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NAVAL POSTGRADUATE SCHOOL
Monterey, California

THESIS

OPTIMIZING MINEFIELD PLANNING AND CLEARANCE

by

Robert Chandler Swallow

March, 1993

Thesis Advisor: Siriphong Lawphongpanich

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SUBJECT: Change in distribution statement for *Optimizing Minefield Planning and Clearance* – March 1993.

1. Reference: Swallow, Robert Charles. *Optimizing Minefield Planning and Clearance*. Monterey, CA: Naval Postgraduate School, March 1993. UNCLASSIFIED, [Distribution limited to U.S. Government Agencies only; Soft3are Documentation; March 1993].

2. Upon consultation with NPS subject matter experts, the School has determined that this thesis may be released to the public with unlimited distribution effective March 27, 2015.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
March 1993

3. REPORT TYPE AND DATES COVERED
Master's Thesis

4. TITLE AND SUBTITLE
OPTIMIZING MINEFIELD PLANNING AND CLEARANCE

5. FUNDING NUMBERS

6. AUTHOR(S)
Robert Chandler Swallow

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Naval Postgraduate School
Monterey, CA 93943-5000

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
The views expressed in this thesis are those of the author and do not reflect the official policy or position of the Department of Defense or the U.S. Government.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
~~Distribution limited to U.S. Government Agencies only; Software Documentation; March 1993. Other requests for this document must be referred to Superintendent, Code 043, Naval Postgraduate School, Monterey, CA 93943-5000 via the Defence Technical Information Center, Cameron Station, Alexandira, VA 22304-6145.~~

12b. DISTRIBUTION CODE

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13. ABSTRACT *(Maximum 200 words)*

With the collapse of the Soviet Union, the role of the United States Navy is changing from that of a blue water navy to one which must meet the challenges of coastal warfare. The mining of the amphibious carrier *USS Tripoli* (LPH-10) and the Aegis guided missile cruiser *USS Princeton* (CG-59), during the Persian Gulf War, shows the impact of mine warfare in these littoral regions. Congress, recognizing these trends, has funded a modern mine countermeasures (MCM) fleet of ships and helicopters to deploy with the proposed Naval Expeditionary Force, increased mine warfare research and development, and restructured the Mine Warfare Command. Currently, the Navy has no specific method to measure the efficiency of these mine warfare assets, thus future procurement and present tactics most often result in plans which are feasible but not necessarily optimal.

This thesis develops two optimization models to improve the efficiency of present and future mine warfare assets. The first model is a tactical decision aid. Taking the known mine threat for various routes requiring clearance, the model determines the tasking for the available MCM assets to clear the minefields in the fewest number of days. The second model simulates many potential mine threats and determines the expected minefield clearance times for a given mix of MCM assets. By varying the MCM asset mix, the relative worth of each asset can be determined. The models can be used for offensive mining by inputting the enemy's MCM capability's and varying the types of mines laid.

14. SUBJECT TERMS
Mine Countermeasures (MCM), Planning, Scheduling, Optimization, Simulation, Mine Warfare (MIW)

15. NUMBER OF PAGES
74

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
Unclassified	Unclassified	Unclassified	UL

NSN 7540-01-280-5500

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

Optimizing Minefield Planning and Clearance

by

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B.S., Tulane University, 1985

Submitted in partial fulfillment
of the requirements for the degree of

MASTER OF SCIENCE IN OPERATIONS RESEARCH

from the

NAVAL POSTGRADUATE SCHOOL
March 1993

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Department of Operations Research

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This thesis develops two optimization models to improve the efficiency of present and future mine warfare assets. The first model is a tactical decision aid. Taking the known mine threat for various routes requiring clearance, the model determines the tasking for the available MCM assets to clear the minefields in the fewest number of days. The second model simulates many potential mine threats and determines the expected minefield clearance times for a given mix of MCM assets. By varying the MCM asset mix, the relative worth of each asset can be determined. The models can be used for offensive mining by inputting the enemy's MCM capability's and varying the types of mines laid.

THESIS DISCLAIMER

The reader is cautioned that computer programs developed in this research may not have been exercised for all cases of interest. While every effort has been made, within the time available, to ensure that the programs are free of computational and logical errors, they cannot be considered validated. Any application of these programs without additional verification is at the risk of the user.

TABLE OF CONTENTS

I. INTRODUCTION

A. UNITED STATES NAVAL LESSONS LEARNED IN MINE WARFARE

Damn the torpedoes! Full speed ahead.

Rear Admiral David Glasgow Farragut after the Monitor class ship *Tecumseh* hit a mine and sunk in the entrance to Mobile Bay on August 5th, 1864. [Ref. 1, p. 3]

We have lost control of the seas to a nation without a Navy, using pre-World War I weapons, laid by vessels that were utilized at the time of the birth of Christ.

Commander Amphibious Task Force, Rear Admiral Allan E. Smith, after losing 2 minesweepers and ninety two men attempting to clear Wonsan harbor on October 10th, 1950, during the Korean War. [Ref. 1, p. 76]

We recently relearned some hard lessons -- how mines can frustrate even the most powerful of naval forces. During Operation Desert Storm, Iraq's extensive minefields all but stymied a planned amphibious strike to liberate Kuwait. The U.S. Navy itself used naval mines to cut off the Iraqi Navy's access to the Northern Persian Gulf. This series of events showed us the clear need for a comprehensive Mine Warfare Plan.

Admiral Frank B. Kelso II, Chief of Naval Operations, in a November 1992 article he wrote on mine warfare after the mining of the amphibious carrier *USS Tripoli* (LPH-10) and the Aegis guided missile cruiser *USS Princeton* (CG-59) during Operation Desert Storm. [Ref. 2, p. 40]

With the collapse of the Soviet Union, the role of the United States Navy is changing from that of a blue water navy to one which must meet the challenges of coastal warfare. In his September 1992 white paper titled '*..FROM THE SEA - PREPARING THE NAVAL SERVICE FOR THE 21ST CENTURY - A NEW DIRECTION FOR THE NAVAL SERVICE*', Secretary of the Navy Sean O'Keefe stresses the need for the Navy "to concentrate more on the capabilities required in the complex operating environment of the 'littoral' or coastlines of the earth" [Ref. 3, p. 93]. O'Keefe repeatedly speaks of the shortcomings in today's mine countermeasures (MCM) forces emphasizing the need for MCM assets to deploy as part of the Naval Expeditionary Force. Looking toward the future, O'Keefe knows that the Naval Expeditionary Forces must be self contained, not reliant on the mood of another North Atlantic Treaty Organization (NATO) nation as to whether they will supply MCM forces for an impending crisis.

Like O'Keefe, Congress recognizes the need for a stronger mine warfare organization. Currently, new construction plans include, fourteen ocean going MCM-1 *Avenger* class ships, twelve coastal minehunting MHC-51 *Osprey* class ships and twenty four minehunting MH-53E *Sea Dragon* mine countermeasures helicopters. (The twenty four new MH-53E helicopters will increase the number of MH-53E helicopters to fifty six) [Ref. 4, pp. 805, 843]. Congress is also funding the conversion of one *Iwo Jima* class amphibious warfare helicopter carrier to a mine countermeasures helicopter support ship in the fiscal year (FY) 94 budget, with a second to convert in FY 96. In FY 98 it is hoped to build or to purchase an existing float-on/float-off heavy-lift cargo ship to rapidly move MCM vessels to the minefields [Ref. 4, p. 842]. Research funding also has been authorized for laser and optical detection of mines and unmanned MCM vessels [Ref. 5, p. 10]. To direct this fleet and research, Congress approved a flag officer billet to lead the consolidated Mine Warfare Command organization.

Given this renewed interest and funding, the future of U.S. mine warfare looks bright. A look at the history of mine countermeasures shows that the future of mine warfare always looks bright after an incident, like the mining of *Tripoli* and *Princeton*, but quickly dims as memory of the incident fades. The decade following the Korean War highlights this point. After the tragic disaster in Wonsan Harbor, the United States Navy built sixty five new ocean going mine sweepers (MSO's), twenty two coastal mine sweepers (MSC's) and one mine hunter ship and converted two amphibious ships to mine countermeasure command ships (MCS's). Additionally, research received significant funding including exploring the use of helicopters in MCM operations and establishing a two year master's degree program in mine warfare at the Naval Postgraduate School (NPS). (The program at NPS existed from 1955 to 1960.) [Ref. 1, pp. 85, 89] The high cost of the Vietnam War and the accompanying focus shift away from mine warfare doomed new MCM funding. Stopgap measures, between 1965 and 1982, to maintain the MCM fleet, along with the notion that the other NATO nations would provide MCM coverage, resulted in only four US MCM ships being available for mine clearance operations during Operation Desert Storm.

The Wonsan generation of mine warfare experts had ten years of high level interest before the Vietnam War changed the emphasis of naval warfare. President Clinton has recommended a downsizing of the Navy's budget by 60 billion dollars over five years and a reduction of the number of ships from 450 to 340 [Ref. 6, p. 33]. This downsizing could end the MCM expansion program before it begins. The budget crisis of the 1990's could easily shift the Navy's current emphasis on mine warfare to an emphasis that will support the funding of ten to twelve carriers. These realities make the bright future of mine warfare anything but guaranteed.

Given the above uncertain picture, it is logical for the mine warfare community to concentrate on utilizing currently available resources in the most effective and efficient manner. To assist in this effort, this thesis addresses two problems. One is how to efficiently use MCM assets in an operation and the other is how to evaluate or measure the efficiency of particular MCM assets. The latter problem is timely, for it impacts purchasing and funding decisions in an environment where construction and research dollars are limited.

B. RESEARCH DIRECTIONS

This study uses the number of days required to clear paths through projected minefields as a measure of efficiency. In particular, MCM assets that can clear a path through mined waters in fewer days are more efficient. One method of making MCM operations more efficient is through optimal scheduling of MCM assets. This thesis formulates the scheduling problem as a mixed integer programming problem and demonstrates that its solution can serve as a decision aid to the on-location mine warfare commander.

To evaluate the efficiency of MCM assets, this thesis embeds a mathematical programming problem in a simulation framework. This approach allows for the evaluation of MCM assets in a probabilistic environment in which the mine threats contain some degree of uncertainty. To illustrate the potential applications of this combination of optimization and simulation techniques, the following issues of interest are explored.

1) What are the advantages of deploying one additional explosive ordinance divers (EOD) team.

2) How does a forward deployed amphibious helicopter carrier for the MH-53E helicopters affect the efficiency of MCM operations.
3) What are the advantages of a new laser detection system over more MCM-1 *Avenger* class ships.

C. OUTLINE

The following chapter describes mine clearance operations to provide a foundation for the models' formulation which is explained in Chapter III. Chapter IV explains the implementation of the Minefield Optimization Tactical Decision Aid (MOPTDA) model and highlights how to read and use the results as a scheduling aid. Chapter V illustrates the use of optimization and simulation techniques in the Minefield Optimization Simulation (MOPS) model. Finally, Chapter IV presents the conclusions, potential applications and areas for further study.

II. MINE CLEARANCE OPERATIONS

The motto of the mine countermeasures community is "where the fleet goes, we've been" [Ref. 1, p. 4] This motto applies to the two main applications of MCM forces. The first is clearing mines from a choke point like the entrance to Mobile Bay as encountered by Admiral Farragut during the Civil War. The second major task for MCM forces is establishing cleared paths for amphibious forces as the Navy attempted to do in Wonsan Harbor in the Korean War and off the coast of Kuwait during Operation Desert Storm. Figure 1 is a map of the MCM channels of Wonsan Harbor.

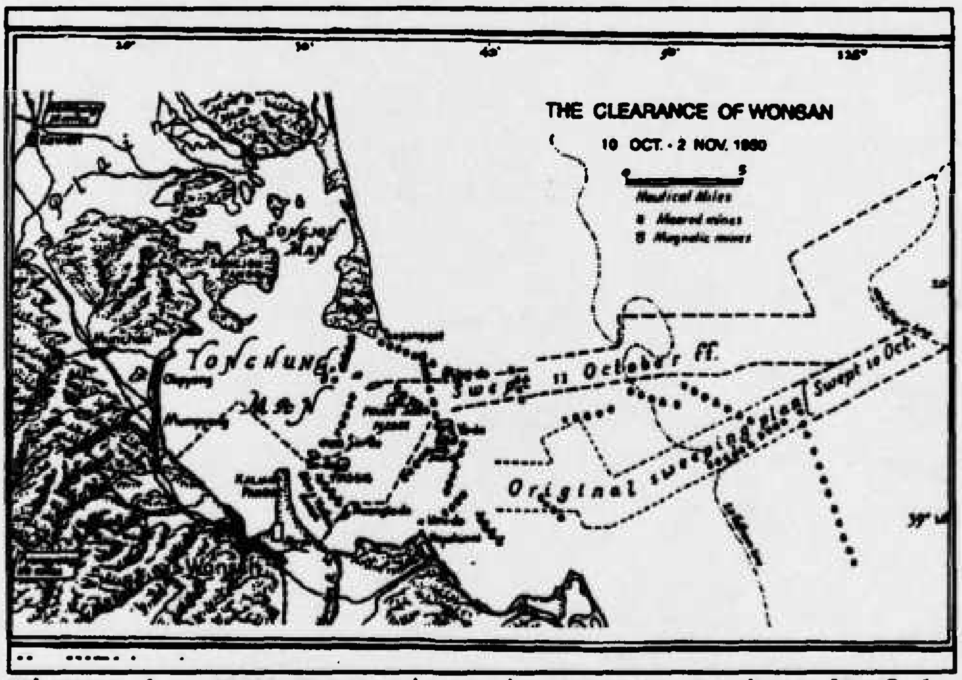

Figure 1. MCM Operations in Wonsan Harbor [Ref 1, p. 71]

The original Wonsan sweeping plan was abandoned when helicopters spotted an extensive system of minefields. While attempting to clear the alternate channel, two steel minesweepers, *Pirate* AM-275 and *Pledge* AM-277, activated magnetic mines resulting in 92 U.S. casualties. A Japanese minesweeper, JMS-19, and a South Korean minesweeper, YMS-516, also were destroyed in the effort to clear the 3000 Soviet supplied mines covering 400-square-miles. The US Army, marching up from the south, captured Wonsan before the MCM forces could recover and finish clearing a channel to the beach [Ref. 1, pp. 75-80].

Another mission of MCM forces is clearance of friendly or enemy mines after the war concludes. Figure 2 shows the various minefields laid by Iraq off the coast of Kuwait during the Persian Gulf War.

Figure 2. Sectors of Iraqi Mines in the Persian Gulf [Ref. 7, p. 32]

Access to the map shown in Figure 2 came after Iraq's surrender. The area where the *Princeton* and *Tripoli* struck mines had previously been thought to be unmined.

To provide the background for discussion in later chapters, the sections below briefly describe some MCM terminology. For an excellent and more detailed unclassified account of mine warfare, see the book titled *"Damn the Torpedoes" A Short History of U.S. Naval Mine Countermeasures, 1777-1991* [Ref. 1].

A. MINEFIELDS

In a MCM operation, the mine danger area is divided into sectors. For ease in clearance, sectors should be divided by mine type. This is possible when accurate intelligence is available on the enemy's minefields or when clearing one's own minefields. For amphibious landings, however, sectors are drawn based on the amphibious landing plan. For example, sector 1 might be the path into the rendezvous area, with sector 2 a path for a feint, sector 3, the rendezvous area itself and sector 4, the area for the surface combatants to perform shore bombardment.

B. MINE THREATS

A mine can be classified by its deployment, activation method and ship counter setting. First, mines can be laid at the bottom or floated beneath the surface. The first type are called ground mines. The latter are called moored mines and they are typically anchored to the bottom by a chain.

To activate mines, two methods are usually employed. One is physical contact with a ship's hull by the mine. The other method involves the mine detecting a transient in the ocean environment caused by a ship. A ship's passage through water emits propeller and engine noises as well as changing the magnetic field in the water around the ship. Acoustic mines activate when the noise level exceeds a certain threshold and magnetic mines explode with a large change in its magnetic field. Acoustic-Magnetic mines require both signals to detonate. Additional activation methods include pressure sensitive mines, light sensitive mines and mines that are detonated from shore.

Ship counter settings refer to mines with the capability to delay activation until a preset number of activation signals have occurred. A mine with a ship counter setting of five would explode when the fifth ship passed over head or after the fifth pass of a minesweeper.

C. MINE COUNTERMEASURES ASSETS

The US Navy performs mine clearance operations using boats, ships, and/or aircraft. Boats and ships in such operations are also referred to as surface MCM (SMCM) assets. The MH-53E MCM helicopters and planes with laser sensors used to locate mines are referred to as air MCM (AMCM) assets. Mine clearance consists of minesweeping and minehunting. Minesweeping involves towing either cutters or emitters. Cutters cut the chains of the moored mines so they float to the surface and can be exploded by an explosive ordinance diver (EOD) team. Acoustic and magnetic emitters are towed to trigger the mines' activation device. Minehunting is simply the determination of mine-like objects. Once the mines are located they can be destroyed using explosives.

D. CLEARANCE RATES

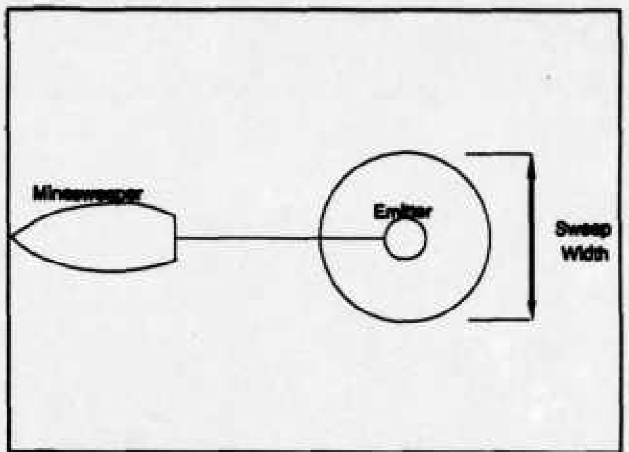

Figure 3 Sweep Width

For mine clearance operations, this thesis defines clearance rate as the area that can be cleared in a day by a MCM asset. Using this definition, the clearance rate will depend on (i) the velocity of the ships or helicopters while performing MCM operations, (ii) the number of hours per day spent clearing and (iii) the range (sweep width) of the cutters, emitters or sonars employed in the clearance operations. (See Figure 3.) When mines have a ship count of one and the environment is ideal, the minesweeper needs to sweep over the mined area once and the clearance rate is simply the product of the assets velocity, hours of clearance per day and sweep width. However, when mines have a ship counter setting greater than one, the mine sweeper must make several passes over the same area during a clearance operation. During a hunting operation, the ship counter setting is of no consequence. Minehunting is affected by the sonar's ability to detect mines among mine like objects on the bottom.

A poor sonar environment would require several passes over the same region. To account for making several passes in calculating the clearance rate, the product of the ship's velocity, hours of clearance per day and sweep width is divided by the number of passes required to clear the mines. In general,

$$CLEARANCE\ RATE = \frac{VELOCITY * SWEEP\ WIDTH}{PASSES} * \frac{HOURS}{DAY} \quad (1)$$

The number of passes in equation (1) is also determined by the required level of clearance for a given operation. A 50% clearance level requires fewer passes than a 95% clearance level. (Note: it is impractical to consider 100% clearance levels.) In an emergency, 50% might be considered an adequate level of clearance. In peace time a 95% clearance level might be required.

III. THE MINEFIELD OPTIMIZATION MODEL FORMULATION

This chapter formulates the problem of scheduling minesweepers to clear all the sectors in a MCM operation as a mixed integer programming problem. Two formulations are presented. The first formulation completely specifies the problem and it is called the Minefield Clearance Optimization Problem. This formulation, however, contains a large number of discrete variables and constraints, making it too time consuming to solve. To eliminate some of the discrete variables, the problem is reformulated to determine whether there exists a feasible schedule for the MCM assets to complete the mine clearance operations in D days. The reformulation is referred to as the Minefield Clearance Feasibility Problem. The following section states the mine clearance scheduling problem and some assumptions. The last two sections of this chapter discuss the two formulations introduced above.

A. PROBLEM STATEMENT

The MCM asset scheduling problem consists of three major components: sectors, jobs and assets. Sectors refer to areas which contain mines. A sector may contain several types of mines requiring different types of assets to clear. Jobs refer to the minehunting or sweeping tasks performed by MCM assets. Such jobs include (i) towing acoustic or magnetic sweep gear, (ii) pulling cutters for moored mines with EOD teams to explode the mines and (iii) using sonar to locate the mines and dropping explosive pouches beside them with remotely operated vehicles. Scheduling the MCM assets means that each asset must be assigned a job in a given sector on days which are not reserved for required maintenance. Based on the measures of efficiency stated in Chapter I, the objective in assigning assets to jobs is to clear the mined sectors in the least number of days.

To state this problem mathematically, it is necessary to make the following assumptions.

1) The mine types in each sector are known with certainty. This assumption is relaxed in later chapters.

2) MCM assets are not destroyed or damaged such that they are considered out of commission. When an asset is out of commission, the available assets should be rescheduled to perform the remaining mine clearance operations.

3) There is no interference between assets performing tasks in the same sector. In practice, EOD teams would not operate within a certain range of active sonars and helicopters would not fly in close proximity of each other to avoid collision.

4) The time resolution for the problem is in days, i.e., an asset is assigned only one job to perform on a given day. To allow assets to perform more than one job on a given day, the time resolution can be refined down to hours. The assumption then is that an asset can only be assigned one job for a given number of hours. This increased detail requires many additional variables and the resulting problem takes longer to solve.

5) As presented, it may appear that the MCM assets are allowed to clear any sector. To account for an instance where an MCM ship would be at risk in a sector with contact mines, the ship's clearance rate for contact mines should be set to zero in the formulation below.

B. COMPLETE FORMULATION

Indices

d,t	days
a	assets
j	jobs
m	mine type, moored or ground

b	activation method
c	the mine's ship counter setting
s	sector

Index Set

Ω	$= \{j$: job j requires an EOD team$\}$

Given and Derived Data

D	the maximum number of days for MCM operations
EOD	the number of EOD teams available
SA_s	the sector area in nautical square miles
Δ	the operating cycle for each asset in days
OFF_a	the number of days off required during an operating cycle
T_a	the number of travel days required for an asset to arrive at the minefields
$TH_{m,b,c,s}$	a binary (0,1) indicator used to establish which types of mines are in each sector
$CR_{a,j,m,b,c}$	the clearance rate in nautical square miles per day for a given asset and job

Binary Variables

$Z_{d,a,j,s}$	1,	if an asset a, performs job j, in sector s, on a particular day d
	0,	otherwise
X_d	1,	if there are some MCM activities ongoing on day d
	0,	otherwise
$Y_{d,a}$	1,	if asset a, is off on day d
	0,	otherwise

The Minefield Clearance Optimization (MCO) Problem

Minimize

$$\sum_{d} X_d \tag{2}$$

Subject to:

$$\sum_{a} \sum_{d \geq T_a} \sum_{j} CR_{a,j,m,b,c}\, Z_{d,a,j,s} \geq SA_s \quad \forall \quad m,b,c,s \text{ such that } TH_{m,b,c,s} = 1 \tag{3}$$

$$\sum_{j} \sum_{s} Z_{d,a,j,s} + Y_{d,a} = 1 \quad \forall \quad a \text{ and } d \text{ such that } d \geq T_a \tag{4}$$

$$\sum_{j \in \Omega} \sum_{a} \sum_{s} Z_{d,a,j,s} \leq EOD \quad \forall \quad d \tag{5}$$

$$\sum_{d=t}^{t+\Delta} Y_{d,a} \geq OFF_a \quad \forall \quad a \text{ and } T_a \leq t \leq D - \Delta \tag{6}$$

$$Z_{d,a,j,s} \leq X_d \quad \forall \quad d,a,j,s \tag{7}$$

$$X_d \leq X_{d-1} \quad \forall \quad d > 1 \tag{8}$$

In the above formulation, equation (2) minimizes the number of days needed to clear all of the mined sectors. Equation (3) ensures that all sectors are cleared. The left hand side defines the total area cleared by assets which must be greater than or equal to the area of each mined sector. Equation (4) limits each asset to exactly one job each day. Equation (5) limits the number of EOD teams used on a given day to the number of EOD teams available. Equation (6) schedules maintenance and rest days for the assets and crews. Equation (7) accounts for every day that the MCM operation is ongoing. Finally, equation (8) guarantees that days used in the MCM operations are contiguous, i.e., there are no superfluous maintenance days in the operation.

As stated above, the MCO problem contains a large number of variables, particularly the Z variables which depend on the indices d, a, j and s. The last three indices are problem dependent and cannot be modified. The range of the d index, i.e., the value of D, however, only has to be large enough to ensure that the problem has a feasible solution. Unfortunately, it is difficult to predict what minimum value to assign D prior to solving the problem. Although a good approximation for the range of D exists, it is not sufficient to make the solution time of the MCO problem acceptable. During our preliminary testing, a MCO problem with ten assets to clear four sectors of mines was solved. This problem contains seven clearance methods and the range of D is 50 days. Solving the resulting MCO problem requires over 30 hours on a 486 33 MHz personal computer. In the next section, the MCO problem is reformulated as a problem which determines the feasibility of scheduling assets to clear mined waters in a given number of days.

C. FEASIBILITY FORMULATION

The formulation described below assumes that the range of index d or the value of D is given and the problem is to determine whether a feasible solution to the MCM scheduling problem exists.

New Variables

$N_{m,b,c,s}$ the area not cleared for each mine threat

<u>The Minefield Clearance Feasibility (MCF) Problem</u>

Minimize

$$\sum_{m} \sum_{b} \sum_{c} \sum_{s} N_{m,b,c,s} \tag{9}$$

Subject to:

$$\sum_{a} \sum_{d=T_a}^{D} \sum_{j} CR_{a,j,m,b,c}\, Z_{d,a,j,s} + N_{m,b,c,s} \geq SA_s \quad \forall \quad m,b,c,s \text{ such that } TH_{m,b,c,s} = 1 \tag{10}$$

$$\sum_{j} \sum_{s} Z_{d,a,j,s} + Y_{d,a} = 1 \quad \forall \quad a \text{ and } d \text{ such that } d \geq T_a \tag{11}$$

$$\sum_{j \in \Omega} \sum_{a} \sum_{s} Z_{d,a,j,s} \leq EOD \quad \forall \quad d \tag{12}$$

$$\sum_{d=t}^{t+\Delta} Y_{d,a} \geq OFF_a \quad \forall \quad a \text{ and } T_a \leq t \leq D - \Delta \tag{13}$$

The objective function, equation (9), minimizes the area not cleared by the MCM assets. Equation (10) is similar to equation (3) in the MCO problem, with the addition of the $N_{m,b,s,c}$ variable to account for the area left uncleared. The remaining equations, (11), (12) and (13) are the same as equations (4), (5) and (6) in the MCO problem.

To solve MCO via MCF, an approximate value of D is selected and the corresponding MCF problem is solved. Because MCF simply seeks a feasible solution to equations (10) to (13), its solution time is relatively quick. For the selected value of D, if MCF yields a zero objective function value; there exists a feasible schedule. In this case the value of D should be decreased and the MCF problem resolved. On the other hand, when MCF yields a positive objective function value, there exists no feasible schedule. Then, D should be increased and the MCF problem resolved. This process continues until the smallest value of D for which the objective function of MCF is zero is found. The details and an example of this process are discussed in the next chapter. Accompanying experiments also demonstrate the efficiency of the process.

IV. THE MINEFIELD OPTIMIZATION TACTICAL DECISION AID MODEL

This chapter describes the implementation of the Minefield Clearance Feasibility Model (MCF) into a scheduling tool called the Minefield Optimization Tactical Decision Aid (MOPTDA). As alluded to in Chapter III, MOPTDA combines the MCF model with a search technique to compute the minimum number of days required to clear minefields. Recall that the models in Chapter III assume that the mine threat is known. When the mine threats are not known with certainty, the technique described in the next chapter can be used to compute the expected number of days to clear the minefields.

A. FINDING AN OPTIMAL INTEGER SOLUTION

To find the minimum number of days, D^*, to clear minefields, the MCF problem must be solved for various values of D, which is the maximum number of days allowed for MCM operations. In particular, D^* is the smallest value of D for which there exists a feasible solution to the MCF problem. To efficiently search for D^*, MOPTDA (i) employs a search technique, (ii) solves the Linear Programming (LP) relaxation of MCF and (iii) uses a heuristic integer restriction. The complete process is stated below.

The Minefield Optimization Tactical Decision Aid (MOPTDA)

Step 1: Set D_{est} to an estimated completion date.

Step 2: Solve the LP relaxation of MCF with $D = D_{est}$. If the objective function equals 0, go to Step 3. Otherwise, set $D_{est} = D_{est} + 1$, and go to Step 4.

Step 3: Set $D_{est} = D_{est} - 1$, and go to Step 2.

Step 4: Solve the MCF problem with $D = D_{est}$ and let $Z^{l}_{d,a,j,s}$ denote the solution.

Step 5: If the objective value of the MCF problem is zero, stop. Otherwise set $D = D_{est} + 1$ and go to Step 7.

Step 6: Solve the MCF problem with $D = D_{est}$ and $Z_{d,a,j,s} = Z^{l}_{d,a,j,s}$ for $d \leq D_{est} - 1$.

Step 7: Set $Z^{l}_{d,a,j,s}$ to the solution obtained in Step 7 and return to Step 6.

Step 1 relies upon a good estimate for D^*. The next chapter describes a mathematical programming problem suitable for obtaining such an estimate. The MCF problems in Steps 4 and 6 contain a small number of binary variables since many are fixed to either 0 or 1. This represents the heuristic restriction in solving the true MCF problem. However, based on our experiments with 200 problems, the process yields a solution within 5% of optimality.

B. IMPLEMENTATION

MOPTDA was implemented in the General Algebraic Modeling System (GAMS) [Ref. 8] and the XA solver [Ref. 9] was used to solve all of the optimization problems. (For the complete listing of this program see Appendix A.) Both GAMS and XA were executed on a 486 33 MHz personal computer with a math coprocessor.

To demonstrate the use and efficiency of MOPTDA, an example MCM operation was created. The example has 4 minefield sectors; each has the same area of 100 nautical miles. Sector 1 and 2 contain contact mines while sectors 3 and 4 contain moored magnetic mines. The MCM task force consists of 4 MH-53E helicopters, 6 MCM1 class ships and 3 EOD teams. Each helicopter requires 2 days to perform maintenance in a seven day cycle. The ships require one day for maintenance in a seven day cycle. The transit time to the minefields is 26 days. For this example, the helicopters and ships can clear moored mines by towing cutters and then destroying the mines with an EOD team. They can also perform acoustic, magnetic and acoustic-magnetic sweeping. Besides these four clearance methods, the model listed in Appendix A allows other MCM techniques such as minehunting with sonar.

As defined in equation (1), the clearance rate of the assets is a function of velocity, sweep width, hours clearing per day and the number of passes required for a given mine threat. Table 1 displays the values for these terms used in the example.

Table 1

EXAMPLE VALUES FOR THE ASSETS' CLEARANCE RATE

Term	Asset Type	Moored Contact Mines	Moored Magnetic Mines With Ship Counter Settings of 1
Velocity	MH-53 Helos	10 Knots	10 Knots
	MCM1 Ships	2.5 Knots	2.5 Knots
Sweep Width	MH-53 Helos	0.1 NM	0.2 NM
	MCM1 Ships	0.1 NM	0.2 NM
Hours/Day Clearing	MH-53 Helos	10	10
	MCM1 Ships	20	20
Passes Required	MH-53 Helos	2	2
	MCM1 Ships	2	2
Clearance Rate	MH-53 Helos	5 NM^2/DAY	10 NM^2/DAY
	MCM1 Ships	2.5 NM^2/DAY	5 NM^2/DAY

Table 1 shows that the clearance rate for helicopters is twice that for ships for the two mine threats examined. Additionally, the clearance rate for the moored magnetic mines was twice the clearance rate of the moored contact mines.

For the above set of input, GAMS/XA produces the output shown in Table 2 in less than 10 minutes on the personal computer mentioned above. Table 2 contains a partial list of all the tasks to be performed on a daily basis for the duration of the operations.

Table 2

SAMPLE MOPTDA OUTPUT

Key: Sector.Job entry display format used
Job 1 is towing cutters and using an EOD team
Job 2 is using acoustic sweeping
Job 3 is using magnetic sweeping
Job 4 is using acoustic magnetic sweeping

Day	MH53-21	MH53-22	MCM1-4	MCM1-5
27	3.3	2.1	4.3	4.3
28	1.1		4.4	3.4
29	2.1	1.1		4.4
30	2.1		3.3	3.4
31		1.1	2.1	2.1
32	1.1	2.1	4.4	4.4
33		2.1	3.4	
34	4.3	2.1	3.4	1.1
35	2.1			3.4
36	2.1		3.4	3.4
37		2.1	4.4	
38	1.1	1.1	1.1	3.4
39	1.1	1.1	4.4	3.4
40		1.1	4.4	4.4

In particular, Table 2 shows the schedules for two helos and two ships. The complete schedule is given in Appendix B. In Table 2, the MCM operation lasts 40 days, 26 of which the assets spend in transit. Each column in Table 2 represents a complete schedule for each asset in the task force. For example, the first entry, 2.1, in the column for

MH53-22 means that the asset is scheduled to tow cutters to clear moored contact mines with an EOD team in sector 2 on day 27. When an asset is scheduled for maintenance downtime, the spaces for those days are left blank, e.g., MH53-21 does maintenance on days 31, 33, 37 and 40.

Given the information in Table 2, the on-scene MCM commander can more efficiently plan MCM operations. When there is a change, e.g., in the availability of assets or, or a change in tactics, input data can be modified and MOPTDA executed again to obtain a new schedule within a few minutes. As demonstrated here, MOPTDA is a useful tool for day-to-day scheduling of MCM operations. However, when planning strategies prior to the actual operations, MOPTDA is not a suitable tool, for it assumes that the mine threats are known with certainty. Most advanced planning involves many uncertainties and a mine threat that cannot be accurately predicted. The next chapter describes a tool which accounts for these uncertainties and is more suitable for advanced planning.

V. MINEFIELD OPTIMIZATION SIMULATION MODEL

To account for the uncertainty in predicting mine threats, this chapter describes a method which embeds the MCO problem within a simulation framework. The method developed is referred to as the Minefield Optimization Simulation (MOPS) model. Figure 4 graphically depicts the simulation framework in MOPS which begins by generating a set of random mine threats. Using these mine threats as input data, the MCO problem is solved approximately and the optimal clearance time is recorded. This process is replicated until a statistically significant amount of data is collected and analyzed. The following section describes the approximate MCO formulation. The second section discusses the implementation of the MOPS model. The third section presents three applications of MOPS, highlighting the use of MOPS as a planning and decision making tool.

A. THE APPROXIMATE MCO FORMULATION

As suggested by Wasburn [Ref. 10], the formulation below removes the index d from the variable Z. Without d, $Z_{d,ajs}$ now represents the total number of days asset a performs job j in sector s. Moreover, the maintenance off-days and available number of EOD teams are accounted for only approximately.

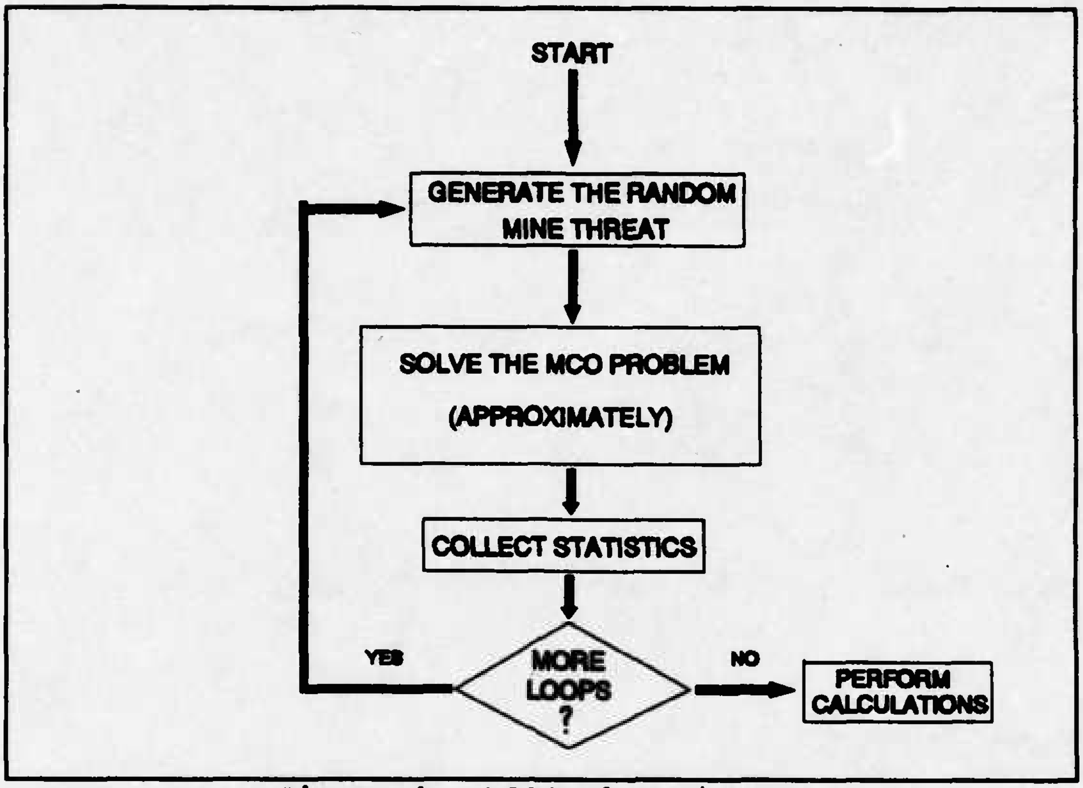

Figure 4. MOPS Flow Diagram

Indices

a	assets
j	jobs
m	mine type, moored or ground
b	activation method
c	the mine's ship counter setting
s	sector

Index Set

Ω = $\{j$: job j requires an EOD team$\}$

Given and Derived Data

EOD	the number of EOD teams available
SA_s	the sector area in nautical square miles
Δ	the operating cycle for each asset in days
OFF_a	the number of days off required during an operating cycle

Given and Derived Data (continued)

M_{big}	a very large positive number (new data)
T_a	the number of travel days required for an asset to arrive at the minefields
T_{min}	the number of travel days until the first assets arrive at the minefields (new data)
$TH_{m,b,c,s}$	a binary (0,1) indicator used to establish which types of mines are in each sector
$CR_{a,j,m,b,c}$	the clearance rate in nautical square miles per day for a given asset and job

Binary Variables

X_a	1,	if that asset arrives soon enough to help clear
	0,	otherwise

Positive Variables

TT	the longest clearance time of all of the assets
$Z_{a,j,s}$	the number of days asset a, performs job j, in sector s

The Minefield Clearance Optimization Approximation (MCOA) Problem

Minimize

$$TT \tag{14}$$

Subject to:

$$TT \geq \sum_{j} \sum_{s} Z_{a,j,s} + T_a X_a \quad \forall a \tag{15}$$

$$\sum_{a} \sum_{j} CR_{a,j,m,b,c} Z_{a,j,s} \frac{(\Delta - Off_a)}{\Delta} \geq SA_s \quad \forall \; m,b,c,s \text{ such that } TH_{m,b,c,s} = 1 \tag{16}$$

$$\sum_{a} \sum_{j \in \Omega} \sum_{s} Z_{a,j,s} \frac{(\Delta - Off_a)}{\Delta} \leq EOD\,(TT - T_{min}) \tag{17}$$

$$\sum_{j} \sum_{s} Z_{a,j,s} \leq X_a M_{big} \quad \forall \; a \tag{18}$$

In the above formulation, equation (14) minimizes the number of days needed to clear all of the mined sectors. Equation (15) determines which asset requires the longest time to complete its clearance tasks. The left hand side of equation (16) defines the total area cleared by assets with off days also taken into account. To ensure that all sectors are cleared, this total area must be greater than or equal to the area of the sectors. Equation (17) limits the number of EOD teams used to the number of EOD teams available. When X_a is assigned a value of one, equation (18) allows asset *a* to be used for the operation. Otherwise, equation (18) forces $Z_{a,j,s}$ to zero for all *j* and *s*.

B. IMPLEMENTATION

As in Chapter IV, MOPS was implemented using GAMS and XA on the same 486 33 MHz personal computer (see Appendix C). The approximation of MCO using the MCOA model yields solutions within one day of the optimal clearance time in 100 replications. Whenever MCOA provides a fractional clearance time, its ceiling is recorded for statistical calculations. For these 100 replications, our implementation of MOPS took 42 minutes on the personal computer.

The example mine clearance problem described in Chapter IV is used to illustrate the statistical analysis performed by MOPS. The random mine threat for each sector is generated according to the following probabilities:

1) Mine types:

P[ground mines] = P[moored mines] = 50%.

2) Activation Methods:

P[acoustic] = P[magnetic] = P[acoustic/magnetic] = P[contact] = 25%

3) Ship Counter Settings:

For contact mines, the ship counter setting is 1.

For all other activation methods:

P[ship counter setting = 1] = 90%

P[ship counter setting = 5] = 8%

P[ship counter setting = 20] = 2%

The results from 100 replications of the example problem are partially displayed in Table 3 and summarized as a histogram in Figure 5. As shown in Table 3, sample mean clearance time and sample standard deviation are 37.2 days and 2.8 days respectively.

Table 3

SELECTED RESULTS OF MOPS FOR THE BASIC SCENARIO

Key: MOR ... Moored Mines
GND ... Ground Mines
MA .... Magnetic-Acoustic activation method
CT .... Contact activation method
MG .... Magnetic activation method
AC .... Acoustic activation method
1 .... Ship counter setting of one
5 .... Ship counter setting of five

Run #	Clearance Time	Threat: Sector 1	Sector 2	Sector 3	Sector 4
1	37	MOR MA 1	MOR MG 1	MOR MA 1	GND MA 1
2	39	GND MA 1	MOR CT 1	GND MG 1	MOR CT 1
3	36	GND MA 1	GND MA 1	MOR AC 1	GND MG 1
...					
13	50	MOR CT 1	MOR CT 1	MOR CT 1	MOR CT 1
...					
23	32	GND MG 1	MOR MG 1	MOR MG 1	MOR AC 1
...					
100	39	MOR MA 1	GND MA 1	MOR AC 5	MOR MA 5

Average time to clear the mined areas = 37.2
Standard deviation of the clearance times = 2.8

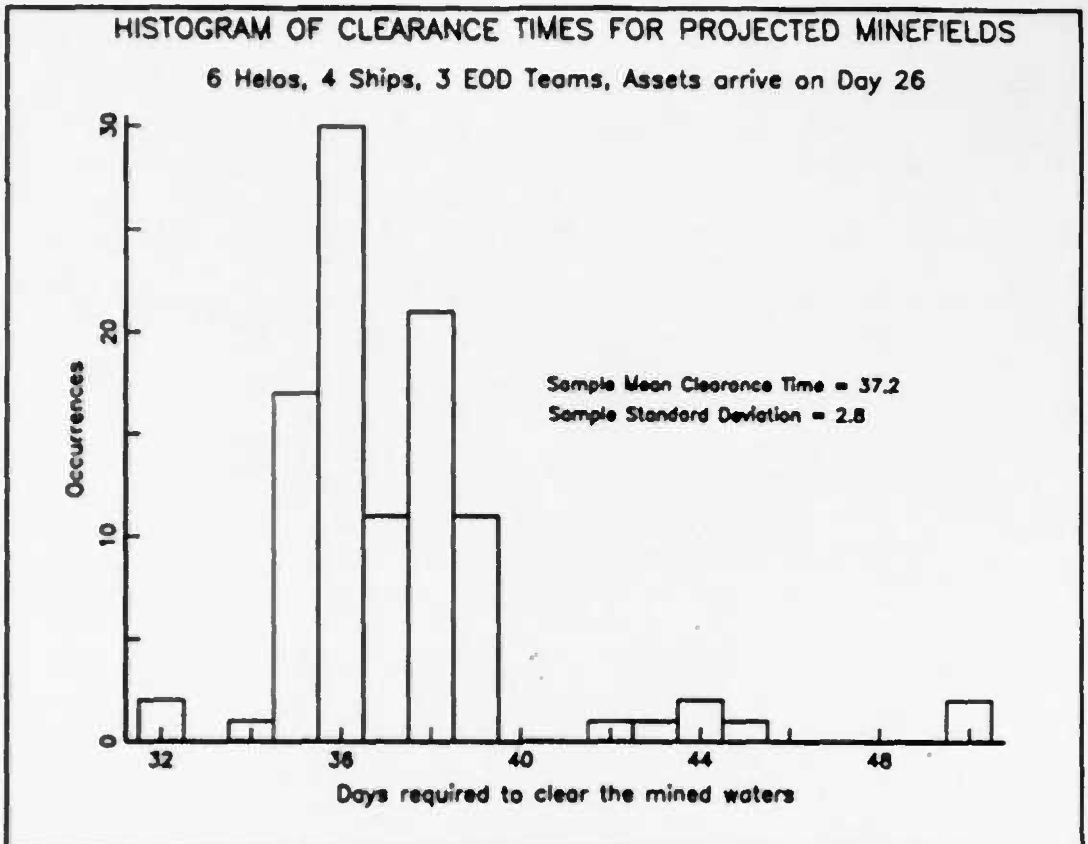

Figure 5. Histogram of the Clearance Days for the Basic Scenario

Assuming normality, a one sided confidence interval is given by,

$$L = \textit{Sample Mean Clearance Time} + \frac{(S)\ t_{1-\alpha}}{\sqrt{R}} \tag{19}$$

where L is the one sided confidence interval value,
S is the sample standard deviation
t indicates the T distribution,
α is the percent not under the curve, for a
95% confidence interval α is 0.5 and
R is the number of replications run.
[Ref. 11, p. 385]

Based on the results shown in Table 3, the 90% and 95% confidence intervals are

L = 37.6 days and L = 37.7 days respectively. However, similar intervals can also be obtained directly from the histogram. Observe that approximately 90% of the replications have a clearance time of less than or equal to 39 days. Thus based on the histogram, the 90% confidence interval is 39. Similar calculations show that the histogram yields a 95% confidence interval of 43 days. The discrepancies in the two sets of confidence intervals can be attributed to the normality assumption assumed in equation (14).

C. APPLICATIONS

This section describes how MOPS can be used to provide insights into the issues raised in Chapter 1.

1. The Advantage of having an Additional EOD Team

Rear Admiral John Pearson, Commander, Mine Warfare Command, in a lecture at the Naval Postgraduate School [Ref. 12] stated that future MCM task forces would consist of four MH-53E helicopters, six MCM ships and three EOD teams. This task force was used in the example problems to test MOPTDA and MOPS. Close analysis of Table 3 shows that the longest clearance times were required to clear a mine threat consisting of all moored contact mines. This result occurred due to the constraint on the number of EOD teams available. Having only three EOD teams left seven MCM assets idle on any given day. To determine the impact of one additional EOD team, MOPS was executed with three and four EOD teams with the probabilistic mine threat described in Section A. The results of this comparison are summarized in Table 4.

Table 4

THE BENEFITS OF ONE EXTRA EOD TEAM

Property	3 EOD Teams	4 EOD Teams
Sample Mean Clearance Time	37.2 days	36.6 days
Sample Standard Deviation	2.8 days	2.1 days
Graphical 90% CI for clearance	≤ 39 days	≤ 38 days
Graphical 95% CI for clearance	≤ 43 days	≤ 41 days
Longest sample clearance time	50 days	46 days

Table 4 shows that one additional EOD team the average minimum clearance time by about one half a day.

Keep in mind that the results of Table 4, and the remaining tables in this chapter are based on fictitious data. They are displayed here for illustration. Any concrete recommendation based on these results would be meaningless.

2. The Advantage of Forward Deployment

Congress has authorized funding for the conversion of an amphibious helicopter carrier into a mine countermeasures helicopter support (MCS) ship. As the defense budget dwindles this program will have to be justified. This example evaluates the benefits of having a forward deployed MCS ship which can get helicopters clearing mines by Day 9. Recall that the transit time for all assets is 26 days for the scenario in Section A. The MOPS results are shown in Table 5.

Table 5

THE BENEFITS OF FORWARD DEPLOYING HELICOPTERS ON A MCS SHIP

Property	Basic Scenario Arrive Day 26	Fwd. Deployed MCS Ship Helos arrive Day 8
Sample Mean Clearance Time	37.2 days	27.2 days
Standard Sample Deviation	2.8 days	2.5 days
Graphical 90% CI for clearance	≤ 39 days	≤ 30 days
Graphical 95% CI for clearance	≤ 43 days	≤ 31 days
Longest sample clearance time	50 days	33 days

Based on our fictitious data, the impact of forward deploying the helicopters is the savings of ten days. These ten additional days of not having control of the seas could easily tilt the balance of a battle.

3. Laser Search Equipment Versus Two Additional MCM1 Ships

Constraints on the defense budget will put the squeeze on research and development (R&D) as well as procurement. This example compares the benefit of supporting a program which promises the doubling of clearance rates by first locating mines using lasers against buying two additional MCM1 class ships. The costs of both programs are considered equal in this example. In one MOPS run, the clearance rate was doubled for all of the assets. The other MOPS run added two additional ships arriving on Day 27. The results of the two MOPS runs are shown in Table 6.

Table 6

COMPARING AN R&D PROPOSAL AGAINST TWO ADDITIONAL SHIPS

Property	R&D which doubles the clearance rate	Adding two extra MCM1 ships
Sample Mean Clearance Time	31.5 days	35.9 days
Sample Standard Deviation	1.5 days	3.4 days
Graphical 90% CI for clearance	≤ 33 days	≤ 39 days
Graphical 95% CI for clearance	≤ 35 days	≤ 42 days
Longest sample clearance time	38 days	50 days

Based on our fictitious data, funding R&D to double the clearance rate is more beneficial than buying two more ships.

VI. CONCLUSIONS AND RECOMMENDATIONS

This thesis develops two tools to improve mine countermeasures operations. The first tool, the Minefield Optimization Tactical Decision Aid (MOPTDA), improves the efficiency of MCM operations by providing a detailed schedule for the MCM assets to clear the mined waters in the shortest possible time. MOPTDA is designed to be used on-location by the MCM commander to accurately predict how long mines will deny the Navy control of the sea. The second tool, the Minefield Optimization Simulation (MOPS) model, combines optimization and simulation techniques to predict clearance times accounting for the uncertainty in the mine threat. MOPS provides decision makers with a planning tool to answer strategic questions which will shape the future of the mine countermeasures community.

This thesis contributes to the mine warfare community in three areas. First, prior to this study, optimization techniques had not been applied to scheduling mine warfare assets or to evaluate their efficiency [Ref. 13]. MOPTDA and MOPS both use the time to complete mine clearance operations as their measure of efficiency while accounting for the travel time required for the assets to arrive at the minefields and the maintenance downtime required by the assets. Second, this thesis develops a solution technique to reduce the solution time of the MCO problem from over thirty hours to less than ten minutes. Finally, MOPS introduces a unique way of combining optimization and simulation to account for the uncertainty in the potential mine threats.

The results of this study also point out potential applications and several research topics for further investigation. The potential applications are not included in this study because of lack of data as well as the desire to maintain the thesis at the unclassified level.

A. POTENTIAL APPLICATIONS

1. Determining the Optimal Mix of AMCM and SMCM Assets

To determine an optimal mix of helicopters (AMCM) and ships (SMCM), MOPS must be run for various combinations of AMCM and SMCM assets to develop a graph similar to the one shown in Figure 6. For the example shown in Figure 6, the cost effective mix for MCM assets is three ships and three helicopters if a fifty day clearance rate is acceptable. Generation of this graph using the actual MCM characteristics with a projected mine threat will allow decision makers to determine the optimal mix for the MCM complement in the Expeditionary Task Force as well as which new construction projects to fund in the future.

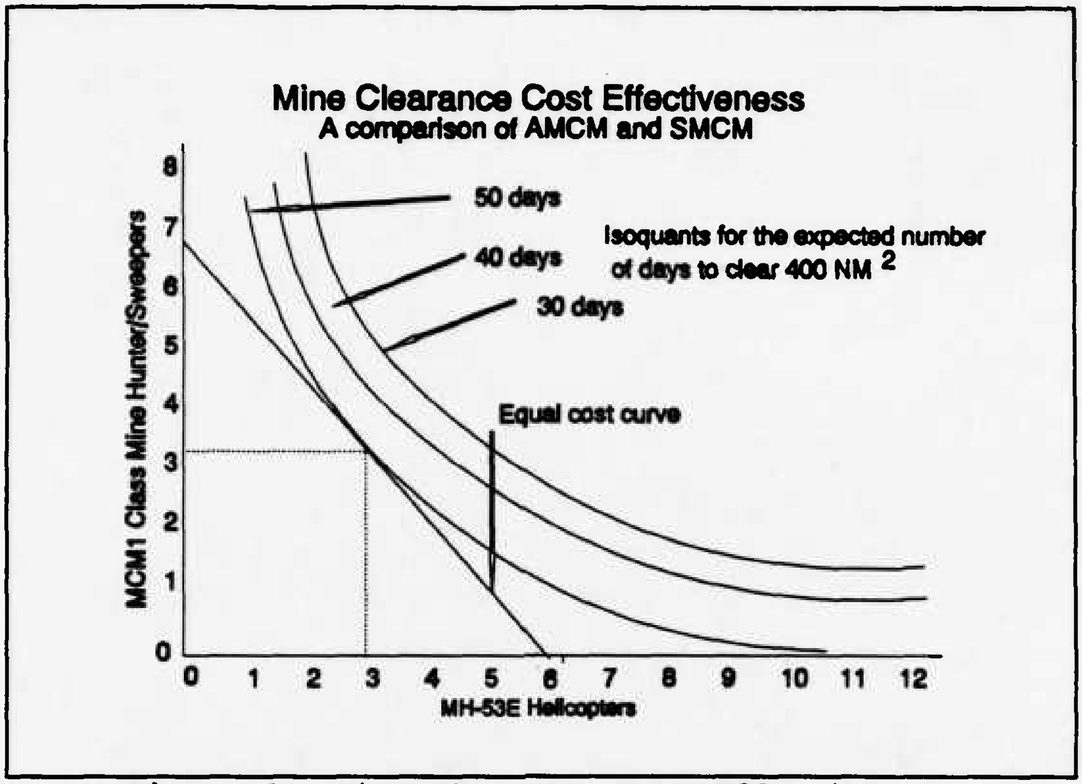

Figure 6. Mine Clearance Cost Effectiveness

2. Mine Laying Tactics

Another application of MOPS involves using the model to increase the effectiveness of mine warfare by determining which mine threats can prolong the enemy's mine clearance the longest. Using the fictitious scenario developed for this thesis, MOPS shows that laying only contact mines will delay mine clearance the longest. The MOPS model can also be made to determine when minefields should be reseeded and which sensitivity setting should be used in the mines in order to best delay the enemy's mine clearance operations.

B. TOPICS FOR RESEARCH

1) Desert Storm pointed out the Navy's weakness in clearing mines in very shallow water. These areas extend from a depth of 40 feet into the surf zone. [Ref. 7, p. 7] New technology must be developed to overcome this problem. The concepts and methods developed in this thesis can be used to identify programs with the most potential to improve MCM operations in shallow water.

2) The validity of the results generated by MOPTDA and MOPS, is dependent on the accuracy of the data base. The analysis of the mine clearance data from Desert Storm, now being performed at the Center For Naval Analysis, should be compared against the MCM capabilities determined through operational testing at the Coastal Systems Station.

3) Similarly, the validity of the results generated by MOPTDA and MOPS is dependent on the quality of the mine threat intelligence. Enemy mine threat capabilities must be studied to determine the proper probabilities for the mine threats of future adversaries.

In summary, MOPTDA and MOPS provide the mine warfare community with tools to improve the efficiency of MCM assets in both their tactical and strategic employments.

APPENDIX A MOPTDA PROGRAM LISTING

```
$TITLE   The MOPTDA Model
*------------- GAMS AND DOLLAR CONTROL OPTIONS ---------------------
$OFFUPPER OFFSYMLIST OFFSYMXREF
OPTIONS
   INTEGER1 = 6,
   LIMCOL = 0,     LIMROW  = 0,     SOLPRINT = OFF,  DECIMALS = 1
   RESLIM =3600, ITERLIM =900000,   OPTCR   = 0.05,  SEED    = 3141;

*---------------- INTRODUCTION -------------------------------------
$ONTEXT

THE MINEFIELD CLEARANCE OPTIMIZATION TACTICAL DECISION AID MODEL
                           (In GAMS Format)

LT R. Chandler Swallow, USN                                 FEB 93

     This program determines the minimum length
of time required to clear a minefield.  The output of this
program shows what each asset would do each day until the
minefield is cleared.  This model assumes the assets are not on
the minefield location when initially required and thus must
travel to the hotspot.

     This is an unclassified model used to prove the feasibility of
the problem in general.  This model is not comprehensive as written:
all possible scenarios are not accounted for.  Minor modifications
of the data tables, however, will easily allow adaptation to new
threats and new technology.

     Applications of this program include:
          i.  Use as a combined MCM Tactical Decision Aid
         ii.  Use for weekly taskings during mine clearance
              operations as accurate sweeping data becomes
              available.
$OFFTEXT

*---------------- DEFINITIONS AND DATA ----------------------------

*----------------------- SETS --------------------------------------
SETS
     D /DAY1 * DAY60/
*                  Where D - The maximum number of days available to
*                            complete the mission.  If the available
*                            assets cannot complete the mission in
*                            this time period a variable NC (stands
*                            for Not Complete) will have a value for
*                            the mine threat area unswept.
```

```
    A                Where A - The specific assets available for the
*                              mission
     / MH53-21
       MH53-22
       MH53-23
       MH53-24
       MCM1-2
       MCM1-3
       MCM1-4
       MCM1-5
       MCM1-6
       MCM1-7 /

    J
*                    Where J - The asset's job that day
     / CUT-EOD             mech cutters and eod
       ACU                 acoustic sweep
       MAG                 magnetic sweep
       M-A                 magnetic and acoustic sweep
       SNR-EOD             sonar and eod hunting
       SNR-ROV             sonar and remotely operated vehicle hunting
       OFFDAY              default tasking value /

    JE(J)
*                    Where JE - Jobs that require EOD
     / CUT-EOD,SNR-EOD /


    MT /MOR, GRND/
*                          Where MT    - Mine types
*                                MOR   - Moored Mines
*                                GRND  - Ground/Bottom Mines

    AM /CT, MG, AC, MA/
*                          Where AM   - Activation method
*                                CT  - Contact
*                                MG  - Magnetic
*                                AC  - Acoustic
*                                MA  - Magnetic and acoustic

    SC /1,5,20/
*                          Where SC - Shipcounter set in the mine
*                                 1 - Used for immediate activation
*                                 5 - Used to provide some counter MCM
*                                20 - Used to provide more counter MCM

    S /S1*S4/
*                         Where  S - Sector to be cleared

    I /ITER-1*ITER-10/
*                    Where I - Used for iterations

ALIAS(D,D1);
*                         Where D1 - is also day of the operation and
*                                    is used in the OPTEMP constraint
```

```
*------------------- SCALARS ------------------------------------
SCALARS
    BIGM      used to control z in the relaxation model /99/
    EODAVAIL  number of eod teams available /3/
    MINTRAVL  the value of the shortest travel time /26/
    GOODRUNS  a summation of the number of satisfactory replications
    CHECK     used for a loop termination control /0/
    BOUND     used for a loop termination control /711/
    NOTSWEPT  that amount of threat area not cleared /99999/
    LASTDAY   last day used to clear mines ;

*-------------------- PARAMETERS --------------------------------
PARAMETERS

AREA(S)
*       Where AREA(S) - The sector area in square nautical miles

                 / S1    100
                   S2    100
                   S3    100
                   S4    100 /

CYCLE(A)
*       Where CYCLE(A) - The operating cycle for each asset in days

               / MH53-21     7
                 MH53-22     7
                 MH53-23     7
                 MH53-24     7
                 MCM1-2      7
                 MCM1-3      7
                 MCM1-4      7
                 MCM1-5      7
                 MCM1-6      7
                 MCM1-7      7 /

OFF(A)
*       Where OFF(A) - The number of days off required for maint-
*                      enance and crew rest during the operating
*                      cycle per asset.
               / MH53-21     2
                 MH53-22     2
                 MH53-23     2
                 MH53-24     2
                 MCM1-2      1
                 MCM1-3      1
                 MCM1-4      1
                 MCM1-5      1
                 MCM1-6      1
                 MCM1-7      1 /

TRAVTIME(A)
*     Where TRAVTIME(A) - The number of travel days required for the
*                         asset to get to the minefield.  Certain
*                         things must be kept in mind; the time for
*                         helos to get there must include the time
*                         for a base to be ready, which might in-
*                         clude the time to get an LHA on location
*                         if no land base was available in the
*                         region.  Nautical mile distances from
```

```
*                                   Texas to the Persian Gulf is approximately
*                                   8500 NM by sea.  If those ships must go
*                                   around the Cape of Good Hope the distance
*                                   is 12000 NM.  Miles traveled in a day are
*                                   approximately 1000 NM by air and 300 NM
*                                   by sea.

                     / MH53-21     26
                       MH53-22     26
                       MH53-23     26
                       MH53-24     26
                       MCM1-2      26
                       MCM1-3      26
                       MCM1-4      26
                       MCM1-5      26
                       MCM1-6      26
                       MCM1-7      26 /

HOURS(A)
*  Where Hours(A) - The number of hours per day an asset can perform
*                   MCM operations

                     / MH53-21     10
                       MH53-22     10
                       MH53-23     10
                       MH53-24     10
                       MCM1-2      20
                       MCM1-3      20
                       MCM1-4      20
                       MCM1-5      20
                       MCM1-6      20
                       MCM1-7      20 / ;

*-------------------- TABLES ----------------------------------
TABLE     THREAT(MT,AM,SC,S)
* Where THREAT(MT,AM,SC,S) - A binary mine threat table which has a
*                            1 where a threat of a certain mine type
*                            (MT), activation method (AM), ship
*                            counter (SC), is in a given sector (S).

              S1        S2        S3        S4
MOR.CT.1      1
MOR.MG.1      1         1
MOR.AC.1      1         1
MOR.MA.1                1                   1
GRND.MG.1                         1
GRND.AC.1                         1
GRND.MA.1                         1         1
MOR.MG.5
MOR.AC.5
MOR.MA.5
GRND.MG.5
GRND.AC.5
GRND.MA.5
MOR.MG.20
MOR.AC.20
MOR.MA.20
GRND.MG.20
GRND.AC.20
GRND.MA.20                   ;
```

```
TABLE
     VELOCITY(A,J)
*       Where VELOCITY(A,J) - A table of velocities in nautical
*                             miles per hour for each asset
*                             performing each job that it is
*                             capable of performing.

             CUT-EOD  ACU  MAG  M-A  SNR-EOD  SNR-ROV
     MH53-21    10     10   10   8
     MH53-22    10     10   10   8
     MH53-23    10     10   10   8
     MH53-24    10     10   10   8
     MCM1-2     2.5   2.5  2.5   2     1.5     1.25
     MCM1-3     2.5   2.5  2.5   2     1.5     1.25
     MCM1-4     2.5   2.5  2.5   2     1.5     1.25
     MCM1-5     2.5   2.5  2.5   2     1.5     1.25
     MCM1-6     2.5   2.5  2.5   2     1.5     1.25
     MCM1-7     2.5   2.5  2.5   2     1.5     1.25 ;

TABLE
     SWEEPWIDTH(A,J)
* Where SWEEPWIDTH(A,J) - A table of sweepwidths in nautical miles
*                         for each asset performing each job that it
*                         is capable of performing.

               CUT-EOD  ACU  MAG  M-A  SNR-EOD  SNR-ROV
     MH53-21       .1    .2   .2   .1
     MH53-22       .1    .2   .2   .1
     MH53-23       .1    .2   .2   .1
     MH53-24       .1    .2   .2   .1
     MCM1-2        .1    .2   .2   .1     .1       .1
     MCM1-3        .1    .2   .2   .1     .1       .1
     MCM1-4        .1    .2   .2   .1     .1       .1
     MCM1-5        .1    .2   .2   .1     .1       .1
     MCM1-6        .1    .2   .2   .1     .1       .1
     MCM1-7        .1    .2   .2   .1     .1       .1 ;

TABLE
     PASSES(A,J,MT,AM,SC)
* Where PASSES(A,J,MT,AM,SC) - A table of the number of passes
*                              required for each asset to clear a
*                              threat to a given clearance level
*                              with that job.  Revised for the errors
*                              with CUT-EOD.

                    MOR.CT.1 MOR.MG.1 MOR.AC.1 MOR.MA.1 GRND.MG.1
MH53-21.CUT-EOD        2        2        2        2
MH53-22.CUT-EOD        2        2        2        2
MH53-23.CUT-EOD        2        2        2        2
MH53-24.CUT-EOD        2        2        2        2
MCM1-2.CUT-EOD         2        2        2        2
MCM1-3.CUT-EOD         2        2        2        2
MCM1-4.CUT-EOD         2        2        2        2
MCM1-5.CUT-EOD         2        2        2        2
MCM1-6.CUT-EOD         2        2        2        2
MCM1-7.CUT-EOD         2        2        2        2
MH53-21.ACU                              2
MH53-22.ACU                              2
MH53-23.ACU                              2
MH53-24.ACU                              2
```

MCM1-2.ACU		2		
MCM1-3.ACU		2		
MCM1-4.ACU		2		
MCM1-5.ACU		2		
MCM1-6.ACU		2		
MCM1-7.ACU		2		
MH53-21.MAG	2			2
MH53-22.MAG	2			2
MH53-23.MAG	2			2
MH53-24.MAG	2			2
MCM1-2.MAG	2			2
MCM1-3.MAG	2			2
MCM1-4.MAG	2			2
MCM1-5.MAG	2			2
MCM1-6.MAG	2			2
MCM1-7.MAG	2			2
MH53-21.M-A	2	2	2	2
MH53-22.M-A	2	2	2	2
MH53-23.M-A	2	2	2	2
MH53-24.M-A	2	2	2	2
MCM1-2.M-A	2	2	2	2
MCM1-3.M-A	2	2	2	2
MCM1-4.M-A	2	2	2	2
MCM1-5.M-A	2	2	2	2
MCM1-6.M-A	2	2	2	2
MCM1-7.M-A	2	2	2	2
MCM1-2.SNR-EOD	1	1	1	1
MCM1-3.SNR-EOD	1	1	1	1
MCM1-4.SNR-EOD	1	1	1	1
MCM1-5.SNR-EOD	1	1	1	1
MCM1-6.SNR-EOD	1	1	1	1
MCM1-7.SNR-EOD	1	1	1	1
MCM1-2.SNR-ROV				1
MCM1-3.SNR-ROV				1
MCM1-4.SNR-ROV				1
MCM1-5.SNR-ROV				1
MCM1-6.SNR-ROV				1
MCM1-7.SNR-ROV				1

+	GRND.AC.1	GRND.MA.1	MOR.MG.5	MOR.AC.5	MOR.MA.5
MH53-21.CUT-EOD			2	2	2
MH53-22.CUT-EOD			2	2	2
MH53-23.CUT-EOD			2	2	2
MH53-24.CUT-EOD			2	2	2
MCM1-2.CUT-EOD			2	2	2
MCM1-3.CUT-EOD			2	2	2
MCM1-4.CUT-EOD			2	2	2
MCM1-5.CUT-EOD			2	2	2
MCM1-6.CUT-EOD			2	2	2
MCM1-7.CUT-EOD			2	2	2
MH53-21.ACU	2			8	
MH53-22.ACU	2			8	
MH53-23.ACU	2			8	
MH53-24.ACU	2			8	
MCM1-2.ACU	2			7	
MCM1-3.ACU	2			7	
MCM1-4.ACU	2			7	
MCM1-5.ACU	2			7	
MCM1-6.ACU	2			7	
MCM1-7.ACU	2			7	

MH53-21.MAG			8		
MH53-22.MAG			8		
MH53-23.MAG			8		
MH53-24.MAG			8		
MCM1-2.MAG			7		
MCM1-3.MAG			7		
MCM1-4.MAG			7		
MCM1-5.MAG			7		
MCM1-6.MAG			7		
MCM1-7.MAG			7		
MH53-21.M-A	2	2	9	9	9
MH53-22.M-A	2	2	9	9	9
MH53-23.M-A	2	2	9	9	9
MH53-24.M-A	2	2	9	9	9
MCM1-2.M-A	2	2	8	8	8
MCM1-3.M-A	2	2	8	8	8
MCM1-4.M-A	2	2	8	8	8
MCM1-5.M-A	2	2	8	8	8
MCM1-6.M-A	2	2	8	8	8
MCM1-7.M-A	2	2	8	8	8
MCM1-2.SNR-EOD	1	1	1	1	1
MCM1-3.SNR-EOD	1	1	1	1	1
MCM1-4.SNR-EOD	1	1	1	1	1
MCM1-5.SNR-EOD	1	1	1	1	1
MCM1-6.SNR-EOD	1	1	1	1	1
MCM1-7.SNR-EOD	1	1	1	1	1
MCM1-2.SNR-ROV	1	1			
MCM1-3.SNR-ROV	1	1			
MCM1-4.SNR-ROV	1	1			
MCM1-5.SNR-ROV	1	1			
MCM1-6.SNR-ROV	1	1			
MCM1-7.SNR-ROV	1	1			

+	GRND.MG.5	GRND.AC.5	GRND.MA.5	MOR.MG.20	MOR.AC.20
MH53-21.CUT-EOD				2	2
MH53-22.CUT-EOD				2	2
MH53-23.CUT-EOD				2	2
MH53-24.CUT-EOD				2	2
MCM1-2.CUT-EOD				2	2
MCM1-3.CUT-EOD				2	2
MCM1-4.CUT-EOD				2	2
MCM1-5.CUT-EOD				2	2
MCM1-6.CUT-EOD				2	2
MCM1-7.CUT-EOD				2	2
MH53-21.ACU		8			28
MH53-22.ACU		8			28
MH53-23.ACU		8			28
MH53-24.ACU		8			28
MCM1-2.ACU		7			26
MCM1-3.ACU		7			26
MCM1-4.ACU		7			26
MCM1-5.ACU		7			26
MCM1-6.ACU		7			26
MCM1-7.ACU		7			26
MH53-21.MAG	8			28	
MH53-22.MAG	8			28	
MH53-23.MAG	8			28	
MH53-24.MAG	8			28	
MCM1-2.MAG	7			26	
MCM1-3.MAG	7			26	

MCM1-4.MAG	7			26	
MCM1-5.MAG	7			26	
MCM1-6.MAG	7			26	
MCM1-7.MAG	7			26	
MH53-21.M-A	9	9	9	28	28
MH53-22.M-A	9	9	9	28	28
MH53-23.M-A	9	9	9	28	28
MH53-24.M-A	9	9	9	28	28
MCM1-2.M-A	7	7	7	26	26
MCM1-3.M-A	7	7	7	26	26
MCM1-4.M-A	7	7	7	26	26
MCM1-5.M-A	7	7	7	26	26
MCM1-6.M-A	7	7	7	26	26
MCM1-7.M-A	7	7	7	26	26
MCM1-2.SNR-EOD	1	1	1	1	1
MCM1-3.SNR-EOD	1	1	1	1	1
MCM1-4.SNR-EOD	1	1	1	1	1
MCM1-5.SNR-EOD	1	1	1	1	1
MCM1-6.SNR-EOD	1	1	1	1	1
MCM1-7.SNR-EOD	1	1	1	1	1
MCM1-2.SNR-ROV	1	1	1		
MCM1-3.SNR-ROV	1	1	1		
MCM1-4.SNR-ROV	1	1	1		
MCM1-5.SNR-ROV	1	1	1		
MCM1-6.SNR-ROV	1	1	1		
MCM1-7.SNR-ROV	1	1	1		

+	MOR.MA.20	GRND.MG.20	GRND.AC.20	GRND.MA.20
MH53-21.CUT-EOD	2			
MH53-22.CUT-EOD	2			
MH53-23.CUT-EOD	2			
MH53-24.CUT-EOD	2			
MCM1-2.CUT-EOD	2			
MCM1-3.CUT-EOD	2			
MCM1-4.CUT-EOD	2			
MCM1-5.CUT-EOD	2			
MCM1-6.CUT-EOD	2			
MCM1-7.CUT-EOD	2			
MH53-21.ACU			27	
MH53-22.ACU			27	
MH53-23.ACU			27	
MH53-24.ACU			27	
MCM1-2.ACU			26	
MCM1-3.ACU			26	
MCM1-4.ACU			26	
MCM1-5.ACU			26	
MCM1-6.ACU			26	
MCM1-7.ACU			26	
MH53-21.MAG		27		
MH53-22.MAG		27		
MH53-23.MAG		27		
MH53-24.MAG		27		
MCM1-2.MAG		26		
MCM1-3.MAG		26		
MCM1-4.MAG		26		
MCM1-5.MAG		26		
MCM1-6.MAG		26		
MCM1-7.MAG		26		
MH53-21.M-A	28	28	28	28
MH53-22.M-A	28	28	28	28

```
MH53-23.M-A          28        28        28        28
MH53-24.M-A          28        28        28        28
MCM1-2.M-A           26        26        26        26
MCM1-3.M-A           26        26        26        26
MCM1-4.M-A           26        26        26        26
MCM1-5.M-A           26        26        26        26
MCM1-6.M-A           26        26        26        26
MCM1-7.M-A           26        26        26        26
MCM1-2.SNR-EOD        1         1         1         1
MCM1-3.SNR-EOD        1         1         1         1
MCM1-4.SNR-EOD        1         1         1         1
MCM1-5.SNR-EOD        1         1         1         1
MCM1-6.SNR-EOD        1         1         1         1
MCM1-7.SNR-EOD        1         1         1         1
MCM1-2.SNR-ROV                  1         1         1
MCM1-3.SNR-ROV                  1         1         1
MCM1-4.SNR-ROV                  1         1         1
MCM1-5.SNR-ROV                  1         1         1
MCM1-6.SNR-ROV                  1         1         1
MCM1-7.SNR-ROV                  1         1         1    ;

PARAMETER CLEARRATE(A,J,MT,AM,SC);
*  Where CLEARRATE(A,J,MT,AM,SC) - A table of clearance rates for a
*  given asset clearing the area to a certain clearance level for a
*  given threat in nautical square miles per day.  This table gets
*  generated automatically.  An example follows.
* The actual table is generated with the code below and can be part
* of the output listing by removing the * from in front of the
* DISPLAY CLEARRATE.

OPTION CLEARRATE:1:2:3;
     CLEARRATE(A,J,MT,AM,SC) =
     (HOURS(A)*VELOCITY(A,J)*SWEEPWIDTH(A,J)/PASSES(A,J,MT,AM,SC))$
                               (PASSES(A,J,MT,AM,SC) GT 0);
*  DISPLAY CLEARRATE;

$ONTEXT
----------  A LIMITED EXAMPLE OF A CLEARRATE TABLE  --------------
TABLE
     CLEARRATE(A,J,MT,AM,SC) clearance rate for percent clearance
                             level and ship count by each platform/
                             system on each type of mine

                 MOR.CT.1 MOR.MG.1 MOR.AC.1 MOR.MA.1 GRND.MG.1
MH53-21.CUT-EOD     5        5        5        5
MH53-22.CUT-EOD     5        5        5        5
MH53-21.ACU                          10
MH53-22.ACU                          10
MH53-21.MAG                 10                          10
MH53-22.MAG                 10                          10
MH53-21.M-A                  4        4        4         4
MH53-22.M-A                  4        4        4         4
MCM1-2.CUT-EOD     2.5      2.5      2.5      2.5
MCM1-3.CUT-EOD     2.5      2.5      2.5      2.5
MCM1-2.ACU                            5
MCM1-3.ACU                            5
MCM1-2.MAG                   5                           5
MCM1-3.MAG                   5                           5
MCM1-2.M-A                   2        2        2         2
MCM1-3.M-A                   2        2        2         2
```

```
MCM1-2.SNR-EOD                3        3        3        3
MCM1-3.SNR-EOD                3        3        3        3
MCM1-2.SNR-ROV                                           2.5
MCM1-3.SNR-ROV                                           2.5
$OFFTEXT

PARAMETER KEY(J)
*  Where KEY - The code number for each job to help read the output
        /CUT-EOD     1
         ACU         2
         MAG         3
         M-A         4
         SNR-EOD     5
         SNR-ROV     6
         OFFDAY      7 /;

*________________________ Variables ____________________________________
POSITIVE VARIABLE
     TT  the longest required total clearance time
     Z(A,J,S)  the number of days the asset must spend on a threat
     NC(MT,AM,SC,S)  the amount of the clearance task not completed;
*                    in square nautical miles for each threat.
     NC.FX(MT,AM,SC,S) $(THREAT(MT,AM,SC,S) EQ 0) = 0 ;

VARIABLE
     OBJVAL  objective value for the minimum total clearance time
     COST the max cost objective which will always be feasible;

BINARY VARIABLE
     X(A)  one if that asset arrives soon enough to help clear
     Z1(D,A,J,S) ;
*    one if that asset is used for that job that day in that sector

*_____________________ Equations _____________________________________
EQUATIONS
* for the Relaxation Model
  OBJ  the objective function to minimize clearance time
  MAXCOST(A)  determines the longest clearing asset
  CLEAR(MT,AM,SC,S)  ensures all minefields are cleared
  EODUSE  accounts for the number of divers available
  COVER(A)  sets z to zero if that asset arrives to late

* for the TDA Model
  MINCOST the cost in days for the minefields to be swept
  CLEAR1(MT,AM,SC,S) ensure all minefields are cleared
  USE1(D,A) each day each asset must have only one job
  EODUSE1(D) jobs requiring eod must not exceed the teams available
  OPTEMP(D,A)   force mcm assets to take off days ;
```

```
*____________ The Relaxation Model Objective Function _______________

*minimize
OBJ..           OBJVAL =E= TT ;

*------ Subject to the Relaxation Model Constraints ----------------
MAXCOST(A).. TT =G= SUM((J,S), Z(A,J,S)) + TRAVTIME(A)*X(A) ;

CLEAR(MT,AM,SC,S)$(THREAT(MT,AM,SC,S) EQ 1).. AREA(S) =L=

SUM((A,J),CLEARRATE(A,J,MT,AM,SC)*Z(A,J,S)*(CYCLE(A)-OFF(A))/CYCLE(A)) ;

EODUSE.. EODAVAIL*(TT - MINTRAVL)
         =G= SUM((A,JE,S), Z(A,JE,S)*(CYCLE(A)-OFF(A))/CYCLE(A)) ;

COVER(A).. X(A)*BIGM =G= SUM((J,S), Z(A,J,S)) ;

MODEL MINEOP /OBJ, MAXCOST, CLEAR, EODUSE, COVER/;


*____________ The TDA Model Objective Function _______________

MINCOST.. COST =E= LASTDAY + 1000*SUM((MT,AM,SC,S)
          $(THREAT(MT,AM,SC,S) EQ 1), NC(MT,AM,SC,S)) ;

*--------- Subject to the TDA Model Constraints ----------------

CLEAR1(MT,AM,SC,S)$(THREAT(MT,AM,SC,S) EQ 1)..
  SUM((D,A,J)$((ORD(D) GT TRAVTIME(A)) AND (ORD(D) LE LASTDAY)),
  CLEARRATE(A,J,MT,AM,SC)*Z1(D,A,J,S)) + NC(MT,AM,SC,S) =G= AREA(S);

USE1(D,A)$((ORD(D) GT TRAVTIME(A)) AND (ORD(D) LE LASTDAY))..
  SUM((J,S),Z1(D,A,J,S)) =E= 1;

EODUSE1(D)$(ORD(D) GT MINTRAVL AND ORD(D) LE LASTDAY)..
  SUM((A,JE,S)$(ORD(D) GT TRAVTIME(A)), Z1(D,A,JE,S)) =L= EODAVAIL;

OPTEMP(D,A)
  $((ORD(D)+CYCLE(A)-1) LE LASTDAY AND ORD(D) GT TRAVTIME(A))..
  SUM(D1$(ORD(D1) GE ORD(D) AND ORD(D1) LE
  (ORD(D) + CYCLE(A) - 1)), Z1(D1,A,'OFFDAY','S1')) =G= OFF(A);

LASTDAY = CARD(D);
MODEL MINEOP1 /MINCOST, CLEAR1, USE1, EODUSE1, OPTEMP/;

*------------------- The Relaxation Model ----------------------
SOLVE MINEOP USING MIP MINIMIZING OBJVAL;

*------------------ The TDA Model (RMIP) -----------------------
LASTDAY = FLOOR(OBJVAL.L) ;
* ----- Begin Lower Bound Check Loop -----
LOOP(I $(CHECK NE BOUND),
    Z1.UP(D,A,J,S) = 1;
    Z1.LO(D,A,J,S) = 0;
    Z1.L(D,A,J,S) = 0;
    Z1.FX(D,A,J,S) $(ORD(D) LE TRAVTIME(A)) = 0 ;
    Z1.FX(D,A,'OFFDAY',S) $(ORD(S) GT 1) = 0 ;
    Z1.FX(D,A,J,S) $(ORD(D) GT LASTDAY) = 0 ;
    Z1.FX(D,A,J,S) $(SUM((MT,AM,SC)$(THREAT(MT,AM,SC,S) EQ 1),
          CLEARRATE(A,J,MT,AM,SC)) EQ 0 AND ORD(J) NE 7) = 0 ;
```

```
    SOLVE MINEOP1 USING RMIP MINIMIZING COST;
    CHECK$(SUM((MT,AM,SC,S), NC.L(MT,AM,SC,S)) GT 0) = BOUND;
    LASTDAY$(SUM((MT,AM,SC,S), NC.L(MT,AM,SC,S)) LE 0) = LASTDAY - 1
    );
* ----- End Lower Bound Check Loop -----

*------------------ The TDA Model (MIP) -----------------------
LOOP(I $(NOTSWEPT GT 0),
    SOLVE MINEOP1 USING MIP MINIMIZING COST;
    NOTSWEPT = SUM((MT,AM,SC,S), NC.L(MT,AM,SC,S)) ;
*   ------- Begin Notswept If Loop -------
    IF ((NOTSWEPT GT 0),
       LASTDAY = LASTDAY + 1;
       Z1.FX(D,A,J,S)$(ORD(D) LT LASTDAY AND Z1.L(D,A,J,S) EQ 1) =1;
       Z1.FX(D,A,J,S)$(ORD(D) LT LASTDAY AND Z1.L(D,A,J,S) LT 1) =0;
       Z1.UP(D,A,J,S)$(ORD(D) EQ LASTDAY) = 1;
       Z1.LO(D,A,J,S)$(ORD(D) EQ LASTDAY) = 0;
       Z1.L(D,A,J,S) = 0;
       Z1.FX(D,A,'OFFDAY',S) $(ORD(S) GT 1) = 0 ;
       Z1.FX(D,A,J,S) $(ORD(D) GT LASTDAY) = 0;
       Z1.FX(D,A,J,S) $(SUM((MT,AM,SC)$(THREAT(MT,AM,SC,S) EQ 1),
            CLEARRATE(A,J,MT,AM,SC)) EQ 0 AND ORD(J) NE 7) = 0 ;
       )
*   ------- End Notswept If Loop -------
    );
*----- End TDA Model (MIP) -----

*-------------------- REPORTS -----------------------------------
* Print the objective function
DISPLAY  NC.L, KEY ;

* Print the schedule
PARAMETER REPORT(D,A) asset schedule with Sector.Job display;
REPORT(D,A)$(ORD(D) LE LASTDAY) = SUM((J,S),
   Z1.L(D,A,J,S)*(ORD(S)$(ORD(J) LT 7)+0.1*(ORD(J)$(ORD(J) LT 7))) );
DISPLAY REPORT;
```

APPENDIX B SAMPLE MOPTDA RESULTS

```
----     KEY

CUT-EOD 1.0,    ACU     2.0,    MAG     3.0,    M-A     4.0,   SNR-EOD
5.0,   SNR-ROV 6.0,    OFFDAY  7.0


----  REPORT1        assest schedule with Sector.Job display
```

	MH53-21	MH53-22	MH53-23	MH53-24	MCM1-2	MCM1-3
DAY27	3.3	2.1	2.1	2.1	3.4	3.4
DAY28	1.1		1.1	2.1	3.3	
DAY29	2.1	1.1	2.1		3.4	3.4
DAY30	2.1		2.1	2.1		3.3
DAY31		1.1			4.4	3.4
DAY32	1.1	2.1		2.1	3.3	4.4
DAY33		2.1	2.1	2.1	4.3	3.3
DAY34	4.3	2.1	1.1		3.3	
DAY35	2.1		1.1	2.1		4.4
DAY36	2.1		1.1	1.1	3.4	3.4
DAY37		2.1	1.1	1.1	4.4	3.4
DAY38	1.1	1.1			4.3	4.4
DAY39	1.1	1.1		1.1	4.4	
DAY40		1.1	1.1	1.1		4.3

+	MCM1-4	MCM1-5	MCM1-6	MCM1-7
DAY27	4.3	4.3		
DAY28	4.4	3.4	4.4	3.4
DAY29		4.4	3.4	4.4
DAY30	3.3	4.4		3.4
DAY31	2.1	2.1	4.3	3.3
DAY32	4.4	4.4	4.4	4.4
DAY33	3.4		4.4	4.4
DAY34	3.4	1.1	3.4	
DAY35		3.4	4.3	3.4
DAY36	3.4	3.4	4.3	3.4
DAY37	4.4			3.4
DAY38	1.1	3.4	4.4	3.3
DAY39	4.4	3.4	3.4	4.3
DAY40	4.4	4.4	3.4	4.3

APPENDIX C MOPS PROGRAM LISTING

```
$TITLE   The Minefield Clearance Optimization and Simulation Model
* with Washburn relaxation
*------------- GAMS AND DOLLAR CONTROL OPTIONS ---------------------
$OFFUPPER OFFSYMLIST OFFSYMXREF
OPTIONS
   INTEGER1 = 6,
   LIMCOL = 0,      LIMROW  = 0,      SOLPRINT = OFF,  DECIMALS = 1
   RESLIM =7200, ITERLIM =900000,     OPTCR   = 0.1,  SEED    = 3141;

*---------------- INTRODUCTION -------------------------------------
$ONTEXT

              A MINEFIELD OPTIMIZATION SIMULATION MODEL
                           (In GAMS Format)

LT R. Chandler Swallow, USN                              FEB  93

     This program determines the minimum length of time required to
clear a minefield for randomly generated minefields.  The results of
each replication are statistically evaluated to produce the mean time
to clear the minefields and a standard deviation for this average.
This model assumes the assets are not on the minefield location when
initially required and thus must travel to the hotspot.

     This is an unclassified model used to prove the feasibility of
the problem in general.  This model is not comprehensive as written:
all possible scenarios are not accounted for.  Minor modifications
of the data tables, however, will easily allow adaptation to new
threats and new technology.

     Applications of this program include:
         i.   Use as a tool to compare the most effective mix of
              MCM assets in terms of minimizing cost with respect to
              clearance time.
         ii.  Use to determine the benefit of new technology in
              the area of mining and mine countermeasures prior
              to manufacturing based on the equipments
              specifications.
         iii. Use from the miners perspective to determine the best
              minefields to lay.
$OFFTEXT

*---------------- DEFINITIONS AND DATA ----------------------------

*---------------------- SETS ---------------------------------------
SETS

     A               Where A - The specific assets available for the
*                              mission
       / MH53-21
         MH53-22
         MH53-23
         MH53-24
         MCM1-2
```

```
          MCM1-3
          MCM1-4
          MCM1-5
          MCM1-6
          MCM1-7 /

      J
*                    Where J - The asset's job that day
        / CUT-EOD          mech cutters and eod
          ACU              acoustic sweep
          MAG              magnetic sweep
          M-A              magnetic and acoustic sweep
          SNR-EOD          sonar and eod hunting
          SNR-ROV          sonar and remotely operated vehicle hunting /

      JE(J)
*                    Where JE - Jobs that require EOD
        / CUT-EOD,SNR-EOD /

      MT /MOR, GRND/
*                         Where MT    - Mine types
*                               MOR   - Moored Mines
*                               GRND  - Ground/Bottom Mines

      AM /CT, MG, AC, MA/
*                         Where AM    - Activation method
*                               CT  - Contact
*                               MG  - Magnetic
*                               AC  - Acoustic
*                               MA  - Magnetic and acoustic

      SC /1,5,20/
*                         Where SC - Shipcounter set in the mine
*                                1 - Used for immediate activation
*                                5 - Used to provide some counter MCM
*                               20 - Used to provide more counter MCM

      S /S1*S4/
*                        Where  S - Sector to be cleared

      REP_NBR /R1*R100/
*                  Where REP_NBR - Used for replications of the model

*------------------- SCALARS ---------------------------------------
SCALARS

     EODAVAIL number of eod teams available /3/
     SUMDAYS  sum of the days needed to clear all the minefields /0/
     BIGM     a large value used to control the z variable /99/
     RAND1    used to set the random mine threat type
     RAND2    used to set the random mine threat activation method
     RAND3    used to set the random mine threat ship count
     RAND4    used to set the random mine threat ship count
     MINTRAVL the shortest travel time /26/
     GOODRUNS sum of the number of satisfactory replications /0/
     MEANTIME the average time to clear paths thru the minefields
     RUN_NBR  a counter needed for the put statement /0/
     STD_DEV  the standard deviation of the mean time to clear ;
```

```
*---------------------- PARAMETERS -------------------------------
PARAMETERS

AREA(S)
*       Where AREA(S) - The sector area in square nautical miles

                 / S1    80
                   S2    85
                   S3    90
                   S4    95 /

CYCLE(A)
*       Where CYCLE(A) - The operating cycle for each asset in days

               / MH53-21      7
                 MH53-22      7
                 MH53-23      7
                 MH53-24      7
                 MCM1-2       7
                 MCM1-3       7
                 MCM1-4       7
                 MCM1-5       7
                 MCM1-6       7
                 MCM1-7       7 /

OFF(A)
*    Where OFF(A) - The number of days off required for maintenance
*                   and crew rest during the operating cycle per
*                   asset.
               / MH53-21      2
                 MH53-22      2
                 MH53-23      2
                 MH53-24      2
                 MCM1-2       1
                 MCM1-3       1
                 MCM1-4       1
                 MCM1-5       1
                 MCM1-6       1
                 MCM1-7       1 /

TRAVTIME(A)
*    Where TRAVTIME(A) - The number of travel days required for the
*                        asset to get to the minefield.  Certain
*                        things must be kept in mind; the time for
*                        helos to get there must include the time
*                        for a base to be ready, which might in-
*                        clude the time to get an LHA on location
*                        if no land base was available in the
*                        region.  Nautical mile distances from
*                        Texas to the Persian Gulf is approximately
*                        8500 NM by sea.  If those ships must go
*                        around the Cape of Good Hope the distance
*                        is 12000 NM.  Miles traveled in a day are
*                        approximately 1000 NM by air and 300 NM by
*                        sea.

               / MH53-21      26
                 MH53-22      26
                 MH53-23      27
                 MH53-24      27
```

```
                    MCM1-2      26
                    MCM1-3      26
                    MCM1-4      26
                    MCM1-5      27
                    MCM1-6      27
                    MCM1-7      27 /

TOTTIME(REP_NBR)
* Where TOTTIME(REP_NBR) - An array of all the total clearance times

HOURS(A)
*  Where Hours(A) - The number of hours per day an asset can perform
*                   MCM operations

                  / MH53-21     10
                    MH53-22     10
                    MH53-23     10
                    MH53-24     10
                    MCM1-2      20
                    MCM1-3      20
                    MCM1-4      20
                    MCM1-5      20
                    MCM1-6      20
                    MCM1-7      20 /

THREAT(MT,AM,SC,S)
* Where THREAT(MT,AM,SC,S) - A binary mine threat table which has a
*                            1 where a threat of a certain mine type
*                            (MT), activation method (AM), ship
*                            counter (SC), is in a given sector (S).

THREATS(REP_NBR,MT,AM,SC,S);
* Where THREATS(REP_NBR,MT,AM,SC,S) - A binary mine threat array
*                            indexed by replication # which has a
*                            1 where a threat of a certain mine type
*                            (MT), activation method (AM), ship
*                            counter (SC), is in a given sector (S).
*                            This is used for output only.

*--------------------- TABLES -----------------------------------

TABLE
     VELOCITY(A,J)
*       Where VELOCITY(A,J) - A table of velocities in nautical
*                             miles per hour for each asset
*                             performing each job that it is
*                             capable of performing.

              CUT-EOD  ACU  MAG  M-A  SNR-EOD  SNR-ROV
     MH53-21     10    10   10   8
     MH53-22     10    10   10   8
     MH53-23     10    10   10   8
     MH53-24     10    10   10   8
     MCM1-2      2.5   2.5  2.5  2       1.5     1.25
     MCM1-3      2.5   2.5  2.5  2       1.5     1.25
     MCM1-4      2.5   2.5  2.5  2       1.5     1.25
     MCM1-5      2.5   2.5  2.5  2       1.5     1.25
     MCM1-6      2.5   2.5  2.5  2       1.5     1.25
     MCM1-7      2.5   2.5  2.5  2       1.5     1.25 ;
```

```
TABLE
     SWEEPWIDTH(A,J)
* Where SWEEPWIDTH(A,J)  - A table of sweepwidths in nautical miles
*                         for each asset performing each job that it
*                         is capable of performing.

                CUT-EOD  ACU  MAG  M-A  SNR-EOD  SNR-ROV
     MH53-21       .1     .2   .2   .1
     MH53-22       .1     .2   .2   .1
     MH53-23       .1     .2   .2   .1
     MH53-24       .1     .2   .2   .1
     MCM1-2        .1     .2   .2   .1     .1       .1
     MCM1-3        .1     .2   .2   .1     .1       .1
     MCM1-4        .1     .2   .2   .1     .1       .1
     MCM1-5        .1     .2   .2   .1     .1       .1
     MCM1-6        .1     .2   .2   .1     .1       .1
     MCM1-7        .1     .2   .2   .1     .1       .1 ;

$INCLUDE C:\GAMSMOD\PASS80.INC
*  This brings in a long table called PASSES(A,J,MT,AM,SC) which
*  states how many passes an asset performing a given job must make
*  to clear a given threat.  Note: To clear to a certain percentage
*  such as 95% vice 80% the PASS80.INC data should be revised.

PARAMETER CLEARRATE(A,J,MT,AM,SC);
*  Where CLEARRATE(A,J,MT,AM,SC) - A table of clearance rates for a
*  given asset clearing the area to a certain clearance level for a
*  given threat in nautical square miles per day.  This table gets
*  generated automatically.  An example follows.
* The actual table is generated with the code below and can be part
* of the output listing by removing the * from in front of the
* DISPLAY CLEARRATE.

OPTION CLEARRATE:1:2:3;
     CLEARRATE(A,J,MT,AM,SC) =
     (HOURS(A)*VELOCITY(A,J)*SWEEPWIDTH(A,J)/PASSES(A,J,MT,AM,SC))$
                                (PASSES(A,J,MT,AM,SC) GT 0);
*  DISPLAY CLEARRATE;

$ONTEXT
---------  A LIMITED EXAMPLE OF A CLEARRATE TABLE  ---------------
TABLE
     CLEARRATE(A,J,MT,AM,SC) clearance rate for percent clearance
                             level and ship count by each platform/
                             system on each type of mine

                  MOR.CT.1 MOR.MG.1 MOR.AC.1 MOR.MA.1 GRND.MG.1
MH53-21.CUT-EOD       5        5        5        5
MH53-22.CUT-EOD       5        5        5        5
MH53-21.ACU                            10
MH53-22.ACU                            10
MH53-21.MAG                   10                          10
MH53-22.MAG                   10                          10
MH53-21.M-A                    4        4        4         4

MH53-22.M-A                    4        4        4         4

MCM1-2.CUT-EOD      2.5      2.5      2.5      2.5
MCM1-3.CUT-EOD      2.5      2.5      2.5      2.5
MCM1-2.ACU                              5
```

```
MCM1-3.ACU                                    5
MCM1-2.MAG                        5                           5
MCM1-3.MAG                        5                           5
MCM1-2.M-A                        2         2         2         2

MCM1-3.M-A                        2         2         2         2

MCM1-2.SNR-EOD                    3         3         3         3

MCM1-3.SNR-EOD                    3         3         3         3

MCM1-2.SNR-ROV                                                2.5
MCM1-3.SNR-ROV                                                2.5
$OFFTEXT

*__________________________ Variables ________________________________________
POSITIVE VARIABLE
     T  the longest required clearance time
     Z(A,J,S)  the number of days the asset must spend on a threat ;

VARIABLE
     OBJVAL  objective value for the minimum total clearance time ;

BINARY VARIABLE
     X(A)  one if that asset arrives soon enough to help clear ;

*______________________ Equations ______________________________________
EQUATIONS
        OBJ  the objective function to minimize clearance time
        MAXCOST(A)  determines the longest clearing asset
        CLEAR(MT,AM,SC,S)  ensures all minefields are cleared
        EODUSE  accounts for the number of divers available
        USE(A)  eliminates assets that arrive to late to help
        COVER(A)  sets z to zero if that asset arrives to late ;

*____________ The minimization model objective function ________________

*minimize
OBJ..          OBJVAL =E= T ;

*________________________ Subject to _________________________________________


MAXCOST(A).. T =G= SUM((J,S), Z(A,J,S)) + TRAVTIME(A)*X(A) ;

CLEAR(MT,AM,SC,S)$(THREAT(MT,AM,SC,S) EQ 1).. AREA(S) =L=

SUM((A,J),CLEARRATE(A,J,MT,AM,SC)*Z(A,J,S)*(CYCLE(A)-OFF(A))/CYCLE(A)) ;

EODUSE.. EODAVAIL*(T - MINTRAVL)
         =G= SUM((A,JE,S), Z(A,JE,S)*(CYCLE(A)-OFF(A))/CYCLE(A)) ;

USE(A).. X(A)*TRAVTIME(A) =L= T ;

COVER(A).. X(A)*BIGM =G= SUM((J,S), Z(A,J,S)) ;

MODEL MINEOP /ALL/;
```

```
*-------------- THE REPLICATION LOOP ----------------------------
FILE RESULTS /RESULTW.DAT/;
PUT RESULTS;
LOOP(REP_NBR,
     TOTTIME(REP_NBR) = 0;
     RUN_NBR = RUN_NBR + 1;

*    ------------- GENERATE THE RANDOM MINE THREAT ----------------
     LOOP(S,
          RAND1 = ROUND(UNIFORM(0.5, CARD(MT) + 0.5));
          RAND2 = ROUND(UNIFORM(0.5, CARD(AM) + 0.5));
          RAND3 = UNIFORM(0,1);
          RAND4 = 1 $(RAND3 LE 0.9) +
                  2 $(RAND3 GT 0.9 AND RAND3 LE 0.98) +
                  3 $(RAND3 GT 0.98);
          THREAT(MT,AM,SC,S) = 1 $(ORD(MT) = RAND1
                                   AND ORD(AM) = RAND2
                                   AND ORD(SC) = RAND4);
          THREAT('MOR','CT','1',S)$
                                   (THREAT('GRND','CT','1',S) EQ 1 OR
                                    THREAT('MOR','CT','5',S) EQ 1 OR
                                    THREAT('GRND','CT','5',S) EQ 1 OR
                                    THREAT('MOR','CT','20',S) EQ 1 OR
                                    THREAT('GRND','CT','20',S)) = 1;
          THREAT('GRND','CT','1',S) = 0;
          THREAT(MT,'CT','5',S) = 0;
          THREAT(MT,'CT','20',S) = 0
*         CONTACT MINES USUALLY ARE NOT PLACED ON THE BOTTOM.  THEY
*         USUALLY HAVE SHIP COUNTERS OF 1.
          );
     THREATS(REP_NBR,MT,AM,SC,S) = 1 $(THREAT(MT,AM,SC,S) EQ 1);

*    --------- The MIP Solution ----------------------------
     Z.UP(A,J,S) = BIGM;
     Z.LO(A,J,S) = 0;
     Z.L(A,J,S) = 0;
     Z.FX(A,J,S) $(SUM((MT,AM,SC)$(THREAT(MT,AM,SC,S) EQ 1),
                 CLEARRATE(A,J,MT,AM,SC)) EQ 0) = 0 ;
     SOLVE MINEOP USING MIP MINIMIZING OBJVAL;
     TOTTIME(REP_NBR) = OBJVAL.L ;

*    -------- STATISTICS CALCULATIONS ----------------------------
     GOODRUNS = GOODRUNS+1 ;
     SUMDAYS = SUMDAYS + OBJVAL.L ;
     TOTTIME(REP_NBR) = OBJVAL.L ;
     );
*    ---- END REPLICATIONS LOOP ----

MEANTIME $(GOODRUNS GT 0) = SUMDAYS/GOODRUNS;
STD_DEV $(GOODRUNS - 1 GT 0) =
          SQRT(SUM(REP_NBR $(TOTTIME(REP_NBR) GT 0),
          POWER(TOTTIME(REP_NBR) - MEANTIME,2)) / (GOODRUNS - 1));
```

```
*------- OUTPUTTING THE DATA TO A FILE ----------
PUT "RESULTS OF THE MOPS MODEL"/
PUT "RUN  DAYS TO CLEAR - THREAT: Sector  1  Sector  2  Sector  3
Sector  4"/
LOOP(REP_NBR,
    PUT REP_NBR.TL:4,"      ",TOTTIME(REP_NBR):2:0,
    PUT "                   "
      LOOP(S,
          LOOP((MT,AM,SC),
              PUT $(THREATS(REP_NBR,MT,AM,SC,S) EQ 1)
                   MT.TL:5, AM.TL:3, SC.TL:3
              );
           );
    PUT /
    );
PUT /
PUT "AVERAGE TIME TO CLEAR THE MINEFIELD"/
PUT MEANTIME/
PUT "STANDARD DEVIATION OF THE CLEARANCE TIMES"/
PUT STD_DEV/;
```

LIST OF REFERENCES

1. Melia, Tamara Moser, *"Damn the Torpedoes" A Short History of U.S. Naval Mine Countermeasures, 1777-1991*, Naval Historic Center, 1991.

2. Kelso, Frank B., Chief of Naval Operations, "Building Blocks of Naval Power", *Naval Institute Proceedings*, November 1992.

3. O'Keefe, Sean, Secretary of the Navy, "... From the Sea Preparing the Naval Service for the 21st Century", *Naval Institute Proceedings*, November 1992.

4. Preselin, Bernard, *The Naval Institute Guide to Combat Fleets of the World 1993 Their Ships, Aircraft, and Armament*, Naval Institute Press, 1993.

5. Kihune, Robert K. U., Assistant Chief of Naval Operations (Surface Warfare), "Statement of Vice Admiral Kihune, USN, Assistant Chief of Naval Operations (Surface Warfare) Before The Subcommittee on Seapower of the House Armed Services Committee on Mine Warfare", 17 March 1992.

6. Church, George J., "Clinton's Seven Most Urgent Decisions", *Time*, 25 January 1993.

7. Trainor, Bernard E., Lieutenant General USMC (Retired), "Still go-ing ... Amphibious Warfare", *Naval Institute Proceedings*, November 1992.

8. Brooke, A., Kendrick, D., Meeraus, A., *GAMS: A User's Guide*, Scientific Press, 1988.

9. *XA Linear and Generalized Integer Program*, Sunset Software Technology, 1991.

10. Washburn, Alan R., Professor, Naval Postgraduate School, private communication, February, 1993.

11. Larson, Harold J., *Introduction to Probability Theory and Statistical Inference*, John Wiley and Sons, 1982.

12. Pearson, John, Commander Mine Warfare Command, "Mine Warfare Lecture at the Naval Postgraduate School", July, 1992.

13. Conversations between Susan Graves, Pentagon, Mine Warfare Branch, Kim Malmin, Center for Naval Analysis, and George Pollitt, Mine Warfare Command, and the author in June 1992.

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