores previous algorithms developed to allocate limited resources to support TSC operations. By examining the strengths and limitations of each algorithm when applied to a specific scenario (world region, planning horizon, number and type of missions, etc.) we continue the development of a decision support tool for personnel involved in planning TSC activities.

B. BACKGROUND

In recent years, the U.S. Navy has conducted several exercises in the Gulf of Guinea (GoG) region of Africa (Figure 1) to employ the concept of TSC. Teams of assistance personnel, called *expeditionary partnership teams* (EPTs) have been used to conduct SSTR *missions* throughout the region with the help of U.S. Navy ships. The Whidbey Island class Landing Ship Dock (LSD), USS Fort McHenry (LSD-43), transited the area with various EPTs to perform TSC missions in 2007. U.S. Naval Forces Southern Command conducted a similar exercise in the Caribbean with the smaller High Speed Vessel (HSV), Swift (HSV-2). These vessels served as the primary sea-based platforms in support of the Global Fleet Station (GFS) concept described in the CNO's and CMC's Naval Operation Concept 2006 (CNO and CMC, 2006).

Figure 1. Area Map of Gulf of Guinea Region of Africa (From: MSN Encarta website).

During the aforementioned 2007 exercises, prioritizing and scheduling, which missions to perform presented a tremendous hurdle to planning personnel. Thesis work conducted at the Naval Postgraduate School (Spitz 2007, Dwyer 2008) has developed models and algorithms for finding the best schedule for a GFS embarked with EPTs. These works further explain the importance that TSC plays in the defense, maritime, and military strategies of various U.S. government organizations.

Spitz (2007) develops a mixed-integer programming (MIP) model, called Central Africa Resource Mission Allocation (CARMA) and uses a formal MIP algorithm (MIP-CARMA) and a rolling-horizon heuristic (RH-CARMA) for solving it. The data set tested for that study focuses on operations during the above mentioned GoG exercises. Prior to the development of the CARMA model few scheduling tools existed to aid planners in finding an optimal schedule for a GFS. Factors contributing to this difficulty are the wide spectrum of mission requirements and TSC values, the length of the planning period, team loading capabilities, budget constraints, logistic requirements, and transit times, among others.

Implemented in the General Algebraic Modeling System (GAMS) (Brooke et al. 1996) and solved with GAMS/CPLEX (2007), MIP-CARMA provides optimal or near-optimal solutions to maximize mission accomplishment while minimizing costs. However, MIP-CARMA can take an extremely long time to produce solutions. RH-CARMA, also implemented in GAMS, produces a heuristic solution that is only guaranteed to be optimal over shorter time periods in the planning horizon. Both GAMS and GAMS/CPLEX are commercial software packages that require individual licenses not readily available to the average Navy operator restricted by the Navy/Marine Corps Intranet system.

The more recent study by Dwyer (2008) shows the possibility of developing a stand-alone heuristic algorithm for CARMA (H-CARMA). Dwyer implements H-CARMA in Visual Basic for Applications (VBA) and uses it to demonstrate the potential to approximate the optimal solution for certain GoG scenarios. The MIP and RH approaches by Spitz require long processing times, while H-CARMA makes certain

assumptions to simplify the algorithm implementation, and employs a greedy, constructive heuristic. H-CARMA significantly reduces the computational time from MIP- and RH-CARMA, but also renders suboptimal solutions.

C. THESIS OBJECTIVES

We explore how changes in the original input affect the performance of the CARMA algorithms to determine their strengths and limitations more precisely. Though suffering from excessive processing time and scalability, the results of MIP-CARMA and RH-CARMA serve as the benchmark for the comparative analysis with H-CARMA. The results, in turn, immediately suggest areas of improvement that could help develop even more robust heuristic algorithms that retain a certain degree of scalability.

For comparison of H-CARMA and RH-CARMA in the 180-day original scenario of Spitz, see Dwyer (2008). This thesis examines scenarios using the LSD base case but for shorter time periods of 30 and 60 days. Our results aim to highlight difficulties not clearly identified in the original scenarios. Studying shorter periods is important not only because some deployments in the GoG or other regions may have shorter durations than in the scenarios explored by Spitz, but also because deployment contingencies may require to re-plan part of the schedule while the ship is already in the area of responsibility. These time horizons are also comparable to those used by each stage in Spitz's RH-CARMA.

In the remainder of this thesis, we review the aforementioned algorithms in Chapter II; then, we compare the algorithms for modified scenarios in Chapter III; and finally, we present our conclusions in Chapter IV.

II. REVIEW OF PREVIOUS ALGORITHMS

This chapter reviews the assumptions made by both Spitz (2007) and Dwyer (2008) in developing their respective approaches to solving the CARMA model. To recall, the following acronyms are used in accordance with Dwyer's nomenclature: (a) MIP-CARMA refers to the mixed-integer programming version of CARMA developed by Spitz in GAMS/CPLEX and solves for the entire planning horizon; (b) RH-CARMA refers to the rolling-horizon heuristic developed by Spitz using GAMS/CPLEX, which also uses formal mixed-integer programming optimization but only solves for a window of time (shorter than the planning horizon) at each iteration, which is advanced after each successive solve; and (c) H-CARMA refers to the stand-alone, heuristic algorithm developed by Dwyer using VBA. Obviously, RH-CARMA and H-CARMA can only guarantee local optimality.

A. OVERVIEW

All algorithms incorporate the primary goal of maximizing the total TSC mission value subject to budget, time and other logistics constraints. Spitz's original research implements a set of missions assigned with a corresponding TSC value ranked on a scale of one to ten. Each of the seven GoG countries in this study, Senegal, Gabon, Ghana, Angola, Sao Tome and Principe (STP), Cameroon, and Liberia, is allotted a predetermined set of missions based on the original data provided by personnel at Naval Forces Europe-Sixth Fleet. Associated with each mission type is at least one specific EPT capable of completing it. Applicable costs are assigned to each mission. A ship incurs port fees that vary by country for each day the ship is in-port.

B. VARIATIONS AND SIMPLIFICATIONS IN H-CARMA

1. Assignment of Teams

The MIP- and RH-CARMA algorithms optimize team loading simultaneously with all other decision variables in the CARMA model. H-CARMA requires that teams

be preloaded to an arbitrary percentage of available berthing spaces. In Dwyer's work, this percentage is set at 70 percent. The algorithm prioritizes initial team loading based on potential TSC value of missions a team can perform.

2. In-Port vs. At-Sea Mission Assignments

The CARMA model accounts for whether or not missions require the ship to be in-port during the execution of a mission. This provides some flexibility for a ship to drop off teams in a given port and conduct at sea missions simultaneously or even go to other ports and drop off other teams while the former mission is being executed. The H-CARMA algorithm presumes that all missions require the ship to be in-port, thus restricting the feasible solution space.

3. Mission Routing Priorities

H-CARMA prioritizes routes exclusively on the capability of performing a mission. It does not directly account for port stops for the sole purpose of replenishing either food or fuel. Thus, it restricts the solution space by avoiding logistic stops at countries where missions do not exist or have already been conducted.

4. Secondary Goal of Minimizing Budget

While maximizing total TSC value is CARMA's main objective, it also has a secondary goal of minimizing costs. H-CARMA does not directly attempt to minimize cost, although by setting a budget limit the algorithm will specify a solution that adheres to that restriction.

5. Returning to Origin

CARMA may require the ship to return to its home port (or any other specified location) by the end of the planning horizon. H-CARMA ignores this restriction, thus relaxing the feasible space.

6. Fuel and Food Re-Supply

H-CARMA assumes that the ship is refueled and replenished to maximum levels at each port capable of providing such services. If a ship remains in a replenishment-capable port for several days, its fuel and food supplies are reset to the maximum level for each day in the port. MIP-CARMA and RH-CARMA allow for below-maximum fuel levels. While this does not have an impact on current solutions, future versions of CARMA (where fuel costs are accounted for) may benefit from flexible refuel options.

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III. TEST CASES, ANALYSIS AND RESULTS

A. TEST CASE DATA AND ASSUMPTIONS

1. Basic Data

The following tables highlight sets of data taken from the scenarios run by both Spitz (2007) and Dwyer (2008) for the LSD ship class. In addition to these, ship characteristics, fuel and food capacities and depletion rates, distances, and trip times between ports remain unchanged.

Team Type	Abbreviated Name	Total Available (# of teams)	Size of Each Team (people/team)
Ship Crew	ship	3	1
Coast Guard Detachment	uscg1	2	4
Explosive Ordnance Detachment	eod	3	12
Naval Construction Force	ncf	4	13
Maritime Civil Affairs Group	mcag	2	6
Expeditionary Training Command	etc	4	4
Maritime Expeditionary Security Force	mesf	4	24
Medical Support	exmed	2	5
Other Reserve Unit	otherRes	2	4
Maritime Domain Awareness	mda	2	4

Table 1. Team Types Available and Sizes (From: Spitz, 2007). For example, each "ncf" (naval construction force) team requires 13 people, and a maximum of four teams are available to conduct missions (but not all available teams of all types can be carried on the ship due to limited rack space)

Table 1 shows the various EPT types. The abbreviated name will be used for display purposes in the remainder of this thesis. For each EPT type we show the total available and the number of personnel associated with each team. Table 2 displays port costs and capabilities (Spitz 2007).

Table 3 provides the initial mission country pairs along with associated durations, costs, and TSC values. The baseline scenario assumes these data inputs from Tables 1–3.

Country	Resupply (x = Yes)	Refuel (x = Yes)	Cost
Senegal	x	x	$185,000
Cameroon			$145,000
Gabon	x	x	$190,000
Ghana	x	x	$72,000
STP			$45,000
Angola			$200,000
Liberia			$115,000
At-Sea			$0

Table 2. Port Capabilities and Costs (After: Spitz, 2007 and Dwyer, 2008). For instance, Ghana can refuel and resupply, and in-port costs are $72,000 per day.

CARMA GOG MISSIONS / ACTIVITIES	GHANA	GABON	STP	CAMEROON	ANGOLA	LIBERIA	ATSEA	SENEGAL	Duration (days)	Cost ($) / mission	Capable Team(s)	TSC value
MEDICAL												
MEDICAL OPS/READINESS	x		x						5	$5,000	exmed	3
HA/DR OF INFECTIOUS DISEASES	x								3	$7,500	exmed	4
INFRASTRUCTURE												
ENG RECONSTRUCTION SMEE, DIG WELLS	x	x	x	x		x			10	$65,000	ncf	5
RENOVATE MEDICAL CLINICS		x	x						3	$10,500	ncf	2
RENOVATE SCHOOLS / YOUTH CLINICS		x	x						3	$10,500	ncf	2
AIRPORT INFRASTRUCT IMPROVEMENTS	x								15	$97,500	ncf	6
ROAD IMPROVEMENTS	x	x	x	x					10	$6,500	ncf	4
UTILITY IMPROVEMENTS	x	x	x	x					10	$6,500	ncf	5
PORT INFRASTRUCT IMPROVEMENTS						x			20	$13,000	ncf	9
INFRASTRUCUTRE GAP ANALYSIS	x	x	x	x					5	$32,500	ncf	5
CIVIL / COMMUNICATIONS												
PUBLIC AFFAIRS SMEE	x	x	x	x	x	x			3	$9,000	mcag	5
BAND LESSONS	x	x	x	x					2	$4,000	othRes	1
COMREL					x	x			2	$1,000	ship	3
SURFACE MARITIME ACTIVITIES												
PORT SECURITY MTT	x					x			5	$45,000	uscg1, nwc, mesf	8
MULTINATIONAL EXERCISE							x		5	$2,500	ship	10
SHIPRIDER EMBARKS							x		5	$2,500	ship	7
SMALL BOAT / BOAT PATROL MAINT MTT	x		x						5	$7,500	ship, etc	6
ISPS ASSIST / CERT VISIT	x	x	x	x					10	$20,000	uscg1, othRes	8
HYDRO SURVEY MTT	x		x						10	$20,000	uscg1	8
MINE CLEARANCE					x				10	$60,000	eod	7
MILITARY & LEADERSHIP TRAINING												
COMMUNICATIONS MTT	x	x		x					5	$10,000	etc	4
OFFICER LEADERSHIP MTT	x			x					5	$7,500	ship, etc	7
NCO PROFESS DEVELOP SMEE/ MTT	x								3	$1,500	ship	6
MARITIME DOMAIN AWARENESS ACTIVITIES												
SHIP VISIT					x	x			5	$2,500	ship	5
MDA SITE SURVEY									5	$10,000	mda	7
AIS RECEIVER SITES CONSTRUCTED	x		x			x			10	$65,000	ncf	9
COOPERATIVE SECURITY LOCATION	x								5	$10,000	mda	10
GFS DEMO							x		3	$6,000	ship	7
GFS DEMO 2							x		2	$4,000	mda	7
LOGISTICS												
LOGISTICS STOP								x	1	$500	ship	1
BASELINE TOTAL TSC VALUE (total far right)	**104**	**41**	**63**	**44**	**20**	**44**	**31**	**1**	**348**	-	-	-

Table 3. Mission Characteristics

2. Timeframe and Modified Starting Point

Our test cases are limited to 30- and 60-day periods only as opposed to the 90- and 180-day scenarios used by Dwyer and Spitz. Originally, those scenarios commence from Rota, Spain on day one. In order to allow for more missions to be examined in our

reduced time horizons, our scenarios assume the ship is already in theater, commencing day one operations from the port of Dakar, Senegal. This eliminates several days of travel from and to Rota in which no mission can take place. (In practice, this equates to our scenarios covering approximately days 1-44 and 1-74, respectively, from the original scenario, where the first and last seven days are in transit.)

3. Return to Homeport Not Required

Given the lack of this capability in H-CARMA, our primary scenarios shall not require the ship to return to any port at the end of the planning horizon.

4. Criteria for Setting Budget Constraint

The original scenarios for the MIP-CARMA, RH-CARMA and H-CARMA studies establish a maximum budget limit of $10 million for a 180-day scenario. Reducing that budget proportionally for 30- and 60-day scenarios results in budgets of approximately $1.7 million and $3.3 million dollars, respectively. In order to study both cases where budget is and is not a limiting aspect, we set the budget to $10 million and $1.5 million for 30-day scenarios, and a unique budget of $3.0 million for 60-day scenarios.

5. Scenarios and Test Cases

We create four basic scenarios for testing:

Scenario 1: Baseline using previous test data

Scenario 2: Mission transfer from Ghana to Angola

Scenario 3: Large TSC value for Angola, reduced for Ghana

Scenario 4: Two groups of three countries with same TSC values

Within each of these scenarios, and based on our budget discussion from the previous paragraph, we create three different cases:

Case A: 30 days and $10 million budget

Case B: 30 days and $1.5 million budget

Case C: 60 days and $3 million budget

In addition, we consider four supplementary cases that restrict all missions to be in-port for Scenarios 1 and 2, Cases A and B. These serve as a basis for comparison between MIP-CARMA and H-CARMA by restricting MIP-CARMA in the same manner inherent to H-CARMA.

B. SELECTION OF RH-CARMA OR MIP-CARMA ALGORITHMS

MIP-CARMA has been used to solve the 30-day scenarios, producing optimal solutions with a relative optimality gap of 1 percent. For all 60-day cases, the MIP-CARMA algorithm fails to improve RH-CARMA solutions in a reasonable amount of time, so we choose the RH-CARMA algorithm.

To improve tractability, RH-CARMA uses the following rolling-horizon scheme: the algorithm first looks at days 1 - 40. It then expands the recommended solution to this period by incorporating the remaining 20 days. Each of these individual stages solves for a near-optimal solution with a relative gap of less than 1%, but overall the solution cannot be guaranteed to be optimal for the entire 60-day period. Of course, good solutions (but without the 1% tolerance) can be found by MIP-CARMA and RH-CARMA in substantially less time.

C. SCENARIO 1: BASELINE USING PREVIOUS TEST DATA

We review the overall results for the scenario, followed by specific analysis of each individual case.

1. Setup and Result Comparison

In the original scenario, Ghana leads all other locations in total TSC value available with 104 TSC points out of 348 for all missions. Table 4 shows the results of comparing MIP-CARMA or RH-CARMA to H-CARMA for the different number of days and budget limits analyzed.

Comparisons for Scenario 1 (Case 1A): Baseline, 30 Days, $10M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	151	100.00%	$1,937,500	24	8,957
H-CARMA	121	80.13%	$1,602,500	20	181
Comparisons for Scenario 1 (Case 1B): Baseline, 30 Days, $1.5M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	144	100.00%	$1,446,000	26	3,690
H-CARMA	108	75.00%	$1,492,000	18	187
Comparisons for Scenario 1 (Case 1C): Baseline, 60 Days, $3M					
Algorithm	TSC	% of RH-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
RH-CARMA	212	100.00%	$2,965,000	39	20,001
H-CARMA	171	80.66%	$3,000,000	30	162

Table 4. Results for Scenario 1 Comparisons

In each case, the H-CARMA solution is no better than 81% of the MIP- and RH-CARMA results. Total costs for Cases 1B and 1C, where the budgets are more severely constrained, are within $50,000. The cost difference for Case 1A is almost $300,000 though the difference in TSC value is considerable. As indicated earlier, we expect the greater run times for MIP-CARMA and RH-CARMA for within 1% gap solutions. While H-CARMA finds a feasible solution in a matter of seconds in this case group, MIP-CARMA and RH-CARMA require at least one hour of processing for the timeliest result and almost seven hours of processing time for the 60-day scenario.

2. Case 1A: 30 Days, $10 Million Budget

Tables 5 and 6 outline the routing schedules that MIP-CARMA and H-CARMA respectively produce. Table 5 reveals the flexibility of MIP-CARMA in allowing a ship to drop off teams to conduct missions in a given country and continue to another country

to perform additional missions. This is clearly evident on day 11 and 12 in Ghana where four teams arrive to commence missions lasting ten days each. The ship leaves port on day 13 to pick up teams in Liberia before returning back to Ghana to conduct more missions and retrieve the teams previously dropped off.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA					UNDERWAY		GHANA		UNDERWAY		LIBERIA		UNDERWAY		GHANA					UNDERWAY	AT-SEA					
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																			EXMED											
	HA/DR OF INFECTIOUS DISEASES																				EXMED										
	ENG RECONSTRUCT SMEE, DIG WELLS																														
	AIRPORT INFRASTRUCTURE IMPROVE																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS											NCF																			
	INFRASTRUCUTRE GAP ANALYSIS																			NCF											
	PUBLIC AFFAIRS SMEE																			MCAG											
	BAND LESSONS																			othRES											
	PORT SECURITY MTT																			USCG1											
	SMALL BOAT / PATROL MAINTEN MTT																			SHIP											
	ISPS ASSIST / CERT VISIT												USCG1																		
	HYDRO SURVEY MTT											USCG1																			
	COMMUNICATIONS MTT																														
	OFFICER LEADERSHIP MTT																			SHIP											
	NCO PROFESS DEVELOP SMEE/MTT																				SHIP										
	COOPERATIVE SECURITY LOCATION																			MDA											
	AIS RECEIVER SITES CONSTRUCTED												NCF																		
AT SEA	MULTINATIONAL EXERCISE																									SHIP					
	SHIPRIDER EMBARKS																										SHIP				
	GFS DEMO																												SHIP		
	GFS DEMO 2																													MDA	
LIBERIA	ENG RECONSTRUCT SMEE, DIG WELLS						NCF																								
	PORT INFRASTRUCTURE IMPROVE																														
	PUBLIC AFFAIRS SMEE						MCAG																								
	COMREL							SHIP																							
	PORT SECURITY MTT				USCG1																										
	SHIP VISIT				SHIP																										
	AIS RECEIVER SITES CONSTRUCTED							NCF																							

Table 5. MIP-CARMA Schedule, Case 1A: 30 Days, $10M

Table 6 displays the resulting schedule that H-CARMA produces for the same data set. In this case, the enumerative process of H-CARMA focuses on the country with the maximum combined TSC mission value: Ghana. H-CARMA completes sixteen of the eighteen available missions in this country. Both models perform all the missions in the At-Sea location predominantly because of the high TSC values and the relatively short duration of these missions.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						GHANA															UNDERWAY	AT-SEA						
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS								EXMED																						
	HA/DR OF INFECTIOUS DISEASES								EXMED																						
	ENG RECONSTRUCT SMEE, DIG WELLS								NCF																						
	AIRPORT INFRASTRUCTURE IMPROVE								NCF																						
	ROAD IMPROVEMENTS								NCF																						
	UTILITY IMPROVEMENTS								NCF																						
	INFRASTRUCUTRE GAP ANALYSIS																														
	PUBLIC AFFAIRS SMEE								MCAG																						
	BAND LESSONS								othRES																						
	PORT SECURITY MIT								USCG1																						
	SMALL BOAT / BOAT PATROL MAINTEN MIT								SHIP																						
	ISPS ASSIST / CERT VISIT								USCG1																						
	HYDRO SURVEY MIT								USCG1																						
	COMMUNICATIONS MIT								ETC																						
	OFFICER LEADERSHIP MIT								SHIP																						
	NCO PROFESS DEVELOP SMEE / MIT								SHIP																						
	COOPERATIVE SECURITY LOCATION								MDA																						
	AIS RECEIVER SITES CONSTRUCTED																														
AT SEA	MULTINATIONAL EXERCISE																								SHIP						
	SHIPRIDER EMBARKS																								SHIP						
	GFS DEMO																								SHIP						
	GFS DEMO 2																								MDA						

Table 6. H-CARMA Schedule, Case 1A: 30 Days, $10M

H-CARMA implements a “stacking” method that reviews the maximum TSC value within a chosen country based on the length of the longest mission it selects. It then chooses all missions of shorter duration that meet the budget and team distribution constraints. As a result, all missions for a selected country commence on the same day and the ship must remain in-port until the longest mission finishes. Table 6 demonstrates this tendency for Ghana and the At-Sea location. The algorithm defaults all missions to be in-port prohibiting the ship from dropping teams off and seeking other high value missions in a different area.

Overall, H-CARMA creates an 81% solution to that of MIP-CARMA in terms of total TSC value accumulated. Run time is drastically shorter and total missions completed only differ by four.

As explained in section A-4 of this chapter, we conduct a supplementary test of this case by forcing all missions in MIP-CARMA to be performed in-port just as H-CARMA requires. The resulting MIP-CARMA schedule generates a total TSC value of 146 compared with 151 in Case 1A. MIP-CARMA results still outperform H-CARMA in terms of TSC value: 146 to 121, respectively. Interestingly, with the greater restriction on the feasible solution, MIP-CARMA run time greatly improves, taking only 265 seconds to solve. This is a surprising result that seems to support the notion that the H-CARMA algorithm logic may be flawed beyond simply requiring all missions be conducted with the ship in-port: Better solutions still exist.

3. Case 1B: 30 Days, $1.5 Million Budget

This case places a $1.5 Million budget constraint on both algorithms. All other inputs are identical to Case 1A. Tables 7 and 8 reflect the schedule output produced by MIP-CARMA and H-CARMA respectively. Both solutions focus the largest concentration of missions in Ghana. The budget restriction forces MIP-CARMA to route the ship to STP instead of Liberia as in Case 1A.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA	UNDERWAY		GHANA		UNDERWAY	AT-SEA	UNDERWAY	GHANA						UNDERWAY	AT-SEA						UNDERWAY	STP				
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS								EXMED																						
	HA/DR OF INFECTIOUS DISEASES															EXMED															
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	AIRPORT INFRASTRUCTURE IMPROVEMENTS																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS								NCF																						
	INFRASTRUCUTRE GAP ANALYSIS												NCF																		
	PUBLIC AFFAIRS SMEE													MCAG																	
	BAND LESSONS												othRES																		
	PORT SECURITY MTT													USCG1																	
	SMALL BOAT / PATROL MAINTENANCE MTT													SHIP																	
	ISPS ASSIST / CERT VISIT								USCG1																						
	HYDRO SURVEY MTT							USCG1																							
	COMMUNICATIONS MTT												ETC																		
	OFFICER LEADERSHIP MTT								SHIP																						
	NCO PROFESSIONAL DEVELOP SMEE/MTT															SHIP															
	COOPERATIVE SECURITY LOCATION												MDA																		
	AIS RECEIVER SITES CONSTRUCTED							NCF																							
STP	MEDICAL OPS/READINESS																										EXMED				
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																												NCF		
	RENOVATE SCHOOLS / YOUTH CLINICS																											NCF			
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS																										NCF				
	PUBLIC AFFAIRS SMEE																												MCAG		
	BAND LESSONS																													othRES	
	SMALL BOAT / PATROL MAINTENANCE MTT																										SHIP				
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	AIS RECEIVER SITES CONSTRUCTED																														
AT SEA	MULTINATIONAL EXERCISE																				SHIP										
	SHIPRIDER EMBARKS																					SHIP									
	GFS DEMO																						SHIP								
	GFS DEMO 2																							MDA							

Table 7. MIP-CARMA Schedule, Case 1B: 30 Days, $1.5M

The H-CARMA solution generates results almost identical to Case 1A. The commencing day of operations for Ghana and the At-Sea location remains unchanged. The algorithm skips two missions in Ghana in order to remain feasible to the new budget. Both algorithms find solutions close to the budget limit.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						GHANA															UNDERWAY	AT-SEA						
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS								EXMED																						
	HA/DR OF INFECTIOUS DISEASES								EXMED																						
	ENG RECONSTRUCTION SMEE, DIG WELLS								NCF																						
	AIRPORT INFRASTRUCTURE IMPROVEMENTS								NCF																						
	ROAD IMPROVEMENTS								NCF																						
	UTILITY IMPROVEMENTS								NCF																						
	INFRASTRUCUTRE GAP ANALYSIS																														
	PUBLIC AFFAIRS SMEE																														
	BAND LESSONS								othRES																						
	PORT SECURITY MTT																														
	SMALL BOAT / PATROL MAINTENANCE MTT								SHIP																						
	ISPS ASSIST / CERT VISIT								USCG1																						
	HYDRO SURVEY MTT								USCG1																						
	COMMUNICATIONS MTT								ETC																						
	OFFICER LEADERSHIP MTT								SHIP																						
	NCO PROFESSIONAL DEVELOP SMEE/ MTT								SHIP																						
	COOPERATIVE SECURITY LOCATION								MDA																						
	AIS RECEIVER SITES CONSTRUCTED																														
AT SEA	MULTINATIONAL EXERCISE																								SHIP						
	SHIPRIDER EMBARKS																								SHIP						
	GFS DEMO																								SHIP						
	GFS DEMO 2																								MDA						

Table 8. H-CARMA Schedule, Case 1B: 30 Days, $1.5M

Once again, we conduct a supplementary case that restricts the ship to remain in-port for all missions in MIP-CARMA. While this limits the feasible region, the budget increase may provide some flexibility. Results show that MIP-CARMA outperforms H-CARMA in total TSC value, 140 to 108. It uses a total budget of $1.49 million. Again, run time is greatly reduced (443 seconds).

4. Case 1C: 60 Days, $3 Million Budget

The expanded duration and budget of the 60-day case should permit each algorithm to accommodate higher value missions in more countries. We execute RH-CARMA in this case to keep run times within a relatively reasonable duration.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA					UNDERWAY		GHANA (REFUEL)		UNDERWAY	AT-SEA					UNDERWAY	GHANA						UNDERWAY	
	UNDERWAY																											
GHANA	MEDICAL OPS/READINESS																					EXMED						
	HA/DR OF INFECTIOUS DISEASES																				EXMED							
	ENG RECONSTRUCT SMEE, DIG WELLS																											
	AIRPORT INFRASTRUCTURE IMPROVE																											
	ROAD IMPROVEMENTS																											
	UTILITY IMPROVEMENTS											NCF																
	INFRASTRUCUTRE GAP ANALYSIS																				NCF							
	PUBLIC AFFAIRS SMEE																				MCAG							
	BAND LESSONS											othRES																
	PORT SECURITY MTT																					USCG1						
	SMALL BOAT / PATROL MAINTEN MTT																					SHIP						
	ISPS ASSIST / CERT VISIT											USCG1																
	HYDRO SURVEY MTT												USCG1															
	COMMUNICATIONS MTT																					ETC						
	OFFICER LEADERSHIP MTT																				SHIP							
	NCO PROFESS DEVEL SMEE/ MTT																				SHIP							
	COOPERATIVE SECURITY LOCATION																					MDA						
	AIS RECEIVER SITES CONSTRUCTED												NCF															
AT SEA	MULTINATIONAL EXERCISE														SHIP													
	SHIPRIDER EMBARKS																											
	GFS DEMO																SHIP											
	GFS DEMO 2																MDA											
LIBERIA	ENG RECONSTRUCT SMEE, DIG WELLS																											
	PORT INFRASTRUCTURE IMPROVE																											
	PUBLIC AFFAIRS SMEE					MCAG																						
	COMREL					SHIP																						
	PORT SECURITY MTT																											
	SHIP VISIT				SHIP																							
	AIS RECEIVER SITES CONSTRUCTED				NCF																							

Table 9. RH-CARMA Schedule, Case 1C: 60 Days, $3M, Days 1-27

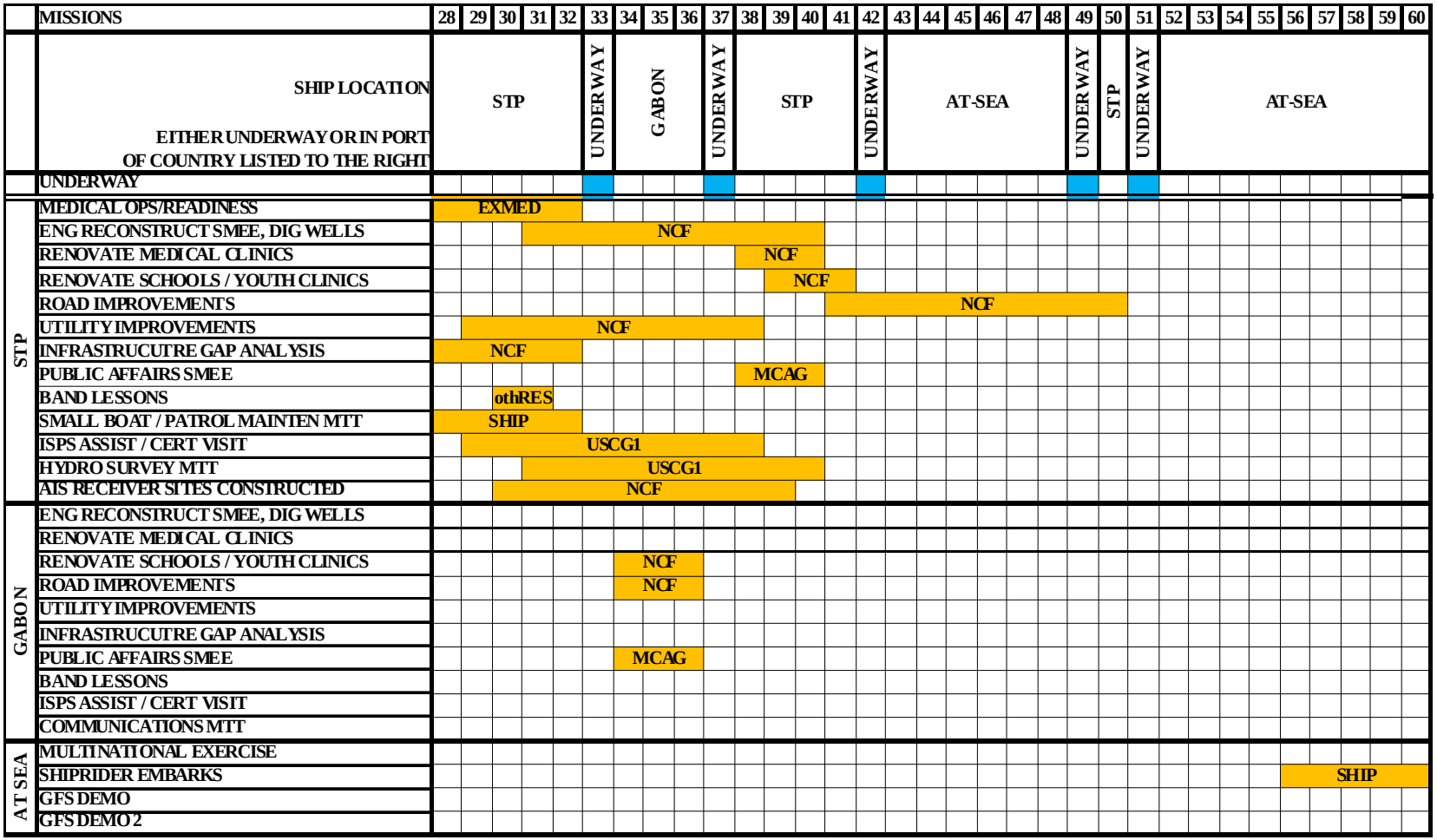

Table 10. RH-CARMA Schedule, Case 1C: 60 Days, $3M, Days 28-60

Tables 9 and 10 display the optimal schedule that RH-CARMA develops. Budget is the limiting factor in this case. The myopic nature of this algorithm attempts to maximize the most TSC value during the first 40 days (first stage). Most of the selected missions finish by day 50 with only one mission scheduled from days 51-60. It completes eleven missions lasting 10 days each, for a total TSC value of 212.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						GHANA																								
	UNDERWAY																																
GHANA	MEDICAL OPS/READINESS								EXMED																								
	HA/DR OF INFECTIOUS DISEASES								EXMED																								
	ENG RECONSTRUCT SMEE, DIG WELLS								NCF																								
	AIRPORT INFRASTRUCTURE IMPROVE								NCF																								
	ROAD IMPROVEMENTS								NCF																								
	UTILITY IMPROVEMENTS								NCF																								
	INFRASTRUCUTRE GAP ANALYSIS																							NCF									
	PUBLIC AFFAIRS SMEE								MCAG																								
	BAND LESSONS								othRES																								
	PORT SECURITY MTT								USCG1																								
	SMALL BOAT / PATROL MAINTEN MTT								SHIP																								
	ISPS ASSIST / CERT VISIT								USCG1																								
	HYDRO SURVEY MTT								USCG1																								
	COMMUNICATIONS MTT								ETC																								
	OFFICER LEADERSHIP MTT								SHIP																								
	NCO PROFESS DEVELOP SMEE/ MTT								SHIP																								
	COOPERATIVE SECURITY LOCATION								MDA																								
	AIS RECEIVER SITES CONSTRUCTED																							NCF									

Table 11. H-CARMA Schedule, Case 1C: 60 Days, $3M, Days 1-32

	MISSIONS	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY		STP										UNDERWAY	AT-SEA					MODEL STOPS MAX BUDGET REACHED (REMAINS AT-SEA)									
	UNDERWAY																												
STP	MEDICAL OPS/READINESS			EXMED																									
STP	ENG RECONSTRUCT SMEE, DIG WELLS																												
STP	RENOVATE MEDICAL CLINICS																												
STP	RENOVATE SCHOOLS / YOUTH CLINICS			NCF																									
STP	ROAD IMPROVEMENTS			NCF																									
STP	UTILITY IMPROVEMENTS			NCF																									
STP	INFRASTRUCUTRE GAP ANALYSIS																												
STP	PUBLIC AFFAIRS SMEE			MCAG																									
STP	BAND LESSONS			othRES																									
STP	SMALL BOAT / PATROL MAINTEN MTT			SHIP																									
STP	ISPS ASSIST / CERT VISIT																												
STP	HYDRO SURVEY MTT			USCG1																									
STP	AIS RECEIVER SITES CONSTRUCTED			NCF																									
AT SEA	MULTINATIONAL EXERCISE														SHIP														
AT SEA	SHIPRIDER EMBARKS														SHIP														
AT SEA	GFS DEMO														SHIP														
AT SEA	GFS DEMO 2																												

Table 12. H-CARMA Schedule, Case 1C: 60 Days, $3M, Days 33-60

Tables 11 and 12 indicate H-CARMA schedules more of the available missions that last 10 days. It even schedules the longest available mission, "Airport Infrastructure Improvements," in Ghana on days 8-22. All but one of these 10-day or longer-duration missions have TSC values of five points or higher. Overall, H-CARMA produces a reasonable approximation of the RH-CARMA results, garnering more than an 80% solution.

D. SCENARIO 2: MISSION TRANSFER FROM GHANA TO ANGOLA

1. Setup

As the Scenario 1 cases demonstrate, Ghana dominates mission priority selections in both algorithms. Its relatively close proximity to the starting point (Senegal) also contributes to it being chosen. Scenario 2 posits a situation where six higher-value missions from Ghana are transferred to Angola, the farthest country from Senegal.

SCENARIO 2: GHANA AND ANGOLA MISSION MODIFICATIONS	GHANA	ANGOLA	TSC value
MEDICAL			
MEDICAL OPS/READINESS	x		3
HA/DR OF INFECTIOUS DISEASES	x		4
INFRASTRUCTURE			
ENG RECONSTRUCTION SMEE, DIG WELLS		x	5
RENOVATE MEDICAL CLINICS			2
RENOVATE SCHOOLS / YOUTH ORGANIZATION CLINICS			2
AIRPORT INFRASTRUCTURE IMPROVEMENTS	x		6
ROAD IMPROVEMENTS	x		4
UTILITY IMPROVEMENTS		x	5
PORT INFRASTRUCTURE IMPROVEMENTS			9
INFRASTRUCUTRE GAP ANALYSIS	x		5
CIVIL / COMMUNICATIONS			
PUBLIC AFFAIRS SMEE	x	x	5
BAND LESSONS	x		1
COMREL		x	3
SURFACE MARITIME ACTIVITIES			
PORT SECURITY MTT	x		8
MULTINATIONAL EXERCISE			10
SHIPRIDER EMBARKS			7
SMALL BOAT / BOAT PATROL MAINTENANCE MTT	x		6
ISPS ASSIST / CERT VISIT		x	8
HYDRO SURVEY MTT		x	8
MINE CLEARANCE		x	7
MILITARY & LEADERSHIP TRAINING			
COMMUNICATIONS MTT	x		4
OFFICER LEADERSHIP MTT		x	7
NCO PROFESSIONAL DEVELOPMENT SMEE/MTT	x		6
MARITIME DOMAIN AWARENESS ACTIVITIES			
SHIP VISIT		x	5
MDA SITE SURVEY			7
AIS RECEIVER SITES CONSTRUCTED		x	9
COOPERATIVE SECURITY LOCATION	x		10
GFS DEMO			7
GFS DEMO 2			7
LOGISTICS			
LOGISTICS STOP			1
ORIGINAL BASELINE TOTAL TSC VALUE	**104**	**20**	**348**
SCENARIO 2 TOTAL TSC VALUE	**62**	**62**	**348**

Table 13. Scenario 2: Mission Transfer from Ghana and Angola

The orange highlighted missions in Table 13 reflect this change in mission allocation. From this shift, both countries now have the same overall TSC value of 62 points. All other locations retain the same values as established in Scenario 1. STP now has the largest available TSC points with a total of 63. For other countries, see Table 3.

Table 14 displays the results of the three cases for this scenario. In Cases 2A and 2B, H-CARMA generates solutions below 60% of MIP-CARMA. Looking more specifically at the schedules each algorithm provides insight as to the large difference in TSC values.

Comparisons for Scenario 2 (Case 2A): Ghana/Angola Partial TSC Change, 30 Days, $10M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	144	100.00%	$1,924,500	27	17,722
H-CARMA	84	58.33%	$1,579,000	19	187
Comparisons for Scenario 2 (Case 2B): Ghana/Angola Partial TSC Change, 30 Days, $1.5M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	137	100.00%	$1,492,500	25	2,228
H-CARMA	70	51.09%	$1,497,000	16	190
Comparisons for Scenario 2 (Case 2C): Ghana/Angola Partial TSC Change, 60 Days, $3M					
Algorithm	TSC	% of RH-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
RH-CARMA	182	100.00%	$2,982,000	36	18,013
H-CARMA	159	87.36%	$2,909,000	30	177

Table 14. Results for Scenario 2 Comparisons

2. Case 2A: 30 Days, $10 Million Budget

Missions as assigned in Table 14 serve as inputs for Case 2A, which limits duration to 30 days and sets a maximum budget of $10 Million. MIP-CARMA produces the schedule shown in Table 15. Despite the added value to Angola, the algorithm does not include it in the optimal schedule. The long transit time does not justify stopping there during the planning horizon given opportunities in other countries. The comparable TSC totals for STP and Ghana provide a better overall solution.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA					UNDERWAY		GHANA					UNDERWAY		STP					UNDERWAY	AT-SEA			UNDERWAY	STP		
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS											EXMED																			
	HA/DR OF INFECTIOUS DISEASES												EXMED																		
	AIRPORT INFRASTRUCTURE IMPROVE																														
	ROAD IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS											NCF																			
	PUBLIC AFFAIRS SMEE													MCAG																	
	BAND LESSONS											oth.RES																			
	PORT SECURITY MTT											USCG1																			
	SMALL BOAT /PATROL MAINT MTT											SHIP																			
	COMMUNICATIONS MTT											ETC																			
	NCO PROFESS DEVELOP SMEE/MTT													SHIP																	
	COOPERATIVE SECURITY LOCATION											MDA																			
STP	MEDICAL OPS/READINESS																		EXMED												
	ENG RECONSTRUCT SMEE, DIG WELLS																					NCF									
	RENOVATE MEDICAL CLINICS																												NCF		
	RENOVATE SCHOOLS / YOUTH CLINICS																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																			NCF											
	INFRASTRUCUTRE GAP ANALYSIS																		NCF												
	PUBLIC AFFAIRS SMEE																		MCAG												
	BAND LESSONS																				othRES										
	SMALL BOAT / PATROL MAINT MTT																		SHIP												
	ISPS ASSIST / CERT VISIT																					USCG1									
	HYDRO SURVEY MTT																				USCG1										
	AIS RECEIVER SITES CONSTRUCTED																				NCF										
AT SEA	MULTINATIONAL EXERCISE																														
	SHIPRIDER EMBARKS																														
	GFS DEMO																								SHIP						
	GFS DEMO 2																								MDA						
LIBERIA	ENG RECONSTRUCT SMEE, DIG WELLS																														
	PORT INFRASTRUCTURE IMPROVE																														
	PUBLIC AFFAIRS SMEE				MCAG																										
	COMREL							SHIP																							
	PORT SECURITY MTT				USCG1																										
	SHIP VISIT				SHIP																										
	AIS RECEIVER SITES CONSTRUCTED																														

Table 15. MIP-CARMA Schedule, Case 2A: 30 Days, $10M

Similarly, MIP-CARMA takes advantage of shorter distance by commencing four missions in Liberia on day four. The schedule for days 18 to 30 reflects the flexibility of MIP-CARMA to perform missions away from port. This allows the ship to drop off several teams in STP and then leave to perform two missions at sea before returning to pick up the teams in STP.

Table 16 shows the results for case 2A using H-CARMA. Similar to MIP-CARMA, this schedule focuses on two countries with large total TSC values available. However, the in-port restriction in H-CARMA prevents the completion of additional missions in the At-Sea and Liberia locations as MIP-CARMA recommends. H-CARMA performs one more mission in Ghana than MIP-CARMA, but it only completes one mission from days 25-30.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						STP										UNDERWAY		GHANA									UNDERWAY
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																				EXMED										
	HA/DR OF INFECTIOUS DISEASES																				EXMED										
	ENG RECONSTRUCT SMEE, DIG WELLS																														
	AIRPORT INFRASTRUCTURE IMPROVE																														
	ROAD IMPROVEMENTS																				NCF										
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS																				NCF										
	PUBLIC AFFAIRS SMEE																				MCAG										
	BAND LESSONS																				othRES										
	PORT SECURITY MTT																				USCG1										
	SMALL BOAT / PATROL MAINT MTT																				SHIP										
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	COMMUNICATIONS MTT																				ETC										
	OFFICER LEADERSHIP MTT																														
	NCO PROF DEVELOP SMEE/MTT																				SHIP										
	COOPERATIVE SECURITY LOCATION																				MDA										
	AIS RECEIVER SITES CONSTRUCTED																														
STP	MEDICAL OPS/READINESS								EXMED																						
	ENG RECONSTRUCT SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS								NCF																						
	RENOVATE SCHOOLS / YOUTH CLINICS								NCF																						
	ROAD IMPROVEMENTS								NCF																						
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS								NCF																						
	PUBLIC AFFAIRS SMEE								MCAG																						
	BAND LESSONS								othRES																						
	SMALL BOAT / PATROL MAINT MTT								SHIP																						
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	AIS RECEIVER SITES CONSTRUCTED																														

Table 16. H-CARMA Schedule, Case 2A: 30 Days, $10M

The stacking procedure in the H-CARMA algorithm creates a group of missions based on the one with the longest duration: as long as other missions are shorter they are scheduled. The mission chosen, “Road Improvements,” only has a TSC value of four, yet its duration affects the entire schedule. This effect occurs again in STP on days 13 through 17 for the same mission. Considering the At-Sea location is only a one-day transit from either STP or Ghana and its four missions have a total TSC value of 31 points and durations of five days or less, the opportunity cost of continuing only one mission for five more days results in a net loss of 27 TSC points.

As performed in Scenario 1, we apply a supplementary case to this framework by looking at how MIP-CARMA performs when all missions require the ship to be in-port. MIP-CARMA produces a schedule with a total TSC value of 137 points compared to the 144 points without the requirement. It significantly surpasses the 84 points of H-CARMA and improves run-time to 204 seconds (very close the 187 seconds required of H-CARMA). It also expends less budget ($1,492,500) than H-CARMA.

3. Case 2B: 30 Days, $1.5 Million Budget

Compared to Case 2A, Table 17 shows the MIP-CARMA schedule adjusts for the budget change by eliminating a port stop in Liberia and focusing on missions in Ghana, STP and the At-Sea locations. Total missions completed in Ghana and STP does not change, but the composition of missions in STP varies slightly. This schedule now includes all four missions in the At-Sea location.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA	UNDERWAY		GHANA					UNDERWAY	AT-SEA						UNDERWAY	STP										
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS							EXMED																							
	HA/DR OF INFECTIOUS DISEASES								EXMED																						
	AIRPORT INFRASTRUCTURE IMPROVE																														
	ROAD IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS							NCF																							
	PUBLIC AFFAIRS SMEE								MCAG																						
	BAND LESSONS							othRES																							
	PORT SECURITY MTT							USCG1																							
	SMALL BOAT / PATROL MAINTEN MTT							SHIP																							
	COMMUNICATIONS MTT							ETC																							
	NCO PROFESS DEVELOP SMEE/MTT									SHIP																					
	COOPERATIVE SECURITY LOCATION							MDA																							
STP	MEDICAL OPS/READINESS																										EXMED				
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																							NCF							
	RENOVATE SCHOOLS / YOUTH CLINICS																						NCF								
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																					NCF									
	INFRASTRUCUTRE GAP ANALYSIS																										NCF				
	PUBLIC AFFAIRS SMEE																												MCAG		
	BAND LESSONS																													othRES	
	SMALL BOAT / PATROL MAINTEN MTT																										SHIP				
	ISPS ASSIST / CERT VISIT																					NCF									
	HYDRO SURVEY MTT																				USCG1										
	AIS RECEIVER SITES CONSTRUCTED																				NCF										
AT SEA	MULTINATIONAL EXERCISE														SHIP																
	SHIPRIDER EMBARKS													SHIP																	
	GFS DEMO																SHIP														
	GFS DEMO 2													MDA																	

Table 17. MIP-CARMA Schedule, Case 2B: 30 Days, $1.5M

The budget constraint affects the H-CARMA solution only by changing the number of missions performed in Ghana. The schedule illustrated in Table 18 contains the exact same dates as in Case 1A for underway time, and for visits to STP and Ghana. H-CARMA completes the identical set of missions in STP and two less in Ghana. The impact of the ten-day long “Road Improvement” mission remains in this schedule, again preventing the completion of additional missions.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						STP										UNDERWAY		GHANA									UNDERWAY
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																				EXMED									
	HA/DR OF INFECTIOUS DISEASES																				EXMED									
	ENG RECONSTRUCT SMEE, DIG WELLS																													
	AIRPORT INFRASTRUCTURE IMPROVE																													
	ROAD IMPROVEMENTS																				NCF									
	UTILITY IMPROVEMENTS																													
	INFRASTRUCUTRE GAP ANALYSIS																													
	PUBLIC AFFAIRS SMEE																				MCAG									
	BAND LESSONS																				othRES									
	PORT SECURITY MTT																													
	SMALL BOAT / PATROL MAINTEN MTT																				SHIP									
	ISPS ASSIST / CERT VISIT																													
	HYDRO SURVEY MTT																													
	COMMUNICATIONS MTT																				ETC									
	OFFICER LEADERSHIP MTT																													
	NCO PROFESSIONAL DEVELOP SMEE/ MTT																				SHIP									
	COOPERATIVE SECURITY LOCATION																				MDA									
	AIS RECEIVER SITES CONSTRUCTED																													
STP	MEDICAL OPS/READINESS								EXMED																					
	ENG RECONSTRUCT SMEE, DIG WELLS																													
	RENOVATE MEDICAL CLINICS								NCF																					
	RENOVATE SCHOOLS / YOUTH CLINICS								NCF																					
	ROAD IMPROVEMENTS								NCF																					
	UTILITY IMPROVEMENTS																													
	INFRASTRUCUTRE GAP ANALYSIS								NCF																					
	PUBLIC AFFAIRS SMEE								MCAG																					
	BAND LESSONS								othRES																					
	SMALL BOAT / PATROL MAINTEN MTT								SHIP																					
	ISPS ASSIST / CERT VISIT																													
	HYDRO SURVEY MTT																													
	AIS RECEIVER SITES CONSTRUCTED																													

Table 18. H-CARMA Schedule, Case 2B: 30 Days, $1.5M

With the additional budget restriction, the performance of H-CARMA produces a schedule with only 51% of the total TSC value generated by MIP-CARMA. The stacking nature of this algorithm and possibly the in-port requirement for all missions limits H-CARMA from creating an optimal schedule closer to that of MIP-CARMA. Cases 2A and 2B clearly demonstrate this drawback.

Our last supplementary case modifies Case 2B, implementing the in-port requirement for all missions in MIP-CARMA. Results greatly favor MIP-CARMA, producing a total TSC value of 137 points compared with 70 for H-CARMA. Budget is just under the $1.5 million threshold and run-time is even better than H-CARMA, 104 to 190 seconds respectively. All four supplementary cases demonstrate that MIP-CARMA generates schedules with significantly higher TSC totals than H-CARMA even when restricted to perform all missions in-port. We conclude that H-CARMA capabilities may be limited not only by the in-port assumption, but also by other aspects of its routing and scheduling logic.

4. Case 2C: 60 Days, $3 Million Budget

In this 60-day case, total costs for both models are very close to the budgetary limits. Tables 19 and 20 show the RH-CARMA solution. Tables 21 and 22 reflect the H-CARMA schedule.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						CAMEROON					UNDERWAY	STP						UNDERWAY	GABON (REFUEL)		UNDERWAY	STP			UNDERWAY
	UNDERWAY																												
STP	MEDICAL OPS/READINESS															EXMED													
	ENG RECONSTRUCT SMEE, DIG WELLS																	NCF											
	RENOVATE MEDICAL CLINICS																									NCF			
	RENOVATE SCHOOLS / YOUTH CLINICS															NCF													
	ROAD IMPROVEMENTS																												
	UTILITY IMPROVEMENTS																		NCF										
	INFRASTRUCUTRE GAP ANALYSIS														NCF														
	PUBLIC AFFAIRS SMEE																									MCAG			
	BAND LESSONS																										othRES		
	SMALL BOAT / PATROL MAINTEN MTT															SHIP													
	ISPS ASSIST / CERT VISIT																	USCG1											
	HYDRO SURVEY MTT																USCG1												
	AIS RECEIVER SITES CONSTRUCTED																NCF												
CAMEROON	ENG RECONSTRUCT SMEE, DIG WELLS																												
	ROAD IMPROVEMENTS																												
	UTILITY IMPROVEMENTS																												
	INFRASTRUCUTRE GAP ANALYSIS								NCF																				
	PUBLIC AFFAIRS SMEE										MCAG																		
	BAND LESSONS										othRES																		
	ISPS ASSIST / CERT VISIT																												
	COMMUNICATIONS MTT								ETC																				
	OFFICER LEADERSHIP MTT								SHIP																				
GABON	ENG RECONSTRUCT SMEE, DIG WELLS																												
	RENOVATE MEDICAL CLINICS																												
	RENOVATE SCHOOLS / YOUTH CLINICS																					NCF							
	ROAD IMPROVEMENTS																												
	UTILITY IMPROVEMENTS																												
	INFRASTRUCUTRE GAP ANALYSIS																												
	PUBLIC AFFAIRS SMEE																					MCAG							
	BAND LESSONS																						othRES						
	ISPS ASSIST / CERT VISIT																												
	COMMUNICATIONS MTT																												

Table 19. RH-CARMA Schedule, Case 2C: 60 Days, $3M, Days 1-28

	MISSIONS	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	AT-SEA						UNDERWAY	GHANA					UNDERWAY	AT-SEA			UNDERWAY	GHANA	UNDERWAY						SENEGAL	UNDERWAY				AT-SEA	UNDERWAY	GHANA (REFUEL)
	UNDERWAY																																
GHANA	MEDICAL OPS/READINESS									EXMED																							
	HA/DR OF INFECTIOUS DISEASES									EXMED																							
	AIRPORT INFRASTRUCTURE IMPROVE																		NCF														
	ROAD IMPROVEMENTS									NCF																							
	INFRASTRUCUTRE GAP ANALYSIS									NCF																							
	PUBLIC AFFAIRS SMEE									MCAG																							
	BAND LESSONS									othRES																							
	PORT SECURITY MTT									USCG1																							
	SMALL BOAT/PATROL MAINTEN MTT									SHIP																							
	COMMUNICATIONS MTT									ETC																							
	NCO PROFESSIONAL DEV SMEE/MTT										SHIP																						
	COOPERATIVE SECURITY LOCATION									MDA																							
AT SEA	MULTINATIONAL EXERCISE	SHIP																															
	SHIPRIDER EMBARKS		SHIP																														
	GFS DEMO				SHIP																												
	GFS DEMO 2					MDA																											

Table 20. RH-CARMA Schedule, Case 2C: 60 Days, $3M, Days 29-60

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						STP										UNDERWAY		GHANA														
	UNDERWAY																																		
GHANA	MEDICAL OPS/READINESS																				EXMED														
	HA/DR OF INFECTIOUS DISEASES																				EXMED														
	AIRPORT INFRASTRUCTURE IMPROVE																				NCF														
	ROAD IMPROVEMENTS																				NCF														
	INFRASTRUCUTRE GAP ANALYSIS																				NCF														
	PUBLIC AFFAIRS SMEE																				MCAG														
	BAND LESSONS																				othRES														
	PORT SECURITY MTT																				USCG1														
	SMALL BOAT / PATROL MAINTEN MTT																				SHIP														
	COMMUNICATIONS MTT																				ETC														
	NCO PROFESSIONAL DEV SMEE/ MTT																				SHIP														
	COOPERATIVE SECURITY LOCATION																				MDA														
STP	MEDICAL OPS/READINESS								EXMED																										
	ENG RECONSTRUCT SMEE, DIG WELLS																																		
	RENOVATE MEDICAL CLINICS								NCF																										
	RENOV SCHOOLS / YOUTH CLINICS								NCF																										
	ROAD IMPROVEMENTS								NCF																										
	UTILITY IMPROVEMENTS																																		
	INFRASTRUCUTRE GAP ANALYSIS								NCF																										
	PUBLIC AFFAIRS SMEE								MCAG																										
	BAND LESSONS								othRES																										
	SMALL BOAT / PATROL MAINTEN MTT								SHIP																										
	ISPS ASSIST / CERT VISIT																																		
	HYDRO SURVEY MTT																																		
	AIS RECEIVER SITES CONSTRUCTED																																		

Table 21. H-CARMA Schedule, Case 2C: 60 Days, $3M, Days 1-34

	MISSIONS	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY		STP										UNDERWAY	AT-SEA					UNDERWAY			LIBERIA		MAX $ REACHED (AT-SEA)		
	UNDERWAY																										
STP	MEDICAL OPS/READINESS																										
	ENG RECONSTRUCT SMEE, DIG WELLS			NCF																							
	RENOVATE MEDICAL CLINICS																										
	RENOVATE SCHOOLS / YOUTH CLINICS																										
	ROAD IMPROVEMENTS																										
	UTILITY IMPROVEMENTS			NCF																							
	INFRASTRUCUTRE GAP ANALYSIS																										
	PUBLIC AFFAIRS SMEE																										
	BAND LESSONS																										
	SMALL BOAT / PATROL MAINTEN MTT																										
	ISPS ASSIST / CERT VISIT			USCG1																							
	HYDRO SURVEY MTT			USCG1																							
	AIS RECEIVER SITES CONSTRUCTED			NCF																							
AT SEA	MULTINATIONAL EXERCISE														SHIP												
	SHIPRIDER EMBARKS														SHIP												
	GFS DEMO														SHIP												
	GFS DEMO 2														MDA												
LIBERIA	ENG RECONSTR SMEE, DIG WELLS																										
	PORT INFRASTRUCTURE IMPROVE																										
	PUBLIC AFFAIRS SMEE																										
	COMREL																						SHIP				
	PORT SECURITY MTT																										
	SHIP VISIT																										
	AIS RECEIVER SITES CONSTRUCTED																										

Table 22. H-CARMA Schedule, Case 2C: 60 Days, $3M, Days 35-60

Here, H-CARMA produces its best result of all the cases compared in this thesis. It generates an 87% of the total TSC value of the RH-CARMA solution. Completing all missions in Ghana and the At-Sea location contribute to this. It also focuses on the longer 10-day missions in STP, which have TSC values ranging from five to nine points.

E. SCENARIO 3: LARGE TSC VALUE FOR ANGOLA, REDUCED FOR GHANA

1. Setup

In Scenario 2, where Angola absorbs some of the Ghana missions, we learned that the greater available total TSC in Angola is not enough for the algorithms to alter schedules. In response, we test both algorithms to see the effects of adding even more TSC value to the country farthest from the starting position in Senegal. To do this, more missions originally assigned to Ghana in Scenario 1 transfer to Angola to increase its overall TSC value. The missions highlighted in blue in Table 23 reflect these changes in addition to missions previously altered in Scenario 2, which are displayed in orange. These changes result in Angola having a total available TSC value of 104 points and reduce Ghana to 20 total points.

SCENARIO 3 CARMA LARGE TRANSFER OF GHANA MISSIONS TO ANGOLA	GHANA	ANGOLA	TSC value
MEDICAL			
MEDICAL OPS/READINESS	x		3
HA/DR OF INFECTIOUS DISEASES	x		4
INFRASTRUCTURE			
ENG RECONSTRUCTION SMEE, DIG WELLS		x	5
RENOVATE MEDICAL CLINICS			2
RENOVATE SCHOOLS / YOUTH ORGANIZATION CLINICS			2
AIRPORT INFRASTRUCTURE IMPROVEMENTS		x	6
ROAD IMPROVEMENTS	x		4
UTILITY IMPROVEMENTS		x	5
PORT INFRASTRUCTURE IMPROVEMENTS			9
INFRASTRUCUTRE GAP ANALYSIS		x	5
CIVIL / COMMUNICATIONS			
PUBLIC AFFAIRS SMEE	x	x	5
BAND LESSONS	x		1
COMREL		x	3
SURFACE MARITIME ACTIVITIES			
PORT SECURITY MTT		x	8
MULTINATIONAL EXERCISE			10
SHIPRIDER EMBARKS			7
SMALL BOAT / BOAT PATROL MAINTENANCE MTT		x	6
ISPS ASSIST / CERT VISIT		x	8
HYDRO SURVEY MTT		x	8
MINE CLEARANCE		x	7
MILITARY & LEADERSHIP TRAINING			
COMMUNICATIONS MTT	x		4
OFFICER LEADERSHIP MTT		x	7
NCO PROFESSIONAL DEVELOPMENT SMEE/MTT	x		6
MARITIME DOMAIN AWARENESS ACTIVITIES			
SHIP VISIT		x	5
MDA SITE SURVEY			7
AIS RECEIVER SITES CONSTRUCTED		x	9
COOPERATIVE SECURITY LOCATION		x	10
GFS DEMO			7
GFS DEMO 2			7
LOGISTICS			
LOGISTICS STOP			1
ORIGINAL BASELINE TOTAL TSC VALUE	104	20	348
SCENARIO 3 TOTAL TSC VALUE	27	97	348

Table 23. Scenario 3 Mission Changes for Ghana and Angola

Table 24 conveys the overall performance that both algorithms produce given the revised inputs. In all cases, H-CARMA creates schedules no better than 73% of total TSC points of those that MIP-CARMA and RH-CARMA generate. Total costs are very similar while the number of completed missions varies. Run times for MIP-CARMA and RH-CARMA remain very long.

Comparisons for Scenario 3 (Case 3A): Large Angola TSC, 30 Days, $10M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	133	100.00%	$3,098,000	21	3,975
H-CARMA	86	64.66%	$3,105,500	14	35
Comparisons for Scenario 3 (Case 3B): Large Angola TSC, 30 Days, $1.5M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	112	100.00%	$1,451,500	21	4,588
H-CARMA	81	72.32%	$1,463,000	13	164
Comparisons for Scenario 3 (Case 3C): Large Angola TSC, 60 Days, $3M					
Algorithm	TSC	% of RH-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
RH-CARMA	166	100.00%	$2,999,500	29	18,023
H-CARMA	115	69.28%	$2,976,500	22	165

Table 24. Results for Scenario 3 Comparisons

Looking at TSC values per day for each case provides contrast in the overall results. In Case 3A, MIP-CARMA garners 4.43 TSC points per day while H-CARMA registers 2.87 points per day. For Case 3B, these numbers are 3.73 and 2.7, respectively. Case 3C results in RH-CARMA generating 2.77 points per day and 1.92 points per day for H-CARMA. Clearly, on a daily basis, MIP-CARMA and RH-CARMA provide greater TSC values for this scenario.

2. Case 3A: 30 Days, $10 Million Budget

Table 25 presents the schedule that MIP-CARMA produces for this case where Angola now holds a very high total TSC value. The budget limit is not restrictive here. Although Ghana provides fewer missions and TSC points than before, MIP-CARMA schedules it as the first port to perform missions. It assigns all missions at sea and has the ship spend the last 11 days in Angola completing 13 of 15 possible missions. It appears the high TSC value offsets the greater distance required to visit Angola.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
		SENEGAL	UNDERWAY		LIBERIA	UNDERWAY		GHANA			UNDERWAY	AT-SEA						UNDERWAY			ANGOLA										
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																														
	HA/DR OF INFECTIOUS DISEASES							EXMED																							
	ROAD IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE							MCAG																							
	BAND LESSONS							othRES																							
	COMMUNICATIONS MTT																														
	NCO PROFESS DEVEL SMEE/ MTT							SHIP																							
ANGOLA	ENG RECONSTRUCT SMEE, DIG WELLS																				NCF										
	AIRPORT INFRASTRUCTURE IMPROVE																														
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS																							NCF							
	PUBLIC AFFAIRS SMEE																												MCAG		
	COMREL																				SHIP										
	ISPS ASSIST / CERT VISIT																				USCG1										
	HYDRO SURVEY MTT																					USCG1									
	OFFICER LEADERSHIP MTT																					SHIP									
	MINE CLEARANCE																				EOD										
	PORT SECURITY MTT																										USCG1				
	SMALL BOAT / PATROL MAINTENANCE MTT																									SHIP					
	SHIP VISIT																										SHIP				
	AIS RECEIVER SITES CONSTRUCTED																					NCF									
	COOPERATIVE SECURITY LOCATION																										MDA				
AT SEA	MULTINATIONAL EXERCISE												SHIP																		
	SHIPRIDER EMBARKS											SHIP																			
	GFS DEMO														SHIP																
	GFS DEMO 2															MDA															

Table 25. MIP-CARMA Schedule, Case 3A: 30 Days, $10M

Table 26 indicates that H-CARMA similarly focuses its schedule on Angola and At-Sea missions. The selection of one short mission in Gabon on day 23 appears to be in order to take advantage of a refueling and resupply stop, but output in H-CARMA does not easily specify this. H-CARMA initially selects the highest overall TSC country to visit first. This prevents the possibility of visiting other ports prior to Angola to improve overall TSC value, as exhibited by MIP-CARMA (Table 25).

In further comparing the results of the two algorithms, H-CARMA limits its selection to only one mission having a maximum length of ten days. The "Utility Improvements" and "Engineering Reconstruction SMEE" missions both have a TSC value of five, a duration of ten days and require the same team type. However, there also exists the "AIS Receiver Sites Constructed" mission of the same duration and team, but a larger TSC value of nine points. H-CARMA fails to schedule this mission and it appears there may be an issue in how the algorithm defaults to prioritizing one of several missions having the same length. MIP-CARMA schedules this mission as well as one of the five point missions during the Angola period, adding to the overall difference in total TSC value achieved. With a $10 million budget, mission costs should not have been a detrimental factor to achieving a larger TSC value.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY							ANGOLA												UNDERWAY		GABON		UNDERWAY	AT-SEA				
	UNDERWAY																														
ANGOLA	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	AIRPORT INFRASTRUCTURE IMPROVE																														
	UTILITY IMPROVEMENTS									NCF																					
	INFRASTRUCUTRE GAP ANALYSIS									NCF																					
	PUBLIC AFFAIRS SMEE									MCAG																					
	COMREL																			SHIP											
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	OFFICER LEADERSHIP MTT									SHIP																					
	MINE CLEARANCE																														
	PORT SECURITY MTT									USCG1																					
	SMALL BOAT/PATROL MAINTENANCE MTT									SHIP																					
	SHIP VISIT									SHIP																					
	AIS RECEIVER SITES CONSTRUCTED																														
	COOPERATIVE SECURITY LOCATION									MDA																					
AT SEA	MULTINATIONAL EXERCISE																										SHIP				
	SHIPRIDER EMBARKS																										SHIP				
	GFS DEMO																										SHIP				
	GFS DEMO 2																										MDA				
GABON	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																														
	RENOVATE SCHOOLS / YOUTH CLINICS																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS																														
	PUBLIC AFFAIRS SMEE																														
	BAND LESSONS																							othRES							
	ISPS ASSIST / CERT VISIT																														
	COMMUNICATIONS MTT																														

Table 26. H-CARMA Schedule, Case 3A: 30 Days, $10M

3. Case 3B: 30 Days, $1.5 Million Budget

Case 3B reduces the budget to $1.5 million. Table 27 shows the MIP-CARMA proposed schedule. The smaller budget prevents the execution of all missions in Angola. To improve overall TSC, the algorithm schedules the ship to perform additional missions in Cameroon and Liberia in addition to Ghana, At-Sea and Angola. Overall TSC value decreases from 133 to 112 points.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA		UNDERWAY		GHANA			UNDERWAY	AT-SEA						UNDERWAY	STP		UNDERWAY	CAMEROON	UNDERWAY	STP	UNDERWAY	CAMEROON	UNDERWAY	STP		
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																														
	HA/DR OF INFECTIOUS DISEASES								EXMED																						
	ROAD IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE								MCAG																						
	BAND LESSONS								othRES																						
	COMMUNICATIONS MTT																														
	NCO PROFESSIONAL DEVELOP SMEE/MTT								SHIP																						
STP	MEDICAL OPS/READINESS																								EXMED						
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																														
	RENOVATE SCHOOLS / YOUTH CLINICS																												NCF		
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																				NCF										
	INFRASTRUCUTRE GAP ANALYSIS																								NCF						
	PUBLIC AFFAIRS SMEE																												MCAG		
	BAND LESSONS																													othRES	
	SMALL BOAT / PATROL MAINTENANCE MTT																														
	ISPS ASSIST / CERT VISIT																				NCF										
	HYDRO SURVEY MTT																			USCG1											
	AIS RECEIVER SITES CONSTRUCTED																			NCF											
CAMEROON	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS																						NCF								
	PUBLIC AFFAIRS SMEE																														
	BAND LESSONS																														
	ISPS ASSIST / CERT VISIT																														
	COMMUNICATIONS MTT																						ETC								
	OFFICER LEADERSHIP MTT																						SHIP								
AT SEA	MULTINATIONAL EXERCISE													SHIP																	
	SHIPRIDER EMBARKS												SHIP																		
	GFS DEMO															SHIP															
	GFS DEMO 2														MDA																
LIBERIA	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	PORT INFRASTRUCTURE IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE																														
	COMREL				SHIP																										
	PORT SECURITY MTT																														
	SHIP VISIT																														
	AIS RECEIVER SITES CONSTRUCTED																														

Table 27. MIP-CARMA Schedule, Case 3B: 30 Days, $1.5M

The H-CARMA results in Table 28 show it selects Angola once again as its starting country, then At-Sea followed by a short visit to Ghana and back to At-Sea. Here the solution forgoes any of the ten-day missions described in Case 3A and schedules multiple five-day missions in Angola. The second stop at the At-Sea location on days 26-30 seems inefficient. With three “ship crew” teams available, there is an opportunity to perform this five-day mission to coincide with the other missions ongoing on days 17-21, leaving days 23-30 for opportunities elsewhere. However, in this case, it does not appear to make a difference in the algorithm’s ability to garner additional TSC value because the budget constraint activates regardless of when this single At-Sea mission occurs. The MIP-CARMA results clearly show other possibilities exist given the limited total cost. As a result, H-CARMA only garners 81 TSC points compared to the 112 points that MIP-CARMA achieves.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY							ANGOLA					UNDERWAY			AT-SEA					UNDERWAY	GHANA		UNDERWAY	AT-SEA				
	UNDERWAY																														
GHANA	MEDICAL OPS/READINESS																														
	HA/DR OF INFECTIOUS DISEASES																														
	ROAD IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE																														
	BAND LESSONS																							othRES							
	COMMUNICATIONS MTT																														
	NCO PROFESSIONAL DEVELOP SMEE/MTT																														
ANGOLA	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	AIRPORT INFRASTRUCTURE IMPROVEM																														
	UTILITY IMPROVEMENTS																														
	INFRASTRUCUTRE GAP ANALYSIS									NCF																					
	PUBLIC AFFAIRS SMEE									MCAG																					
	COMREL									SHIP																					
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	OFFICER LEADERSHIP MTT									SHIP																					
	MINE CLEARANCE																														
	PORT SECURITY MTT									USCG1																					
	SMALL BOAT / PATROL MAINTENANCE MTT									SHIP																					
	SHIP VISIT									SHIP																					
	AIS RECEIVER SITES CONSTRUCTED																														
	COOPERATIVE SECURITY LOCATION									MDA																					
AT SEA	MULTINATIONAL EXERCISE																	SHIP													
	SHIPRIDER EMBARKS																										SHIP				
	GFS DEMO																	SHIP													
	GFS DEMO 2																	MDA													

Table 28. H-CARMA Schedule, Case 3B: 30 Days, $1.5M

4. Case 3C: 60 Days, $3 Million Budget

The results for RH-CARMA appear in Tables 29 and 30. The budget limit restricts the algorithm to complete only one mission in the last ten days of the horizon. Overall, it achieves a total TSC value of 204 points while conducting missions in five locations. Despite a restricted budget, mission-rich Angola attracts inclusion in the schedule as seen in tables 28-29. The potential value in Angola exceeds the distance penalty in this example contrary to the results in Case 3B.

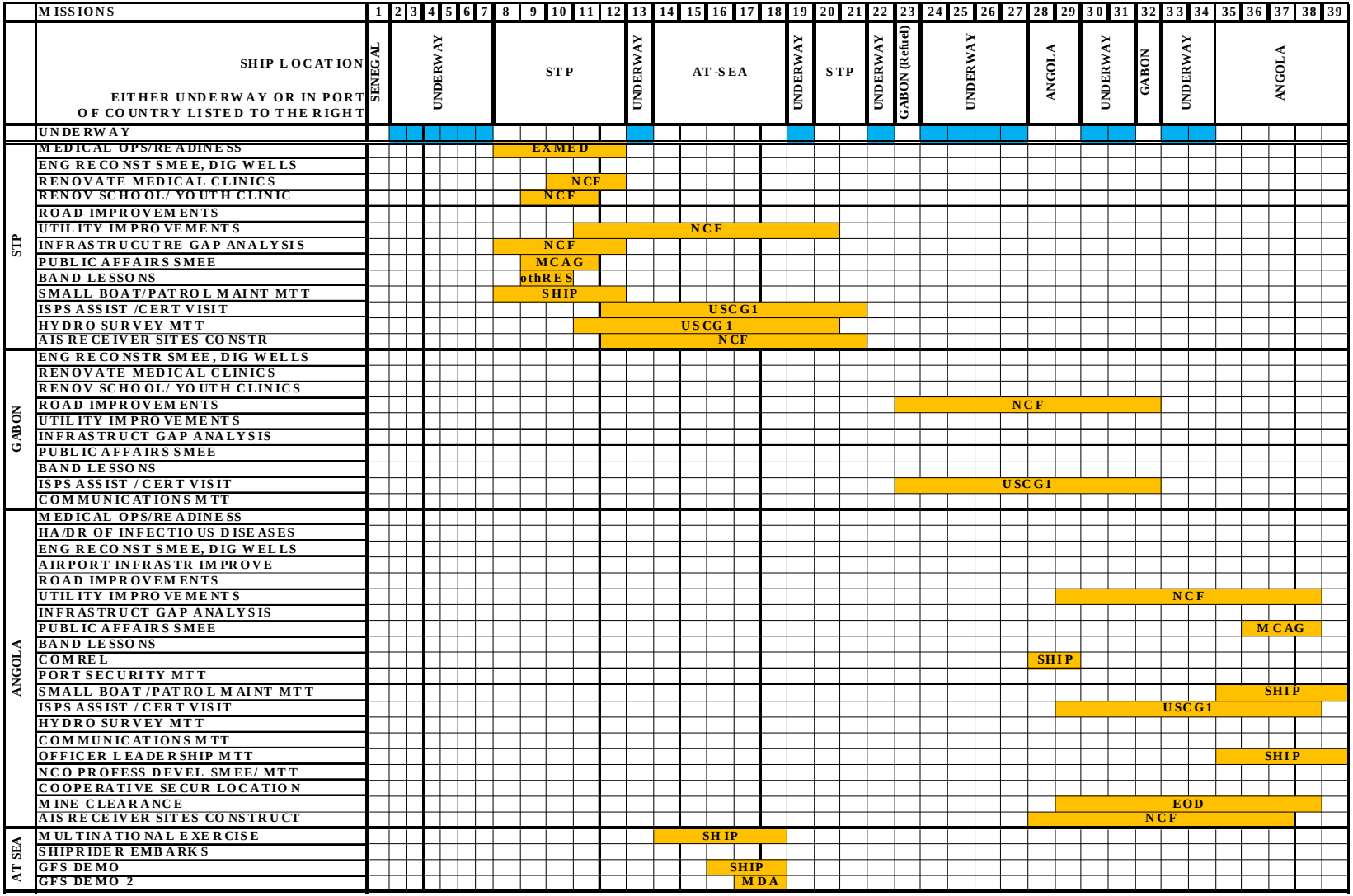

Table 29. RH-CARMA Schedule, Case 3C: 60 Days, $3M, Days 1-39

	MISSIONS	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY				GHANA	U/W to AT-SEA	U/W to GHANA	GHANA		GHANA (Refuel)	UNDERWAY	AT-SEA									
	UNDERWAY																					
AT SEA	MULTINATIONAL EXERCISE																					
AT SEA	SHIPRIDER EMBARKS																	SHIP				
AT SEA	GFS DEMO																					
AT SEA	GFS DEMO 2																					
GHANA	MEDICAL OPS/READINESS					EXMED																
GHANA	HA/DR OF INFECTIOUS DISEASES								EXMED													
GHANA	ENG RECONSTRUCT SMEE, DIG WELLS																					
GHANA	AIRPORT INFRASTRUCTURE IMPROVE																					
GHANA	ROAD IMPROVEMENTS																					
GHANA	UTILITY IMPROVEMENTS																					
GHANA	INFRASTRUCUTRE GAP ANALYSIS																					
GHANA	PUBLIC AFFAIRS SMEE								MCAG													
GHANA	BAND LESSONS																					
GHANA	PORT SECURITY MTT																					
GHANA	SMALL BOAT / PATROL MAINTEN MTT																					
GHANA	ISPS ASSIST / CERT VISIT																					
GHANA	HYDRO SURVEY MTT																					
GHANA	COMMUNICATIONS MTT																					
GHANA	OFFICER LEADERSHIP MTT																					
GHANA	NCO PROFESS DEVELOP SMEE/ MTT								SHIP													
GHANA	COOPERATIVE SECURITY LOCATION																					
GHANA	AIS RECEIVER SITES CONSTRUCTED																					

Table 30. RH-CARMA Schedule, Case 3C: 60 Days, $3M, Days 40-60

Tables 31 and 32 reflect the schedule H-CARMA attains. The recommended course also includes Angola and schedules the majority of total missions here. By front-loading TSC value accumulation in the first port visit, the budget is spent by day 40. The remainder of the period the ship remains at sea, where it fails to generate additional value. H-CARMA performs only one mission in STP on days 22-23, but returns on days 32-34 to conduct three additional missions. The total cost is close to that of RH-CARMA yet total TSC value falls far below.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	31
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY							ANGOLA										UNDERWAY			STP		UNDERWAY	GHANA					UNDERWAY	
	UNDERWAY																															
GHANA	MEDICAL OPS/READINESS																									EXMED						
	HA/DR OF INFECTIOUS DISEASES																									EXMED						
	ROAD IMPROVEMENTS																															
	PUBLIC AFFAIRS SMEE																									MCAG						
	BAND LESSONS																									othRES						
	COMMUNICATIONS MTT																									ETC						
	NCO PROFESS DEVELOP SMEE/MTT																									SHIP						
STP	MEDICAL OPS/READINESS																															
	ENG RECONSTRUCT SMEE, DIG WELLS																															
	RENOVATE MEDICAL CLINICS																															
	RENOVATE SCHOOLS/ YOUTH CLINICS																															
	ROAD IMPROVEMENTS																															
	UTILITY IMPROVEMENTS																															
	INFRASTRUCUTRE GAP ANALYSIS																															
	PUBLIC AFFAIRS SMEE																															
	BAND LESSONS																						othRES									
	SMALL BOAT/ PATROL MAINTEN MTT																															
	ISPS ASSIST / CERT VISIT																															
	HYDRO SURVEY MTT																															
	AIS RECEIVER SITES CONSTRUCTED																															
ANGOLA	ENG RECONSTRUCTSMEE, DIG WELLS																															
	AIRPORT INFRASTRUCTURE IMPROVE																															
	UTILITY IMPROVEMENTS									NCF																						
	INFRASTRUCUTRE GAP ANALYSIS									NCF																						
	PUBLIC AFFAIRS SMEE									MCAG																						
	COMREL																															
	ISPS ASSIST / CERT VISIT																															
	HYDRO SURVEY MTT																															
	OFFICER LEADERSHIP MTT									SHIP																						
	MINE CLEARANCE																															
	PORT SECURITY MTT									USCG1																						
	SMALL BOAT/ PATROL MAINTEN MTT									SHIP																						
	SHIP VISIT									SHIP																						
	AIS RECEIVER SITES CONSTRUCTED																															
	COOPERATIVE SECURITY LOCATION									MDA																						

Table 31. H-CARMA Schedule, Case 3C: 60 Days, $3M, Days 1-31

	MISSIONS	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	STP			UNDERWAY	AT-SEA					MODEL STOPS MAX BUDGET REACHED (REMAINS AT-SEA)																				
	UNDERWAY																													
STP	MEDICAL OPS/READINESS																													
	ENG RECONSTRUCT SMEE, DIG WELLS																													
	RENOVATE MEDICAL CLINICS	NCF																												
	RENOVATE SCHOOLS / YOUTH CLINICS	NCF																												
	ROAD IMPROVEMENTS																													
	UTILITY IMPROVEMENTS																													
	INFRASTRUCUTRE GAP ANALYSIS																													
	PUBLIC AFFAIRS SMEE	MCAG																												
	BAND LESSONS																													
	SMALL BOAT / PATROL MAINTEN MTT																													
	ISPS ASSIST / CERT VISIT																													
	HYDRO SURVEY MTT																													
	AIS RECEIVER SITES CONSTRUCTED																													
AT SEA	MULTINATIONAL EXERCISE					SHIP																								
	SHIPRIDER EMBARKS					SHIP																								
	GFS DEMO					SHIP																								
	GFS DEMO 2					MDA																								

Table 32. H-CARMA Schedule, Case 3C: 60 Days, $3M, Days 32-60

F. SCENARIO 4: TWO GROUPS OF THREE COUNTRIES WITH SAME TSC VALUES

1. Setup

To challenge both algorithms further, we create a scenario that gives the same mission sets to three countries. The country groups are split into two mission sets. These two groups are based on alternating proximity among the countries. The first group, Liberia, Ghana and Gabon, contains the same mission set with a total value of 65 TSC points for each country. The second group, comprising Angola, Cameroon and STP, has missions totaling 81 TSC points in each country. Table 33 lists the missions assigned to all countries. Missions in the At-Sea location and Senegal do not change.

SCENARIO 4 (2 SETS OF 3 COUNTRIES WITH SAME MISSONS) CARMA GOG MISSIONS / ACTIVITIES	GHANA	GABON	STP	CAMEROON	ANGOLA	LIBERIA	AT SEA	SENEGAL	TSC value
MEDICAL									
MEDICAL OPS/READINESS	x	x				x			3
HA/DR OF INFECTIOUS DISEASES			x	x	x				4
INFRASTRUCTURE									
ENG RECONSTRUCTION SMEE, DIG WELLS			x	x	x				5
RENOVATE MEDICAL CLINICS			x	x	x				2
RENOVATE SCHOOLS / YOUTH ORGANIZATION CLINICS			x	x	x				2
AIRPORT INFRASTRUCTURE IMPROVEMENTS	x	x				x			6
ROAD IMPROVEMENTS			x	x	x				4
UTILITY IMPROVEMENTS			x	x	x				5
PORT INFRASTRUCTURE IMPROVEMENTS	x	x				x			9
INFRASTRUCUTRE GAP ANALYSIS	x	x				x			5
CIVIL / COMMUNICATIONS									
PUBLIC AFFAIRS SMEE	x	x	x	x	x	x			5
BAND LESSONS	x	x	x	x	x	x			1
COMREL			x	x	x				3
SURFACE MARITIME ACTIVITIES									
PORT SECURITY MTT			x	x	x				8
MULTINATIONAL EXERCISE							x		10
SHIPRIDER EMBARKS							x		7
SMALL BOAT / BOAT PATROL MAINTENANCE MTT	x	x				x			6
ISPS ASSIST / CERT VISIT	x	x	x	x	x	x			8
HYDRO SURVEY MTT			x	x	x				8
MINE CLEARANCE			x	x	x				7
MILITARY & LEADERSHIP TRAINING									
COMMUNICATIONS MTT			x	x	x				4
OFFICER LEADERSHIP MTT	x	x				x			7
NCO PROFESSIONAL DEVELOPMENT SMEE/MTT	x	x				x			6
MARITIME DOMAIN AWARENESS ACTIVITIES									
SHIP VISIT			x	x	x				5
MDA SITE SURVEY									7
AIS RECEIVER SITES CONSTRUCTED	x	x				x			9
COOPERATIVE SECURITY LOCATION			x	x	x				10
GFS DEMO							x		7
GFS DEMO 2							x		7
LOGISTICS									
LOGISTICS STOP								x	1
ORIGINAL BASELINE TOTAL TSC VALUE	104	41	63	44	20	44	31	1	348
SCENARIO 4 TOTAL TSC VALUE	65	65	81	81	81	65	31	1	470

Table 33. Scenario 4 Mission Changes for All Locations Except Senegal and At-Sea

The total TSC value available to each algorithm increases to 470 points from the 348 of the inputs used in Scenarios 1-3.

The same three cases developed for Scenarios 1-3 are implemented again to compare how both algorithms respond to the changes in data input. The results of the six cases appear in Table 34. MIP-CARMA provides a solution in Case 4A where the total cost is less than that of H-CARMA. Even with more competitive countries in terms of total TSC points available, in its best case, H-CARMA only musters a 72% solution to that of MIP-CARMA for Case 4B. For Cases 4A and 4C, H-CARMA generates 61% and 67% solutions in comparison to MIP-CARMA and RH-CARMA, respectively. In terms of missions completed, RH-CARMA completes more than twice as many missions as H-CARMA in case 4C; Case 4A is nearly double for the MIP-CARMA algorithm.

Comparisons for Scenario 4 (Case 4A): Two Sets of Even TSC Countries, 30 Days, $10M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	174	100.00%	$2,614,000	37	26,551
H-CARMA	106	60.92%	$3,008,500	19	200
Comparisons for Scenario 4 (Case 4B): Two Sets of Even TSC Countries, 30 Days, $1.5M					
Algorithm	TSC	% of MIP-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
MIP-CARMA	142	100.00%	$1,497,000	22	17,757
H-CARMA	102	71.83%	$1,365,000	12	184
Comparisons for Scenario 4 (Case 4C): Two Sets of Even TSC Countries, 60 Days, $3M					
Algorithm	TSC	% of RH-CARMA	Total Cost ($)	Total Missions Completed	Run Time (Seconds)
RH-CARMA	204	100.00%	$2,992,500	38	20,001
H-CARMA	136	66.67%	$2,969,500	18	202

Table 34. Results for Scenario 4 Comparisons

2 Case 4A: 30 Days, $10 Million Budget

Tables 35 and 36 illustrate the breakdown of the MIP-CARMA schedule into two periods: days 1-17 and days 16-30. The route begins with the same exact mission sets in both Liberia and Ghana before implementing some overlapping missions in Cameroon and STP. MIP-CARMA selects three ten-day missions from days 21-30 in STP that allow the ship to leave port and conduct ten additional missions in Cameroon.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY		LIBERIA					UNDERWAY		GHANA					UNDERWAY	
	UNDERWAY																	
LIBERIA	MEDICAL OPS/READINESS				EXMED													
	AIRPORT INFRASTRUCTURE IMPROVE																	
	PORT INFRASTRUCTURE IMPROVEM																	
	INFRASTRUCTURE GAP ANALYSIS				NCF													
	PUBLIC AFFAIRS SMEE					MCAG												
	BAND LESSONS						oth.RES											
	SMALL BOAT / PATROL MAINTEN MTT				SHIP													
	ISPS ASSIST / CERT VISIT																	
	OFFICER LEADERSHIP MTT				SHIP													
	NCO PROFESS DEVELOP SMEE/MTT						SHIP											
	AIS RECEIVER SITES CONSTRUCTED																	
GHANA	MEDICAL OPS/READINESS											EXMED						
	AIRPORT INFRASTRUCTURE IMPROVE																	
	PORT INFRASTRUCTURE IMPROVE																	
	INFRASTRUCTURE GAP ANALYSIS											NCF						
	PUBLIC AFFAIRS SMEE													MCAG				
	BAND LESSONS													oth.RES				
	SMALL BOAT / PATROL MAINTEN MTT											SHIP						
	ISPS ASSIST / CERT VISIT																	
	OFFICER LEADERSHIP MTT											SHIP						
	NCO PROFESS DEVELOP SMEE/MTT												SHIP					
	AIS RECEIVER SITES CONSTRUCTED																	

Table 35. MIP-CARMA Schedule, Case 4A: 30 Days, $10M, Days 1-17

	MISSIONS	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY		STP					UNDERWAY	CAMEROON					UNDERWAY	STP
	UNDERWAY															
STP	HA/DR OF INFECTIOUS DISEASES			EXMED												
	ENG RECONSTRUCTION SMEE, DIG WELLS						NCF									
	RENOVATE MEDICAL CLINICS					NCF										
	RENOVATE SCHOOLS / YOUTH CLINICS				NCF											
	ROAD IMPROVEMENTS															
	UTILITY IMPROVEMENTS															
	PUBLIC AFFAIRS SMEE					MCAG										
	BAND LESSONS					oth.RES										
	COMREL					SHIP										
	PORT SECURITY MTT			USCG1												
	ISPS ASSIST / CERT VISIT						USCG1									
	HYDRO SURVEY MTT															
	MINE CLEARANCE						EOD									
	COMMUNICATIONS MTT			ETC												
	SHIP VISIT			SHIP												
	COOPERATIVE SECURITY LOCATION			MDA												
CAMEROON	HA/DR OF INFECTIOUS DISEASES									EXMED						
	ENG RECONSTRUCTION SMEE, DIG WELLS															
	RENOVATE MEDICAL CLINICS									NCF						
	RENOVATE SCHOOLS / YOUTH CLINICS											NCF				
	ROAD IMPROVEMENTS															
	UTILITY IMPROVEMENTS															
	PUBLIC AFFAIRS SMEE									MCAG						
	BAND LESSONS										oth.RES					
	COMREL										SHIP					
	PORT SECURITY MTT									USCG1						
	ISPS ASSIST / CERT VISIT															
	HYDRO SURVEY MTT															
	MINE CLEARANCE															
	COMMUNICATIONS MTT									ETC						
	SHIP VISIT									SHIP						
	COOPERATIVE SECURITY LOCATION									MDA						

Table 36. MIP-CARMA Schedule, Case 4A: 30 Days, $10M, Days 17-30

Using the updated data, H-CARMA generates the schedule shown in Tables 37 and 38. Though budget is not a limiting factor, H-CARMA requires a higher overall cost yet produces a total TSC value nearly 39% less than that of MIP-CARMA.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						CAMEROON										UNDERWAY
	UNDERWAY																		
CAMEROON	HA/DR OF INFECTIOUS DISEASES								EXMED										
	ENG RECONSTRUCT SMEE, DIG WELLS								NCF										
	RENOVATE MEDICAL CLINICS								NCF										
	RENOVATE SCHOOLS / YOUTH CLINICS								NCF										
	ROAD IMPROVEMENTS																		
	UTILITY IMPROVEMENTS																		
	PUBLIC AFFAIRS SMEE								MCAG										
	BAND LESSONS								oth.RES										
	COMREL								SHIP										
	PORT SECURITY MTT								USCG1										
	ISPS ASSIST / CERT VISIT																		
	HYDRO SURVEY MTT																		
	MINE CLEARANCE																		
	COMMUNICATIONS MTT								ETC										
	SHIP VISIT								SHIP										
	COOPERATIVE SECURITY LOCATION								MDA										

Table 37. H-CARMA Schedule, Case 4A: 30 Days, $10M, Days 1-18

	MISSIONS	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	UNDERWAY	STP			UNDERWAY	GABON					UNDERWAY	AT-SEA	
	UNDERWAY													
GABON	MEDICAL OPS/READINESS						EXMED							
	AIRPORT INFRASTRUCTURE IMPROVE													
	PORT INFRASTRUCTURE IMPROVE													
	INFRASTRUCTURE GAP ANALYSIS						NCF							
	PUBLIC AFFAIRS SMEE						MCAG							
	BAND LESSONS						oth.RES							
	SMALL BOAT / PATROL MAINTENMTT						SHIP							
	ISPS ASSIST / CERT VISIT													
	OFFICER LEADERSHIP MTT						SHIP							
	NCO PROFESS DEVELOP SMEE/MTT						SHIP							
	AIS RECEIVER SITES CONSTRUCTED													
AT SEA	MULTINATIONAL EXERCISE													
	SHIPRIDER EMBARKS													
	GFS DEMO													
	GFS DEMO 2												MDA	
STP	HA/DR OF INFECTIOUS DISEASES		EXMED											
	ENG RECONSTRUCTSMEE, DIG WELLS													
	RENOVATE MEDICAL CLINICS		NCF											
	RENOVATE SCHOOLS / YOUTH CLINICS		NCF											
	ROAD IMPROVEMENTS													
	UTILITY IMPROVEMENTS													
	PUBLIC AFFAIRS SMEE		MCAG											
	BAND LESSONS		oth.RES											
	COMREL		SHIP											
	PORT SECURITY MTT													
	ISPS ASSIST / CERT VISIT													
	HYDRO SURVEY MTT													
	MINE CLEARANCE													
	COMMUNICATIONS MTT													
	SHIP VISIT													
	COOPERATIVE SECURITY LOCATION													

Table 38. H-CARMA Schedule, Case 4A: 30 Days, $10M, Days 18-30

3. Case 4B: 30 Days, $1.5 Million Budget

MIP-CARMA produces the schedule shown in Table 39. The new allocation of TSC values allows MIP-CARMA to assign missions in the At-Sea location, Ghana, STP and Cameroon. This example clearly reveals the drop-off, pick-up component of MIP-CARMA from days 19-30. The ship alternates between STP, Cameroon and underway to save costs while ensuring it picks the most possible missions. In both cases, 4A and 4B, the distance to Angola makes it a less attractive option.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SEN	U/W					GHANA					U/W	AT-SEA						U/W	STP		U/W	CAM	U/W	STP	U/W	CAM	U/W	STP	
	UNDERWAY																														
AT SEA	MULTINATIONAL EXERCISE														SHIP																
	SHIPRIDER EMBARKS													SHIP																	
	GFS DEMO															SHIP															
	GFS DEMO 2													MDA																	
CAMEROON	HA/DR OF INFECTIOUS DISEASES																														
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																														
	RENOVATE SCHOOLS / YOUTH CLINICS																														
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE																														
	BAND LESSONS																														
	COMREL																														
	PORT SECURITY MTT																							USCG1							
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	MINE CLEARANCE																														
	COMMUNICATIONS MTT																							ETC							
	SHIP VISIT																														
	COOPERATIVE SECURITY LOCATION																							MDA							
GHANA	MEDICAL OPS/READINESS							EXMED																							
	AIRPORT INFRASTRUCTURE IMPROVEMENTS																														
	PORT INFRASTRUCTURE IMPROVEMENTS																														
	INFRASTRUCTURE GAP ANALYSIS							NCF																							
	PUBLIC AFFAIRS SMEE							MCAG																							
	BAND LESSONS																														
	SMALL BOAT / PATROL MAINTENANCE MTT							SHIP																							
	ISPS ASSIST / CERT VISIT																														
	OFFICER LEADERSHIP MTT							SHIP																							
	NCO PROFESSIONAL DEVELOPMENT SMEE/MTT									SHIP																					
	AIS RECEIVER SITES CONSTRUCTED																														
STP	HA/DR OF INFECTIOUS DISEASES																														
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS																														
	RENOVATE SCHOOLS / YOUTH CLINICS																														
	ROAD IMPROVEMENTS																				NCF										
	UTILITY IMPROVEMENTS																					NCF									
	PUBLIC AFFAIRS SMEE																									MCAG					
	BAND LESSONS																													SHIP	
	COMREL																														
	PORT SECURITY MTT																					USCG1									
	ISPS ASSIST / CERT VISIT																				NCF										
	HYDRO SURVEY MTT																					USCG1									
	MINE CLEARANCE																					EOD									
	COMMUNICATIONS MTT																									ETC					
	SHIP VISIT																														
	COOPERATIVE SECURITY LOCATION																														

Table 39. MIP-CARMA Schedule, Case 4B: 30 Days, $1.5M

The H-CARMA schedule in Table 40 stops assigning missions by day 22. The algorithm fails to select any further missions though there is still over $130,000 available for additional port and mission expenses. Compared with MIP-CARMA, the H-CARMA answer is 28% inferior.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY						CAMEROON					UNDERWAY	STP					UNDERWAY	AT-SEA		STOPS SCHEDULING MISSIONS (REMAINS AT SEA)							
	UNDERWAY																														
AT SEA	MULTINATIONAL EXERCISE																														
	SHIPRIDER EMBARKS																														
	GFS DEMO																				SHIP										
	GFS DEMO 2																				MDA										
CAMEROON	HA/DR OF INFECTIOUS DISEASES								EXMED																						
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS								NCF																						
	RENOVATE SCHOOLS / YOUTH CLINICS								NCF																						
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE								MCAG																						
	BAND LESSONS								oth.RES																						
	COMREL								SHIP																						
	PORT SECURITY MTT								USCG1																						
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	MINE CLEARANCE																														
	COMMUNICATIONS MTT								ETC																						
	SHIP VISIT								SHIP																						
	COOPERATIVE SECURITY LOCATION								MDA																						
STP	HA/DR OF INFECTIOUS DISEASES														EXMED																
	ENG RECONSTRUCTION SMEE, DIG WELLS																														
	RENOVATE MEDICAL CLINICS														NCF																
	RENOVATE SCHOOLS / YOUTH CLINICS														NCF																
	ROAD IMPROVEMENTS																														
	UTILITY IMPROVEMENTS																														
	PUBLIC AFFAIRS SMEE														MCAG																
	BAND LESSONS														oth.RES																
	COMREL														SHIP																
	PORT SECURITY MTT														USCG1																
	ISPS ASSIST / CERT VISIT																														
	HYDRO SURVEY MTT																														
	MINE CLEARANCE																														
	COMMUNICATIONS MTT														ETC																
	SHIP VISIT														SHIP																
	COOPERATIVE SECURITY LOCATION														MDA																

Table 40. H-CARMA Schedule, Case 4B: 30 Days, $1.5M

4. Case 4C: 60 Days, $3 Million Budget

For the 60-day case, both algorithms reach the maximum budget limit well before the end of the horizon. Tables 41 and 42 reveal the RH-CARMA schedule. The ship remains at sea for the last 20 days of the horizon. In the countries chosen, however, the algorithm completes 13 of 15 missions in Cameroon and STP, all the At-Sea missions and eight of 11 possible missions in Gabon. Port costs restrict further missions in different countries from being completed but the algorithm performs well in maximizing mission completion in the countries chosen.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY							STP					UNDERWAY	AT-SEA						UNDERWAY	STP		UNDERWAY
	UNDERWAY																								
AT SEA	MULTINATIONAL EXERCISE															SHIP									
AT SEA	SHIPRIDER EMBARKS																SHIP								
AT SEA	GFS DEMO																	SHIP							
AT SEA	GFS DEMO 2																	MDA							
STP	HA/DR OF INFECTIOUS DISEASES									EXMED															
STP	ENG RECONSTRUCT SMEE, DIG WELLS																								
STP	RENOV MEDICAL CLINICS											NCF													
STP	RENOV SCHOOLS / YOUTH CLINICS										NCF														
STP	ROAD IMPROVEMENTS																								
STP	UTILITY IMPROVEMENTS													NCF											
STP	PUBLIC AFFAIRS SMEE										MCAG														
STP	BAND LESSONS											othRES													
STP	COMREL												SHIP												
STP	PORT SECURITY MTT									USCG1															
STP	ISPS ASSIST / CERT VISIT																								
STP	HYDRO SURVEY MTT													NCF											
STP	MINE CLEARANCE													EOD											
STP	COMMUNICATIONS MTT									ETC															
STP	SHIP VISIT									SHIP															
STP	COOPERATIVE SEC LOCATION									MDA															

Table 41. RH-CARMA Schedule, Case 4C: 60 Days, $3M, Days 1-24

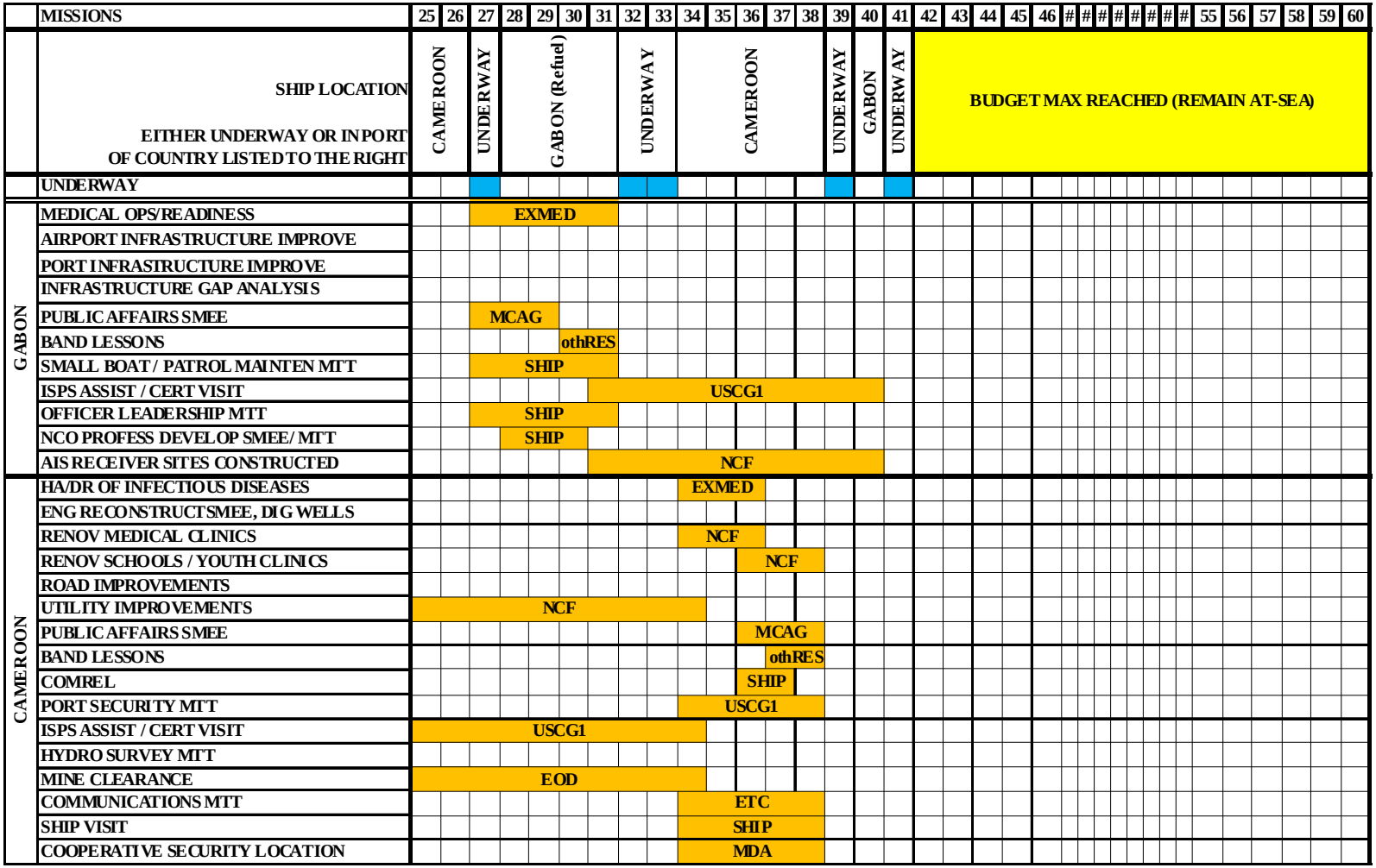

Table 42. RH-CARMA Schedule, Case 4C: 60 Days, $3M, Days 25-60

H-CARMA reaches budgetary limits by day 40. Tables 43 and 44 show the recommended schedule. Mission selections are curious: From days 20-28, the ship stops in STP to perform only one mission and Gabon to complete only three of 11 available missions. With no built-in mechanism to consider budgetary constraints as a maximum TSC value develops, the H-CARMA algorithm lacks the flexibility to evaluate less costly mission sets properly. This results in a ship course that produces 20 fewer complete missions and 70 fewer TSC points than RH-CARMA.

	MISSIONS	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	SENEGAL	UNDERWAY					GHANA											UNDERWAY						UNDERWAY	GABON			UNDERWAY
	UNDERWAY																												
GABON	MEDICAL OPS/READINESS																												
	AIRPORT INFRASTRUCTURE IMPROVE																												
	PORT INFRASTRUCTURE IMPROVE																												
	INFRASTRUCTURE GAP ANALYSIS																												
	PUBLIC AFFAIRS SMEE																									MCAG			
	BAND LESSONS																									othRES			
	SMALL BOAT / PATROL MAINTEN MTT																												
	ISPS ASSIST / CERT VISIT																												
	OFFICER LEADERSHIP MTT																												
	NCO PROFESS DEVELOP SMEE / MTT																									SHIP			
	AIS RECEIVER SITES CONSTRUCTED																												
CAMEROON	HA/DR OF INFECTIOUS DISEASES								EXMED																				
	ENG RECONSTRUCT SMEE, DIG WELLS								NCF																				
	RENOV MEDICAL CLINICS								NCF																				
	RENOV SCHOOLS / YOUTH CLINICS								NCF																				
	ROAD IMPROVEMENTS																												
	UTILITY IMPROVEMENTS																												
	PUBLIC AFFAIRS SMEE								MCAG																				
	BAND LESSONS								th.RE																				
	COMREL								SHIP																				
	PORT SECURITY MTT								USCG 1																				
	ISPS ASSIST / CERT VISIT																												
	HYDRO SURVEY MTT																												
	MINE CLEARANCE																												
	COMMUNICATIONS MTT								ETC																				
	SHIP VISIT								SHIP																				
	COOPERATIVE SECURITY LOCATION								MDA																				
STP	HA/DR OF INFECTIOUS DISEASES																												
	ENG RECONSTRUCTSMEE, DIG WELLS																												
	RENOV MEDICAL CLINICS																												
	RENOV SCHOOLS / YOUTH CLINICS																												
	ROAD IMPROVEMENTS																												
	UTILITY IMPROVEMENTS																												
	PUBLIC AFFAIRS SMEE																												
	BAND LESSONS																												
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	PORT SECURITY MTT																												
	ISPS ASSIST / CERT VISIT																												
	HYDRO SURVEY MTT																												
	MINE CLEARANCE																												
	COMMUNICATIONS MTT																												
	SHIP VISIT																					SHIP							
	COOPERATIVE SEC LOCATION																												

Table 43. H-CARMA Schedule, Case 4C: 60 Days, $3M, Days 1-28

	MISSIONS	29	30	31	32	33	34	35	36	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
	SHIP LOCATION EITHER UNDERWAY OR IN PORT OF COUNTRY LISTED TO THE RIGHT	STP					UNDERWAY	AT-SEA					MODEL STOPS MAX AMOUNT REACHED (REMAINS AT-SEA)																					
	UNDERWAY																																
AT SEA	MULTINATIONAL EXERCISE							SHIP																									
AT SEA	SHIPRIDER EMBARKS							SHIP																									
AT SEA	GFS DEMO							SHIP																									
AT SEA	GFS DEMO 2							MDA																									
STP	HA/DR OF INFECTIOUS DISEASES	EXMED																															
STP	ENG RECONSTRUCTSMEE, DIG WELLS																																
STP	RENOV MEDICAL CLINICS	NCF																															
STP	RENOV SCHOOLS / YOUTH CLINICS	NCF																															
STP	ROAD IMPROVEMENTS																																
STP	UTILITY IMPROVEMENTS																																
STP	PUBLIC AFFAIRS SMEE	MCAG																															
STP	BAND LESSONS	othRES																															
STP	COMREL	SHIP																															
STP	PORT SECURITY MTT	USCG1																															
STP	ISPS ASSIST / CERT VISIT																																
STP	HYDRO SURVEY MTT																																
STP	MINE CLEARANCE																																
STP	COMMUNICATIONS MTT	ETC																															
STP	SHIP VISIT																																
STP	COOPERATIVE SEC LOCATION	MDA																															

Table 44. H-CARMA Schedule, Case 4C: 60 Days, $3M, Days 29-60

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IV. CONCLUSIONS AND RECOMMENDATIONS

A. CONCLUSIONS

1 Review of Results

In his original comparison of algorithms, Dwyer's analysis is limited to planning horizons of 90 and 180 days. The results show H-CARMA solutions to be within 7% of those generated by Spitz's RH-CARMA algorithm. This thesis develops 12 trial cases to test the H-CARMA algorithm with MIP-CARMA for 30-day scenarios and with RH-CARMA for 60-day scenarios. In all but one case, H-CARMA generates solutions with total TSC value less than 81% of those obtained using Spitz's algorithms, and, in the worst of these cases, the solutions only achieve 51% of optimal.

When there is no slack in terms of time and budget, MIP- and RH- CARMA give significantly better solutions than H-CARMA, by more than 25% in most cases this study examines. It seems the length of the original schedules may provide more leeway for the H-CARMA algorithm as it has the opportunity to examine each country based on maximum TSC value available. The additional time allows for the development of schedules that go back to enough countries to gain a significant amount of TSC value. Run times for the H-CARMA algorithm are drastically shorter than those of MIP-CARMA and RH-CARMA. Thus, scalability does not appear to be a factor even when the total number of missions increases by 20 in Scenario 4.

2. Inefficiencies of the H-CARMA Algorithm

It is not evident whether the assumption that all missions require the ship to be in-port hurts H-CARMA significantly. The four supplementary cases performed in Scenarios 1 and 2 show that MIP-CARMA is still capable of generating significantly better results in terms of total TSC value than H-CARMA even when restricted to in-port missions only. While it was originally suspected that the in-port restriction played a

significant factor, it appears more likely that other aspects of the algorithm's routing and scheduling logic prevent it from achieving better results. Again, longer horizon lengths and larger budgets seem to hide this tendency in the original scenarios.

Unfortunately, the enumerative process in the H-CARMA model proves to be less efficient in developing short-term schedules than the other algorithms. By strictly focusing on the country with the most available TSC value, it misses opportunities for adding value along the way. This is evident in Scenario 3 where Angola has the largest possible TSC value: H-CARMA bypasses potential value in other countries along the way to go straight to Angola. MIP-CARMA and RH-CARMA both incorporate additional ports and missions to improve total TSC value. In this scenario, H-CARMA produces no better than a 73% solution compared to Spitz's algorithms.

3. Competitive Choices Present Difficulties for H-CARMA

Both H-CARMA's worst and best results occur in Scenario 2. By transferring several missions from Ghana to Angola, three countries contain total TSC value within one point of one another. Ghana and Angola have 62 available TSC points each and STP has 63 potential points. In the 30-day cases, the tendency for H-CARMA to implement a "packing routine" based first on maximum TSC available, and second on the length of the longest mission, prevents it from seeking alternatives that support the overall TSC value. As a result, the algorithm will always start in the country with the highest total TSC value even if only one point differentiates one country from the next. In Cases 2A and 2C, the recommended course bypasses Ghana to start in STP even though Ghana is closer to the starting point in Senegal.

B. FUTURE AND RECOMMENDATIONS

1. More Realistic Assumptions

All of the algorithms this thesis reviews make assumptions necessary to develop solutions. For H-CARMA, the notion that a ship must remain in-port while EPTs carry out any mission will not apply in most practical scenarios. As this study shows, in short

periods these port costs greatly impact this algorithm's ability to maximize TSC value (by avoiding opportunities to perform missions in other countries) while meeting budget constraints (because of additional in-port costs), and even less to minimize cost.

2. Development of MIP- and RH-CARMA

While further improvements and applications of H-CARMA have not been formally reviewed, development continues on the original CARMA model. Expansions on Spitz's model now include tighter schedules (including new restrictions on missions and ports), additional countries, mission types, and teams, and changes in the base platform acting as a GFS. A more user-friendly Microsoft Excel interface has been developed to allow end users to easily change parameters, which feed the underlying GAMS software and see results through this interface (A. Rowe and J. Salmeron, personal communication, February 13, 2009). This latest version of CARMA is currently being tested in support of the Trident Warrior exercise from February to July 2009. Clearly, operational planners seek alternative means to aid in scheduling efforts. Run times still tend to be lengthy, but if planners implement this model for long-range planning, this may not hinder its application.

3 More User-Friendly Heuristic

Despite the short run-times, the current version of H-CARMA is not particularly user-friendly. Knowing which fields can be updated requires a significant amount of set-up time. Similarly, the results display in a matrix format that must be cross-referenced and manually updated with mission-country pairs to be useful. Adjusting the input and output incur additional time beyond simply run-time. In that regard, MIP- and RH-CARMA, with the new Microsoft Excel interface, may require much less pre-computation time, narrowing the gap in overall processing time from beginning data entry to generating a recommended schedule.

4 General H-CARMA Improvements

While practical to users lacking access to the software necessary to run MIP-CARMA and RH-CARMA, the H-CARMA algorithm underperforms for the cases this thesis address, even in the supplementary cases where all factors are equal. H-CARMA needs improvement to address shortcomings described in this section toward the main objective of maximizing TSC value. It should also prioritize minimizing cost as a secondary goal.

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