ABSTRACT

OVALI, MELIK HACI AHMET. Dynamic Allocation and Scheduling Mine Counter Measure Vessels in a Comprehensive Sea Mines Clearance Effort. (Under the direction of Dr. Thom J. Hodgson.)

Open sea lines of communication is vital not only for world's trade but also for defense purposes of a nation. Keeping in mind that it is trivial to deploy a mine which is cheap and able to block a sea way, it is crucial for a nation to have effective mine clearance policies in order to sustain a stable economy and to take early military actions when there is even the implicit presence of mine threat. The current trends on defense budgets, with improvements in the mine technology, leads navies to utilize fully on hand inventories in order to meet service needs.

The problem we approach deals with the surface mine counter measures which is one branch of the mine clearance efforts at sea. The objective is to develop models for a selected test site (Turkey) that provide results for different scenarios. Primary concern is to clear pre-determined channels (seaways) connecting the coastal landmarks to open seas within a limited amount of time using the vessel inventory. Models are built with open source information, methods are developed with experiments and field experience. Simio® simulation software is used to develop and analyze the models. Parameters of the models are defined as model properties so that real values can replace the notional ones to test the models later. Different parameter values are tested and a number of additional vessels is required to minimize the mine clearance operations period.

Dynamic Allocation and Scheduling of Mine Counter Measure Vessels in a Comprehensive Sea Mines Clearance Effort

by
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DEDICATION

To the Republic of Turkey

"Denize hakim olan, cihana hakim olur." Barbaros Hayrettin Paşa (1478-1546)

“The one who rules the sea, rules the world.” Ottoman Adm. Barbaros Hayrettin Pasha (1478-1546)

BIOGRAPHY

Melik Haci Ahmet Ovali was born in November 25, 1989, Taskopru, Kastamonu, Turkey as the only son among five siblings. In 2004, he entered Turkish Navy's High School at Heybeliada, Istanbul as a first step into being a navy officer. In 2008, he graduated from Naval High School and entered Turkish Naval Academy in Tuzla, Istanbul. In 2012, he graduated from the navy academy with a BSc degree in Industrial Engineering and served on board of Alpha and Echo class mine hunter coastal vessels of Turkish Navy for three years. In 2015, he joined North Carolina State University to pursue his MSc in Operations Research.

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There are both people and organizations that have contributions to this study. First of all, I would like to thank Turkish Navy for providing this opportunity to study abroad. Then, I would like to mention my advisor Dr. Thom J. Hodgson with deep gratitude. From my first day at the campus till the last, he has provided support, help and inspiration all the time with his endless enthusiasm. Whenever I felt like I were locked in a room (which was often, not surprisingly), he was there to open the door with the right key. Without his support, let alone this research, completing the program would not be possible. I also would like to express my gratitude to Dr. Michael G. Kay who has helped me out throughout the program as our OR program advisor and also as my committee member. I also wish to express my sincere gratitude to Dr. Russell E. King who served on my committee. Knowing that a faculty (Dr. King) is very familiar with your country and aware of the situations there, is precious for an international student. There is also another name that I can't leave behind now, nor the rest of my life. Our program secretary Linda Smith. The very first day of the classes, after a couple of minutes I said hello to her, she introduced me to Dr. Hodgson and then she accompanied me to the bookstore that proved early that this community consists of wonderful people. Another graduate student saver is Brandon McConnell who helps anyone-anytime whenever he is asked to. I also need to thank my buddy Kangwon Kim for providing relentless help and fun every semester.

Aside from the support on campus, there are also others who provided support so that months of hard work ended in something desired. It is my family that generates my motivation so that I can get on my feet and take a step further. The hardest part of the past months was to be away thousands of miles from my family members who never complained but always stand behind me.

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LIST OF ACRONYMS AND ABBREVIATIONS

AAW	Anti-Air Warfare
ASV	Air-To-Surface Vessel
ASW	Anti-Submarine Warfare
ASuW	Anti-Surface Ship Warfare
CG	Guided Missile Cruiser
DD	Destroyer
EOD	Explosive Ordnance Disposal
FY	Fiscal Year
HBX	High Blast Explosive
IHS	Information Handling Services
JFS	Jane’s Fighting Ships
LCS	Littoral Combat Ship
MANPADS	Man-Portable Air-Defense System
MCM	Mine Counter Measures
MHC	Mine Hunter Coastal
MILCO	Mine-Like Contact
MILEC	Mine-Like Echo
MH	Mine Hunter
MS	Mine Sweeper
MTA	Mine Threat Area
MW	Mine Warfare
NM	Nautical Mile
NOMBO	Non-Mine Bottom Object
RMS	Remote Minehunting System
ROV	Remotely Operated Vehicle
SLOC	Sea Lines of Communication
SONAR	Sound & Navigation System
TAF	Turkish Armed Forces
TNT	Tri Nitro Toluene
Tu	Turkey or Turkish
UAV	Unmanned Aerial Vehicle
USN	United States Navy
UUV	Unmanned Underwater Vehicle
VDS	Variable Depth Sonar
WW I	World War I
WW II	World War II

Chapter 1

Introduction

Naval mines have been used since 14th century. In the literature, the first use was by the Chinese against Japanese pirates [12]. The first designs were contact mines which detonate by a physical interaction with the target. The first design close to today's contact mines was invented by David Bushnell and it was used against the British in the American War of Independence [13]. Use of naval mines continued to increase especially in World War I and World War II (WWI and WWII). Widespread use of naval mines was also observed during the Korean Conflict, Vietnam War and Middle Eastern Conflicts. Since WW II there have been 20 US Navy ships sunk or seriously damaged, 15 of which caused by naval mines than all other forms of attack combined [14].

The widespread use of naval mines stems from the fact that deploying naval mines is trivial and naval mines are rather cheap. Though they can have sophisticated built-in functions such as ship counters and can be guidable with a propeller. Deploying sea mines is trivial because deployment can be done using surface ships, aircraft, pleasure boats, submarines, combat divers, or even pushing them off the back of pickup trucks as they cross over bridges [14]. Not only are they easy to deploy, naval mines are a real challenge for mine clearing units. Mine clearing operations are tedious and time consuming. The time it takes to clear the mines can take as long as two hundred times what it takes to lay the mines [8]. In addition, mine clearing operations may not be always possible. Weather conditions and sea state play big roles in sailing and thus on mine clearance operations. In addition to weather and sea conditions, clutters and type of seabed are also crucial for mine clearance operations. High clutter level makes further examination of mine like contacts (MILCOs) impossible. A rocky seabed reflects SONAR (Sound Navigation & Ranging) echo's and makes mine exploratory operations futile.

Naval mine technology has greatly improved over the decades. Modern naval mines are so sophisticated that they use microcomputers which have the ability to not only detect a target, but determine if it is a ship or a mine sweeper and are able resolve the ideal time to detonate as the vessel passes [18]. Naval mines can contain explosives (i.e. TNT, HBX) from a few pounds up to tons. They are cost efficient to produce and store. In addition to being cheap, naval mines are also extremely effective weapons. A single mine is capable of blocking a Sea Line of Communication (SLOC) such as a strait or an approach to a valuable port. Sea mines, or the implicit threat of their possible presence, may deny the enemy use of sea areas vital to their operations [28]. For this reason, false declaration of mining a sea field is very advantageous for the coastal nation and it will force the enemy to allocate time and resources to render the mine threat area (MTA) safe again.

Having a high effect/cost ratio makes naval mines very attractive to most nations. In 2009, it was reported by US Navy that there are 50 different countries with 300 different varieties of naval mines. There are more than thirty countries around the world that produce naval mines, more than twenty of which will export them. It was reported that there is a worldwide surplus of quarter million naval mines, excluding those in United States [14, 18]. Naval mines are a subject of intense study and have been steadily improved over time. These improvements have gone far beyond the international conventions on restrictions of weapons. For example, North Korea reportedly has nuclear naval mines, with the intension to use them to counteract any advantage the United States or any other country's forces could have over them in a conflict [15].

Aside from governmental organizations, terrorist organizations also consider naval mines as must-have weapons. The line between traditional naval mine warfare and terrorists using improvised explosive devices is becoming blurred; the U.S. Secretary of Defense described this as "hybrid wars" [14, 18]. The severity of the threat posed by terrorist organizations on Sea Lines of Communication can be envisioned when it is considered that over ninety percent of world trade depends on the sea.

Naval mines can be used to create defensive fields for coastal nations, but they can also be used to create offensive fields for an enemy, which are going to be referred as defensive mining and offensive mining respectively. Offensive mining can be conducted in harbors or approaches thereto, straits and territorial waters that normally are under the control of an enemy, although under certain circumstances, it may be conducted in neutral or international waters [11]. This tactic is not a permanent solution, but an offensive mining can give the mining nation valuable time to prepare other military forces [26]. During the initial stages of a mining campaign, offensive operations are likely to be confined to ports, harbors, and focal points where traffic concentrations can be foreseen [11].

Mine warfare includes the whole field of designing, producing and laying mines and the parallel effort of designing, producing and operating all forms of mine counter measures (MCM) to combat an enemy's mining campaign [11].

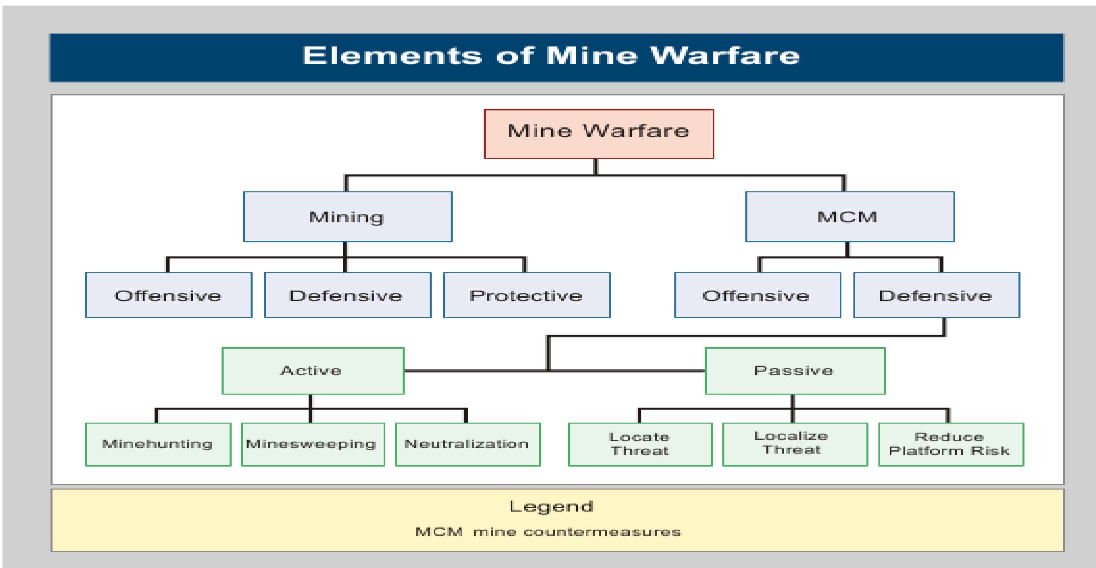


Figure 1.1: Mine Warfare Diagram [8]

Mine countermeasures (MCM) is the second branch of mine warfare and comes after a mining campaign. The aim of MCM is to permit allied warships and merchant vessels to use the seas and enter and leave ports, as necessary, to further the war effort and support the population, without sustaining unacceptable damage or losses from enemy mines. This can be achieved by offensive and defensive MCM [7]. Destroying enemy's mine producing plants is one of offensive MCM efforts.

For a mining campaign, there are two major kinds of sea mines. The first kind is contact mines, which is the simplest design and has also simple logic (you touch it, it explodes).

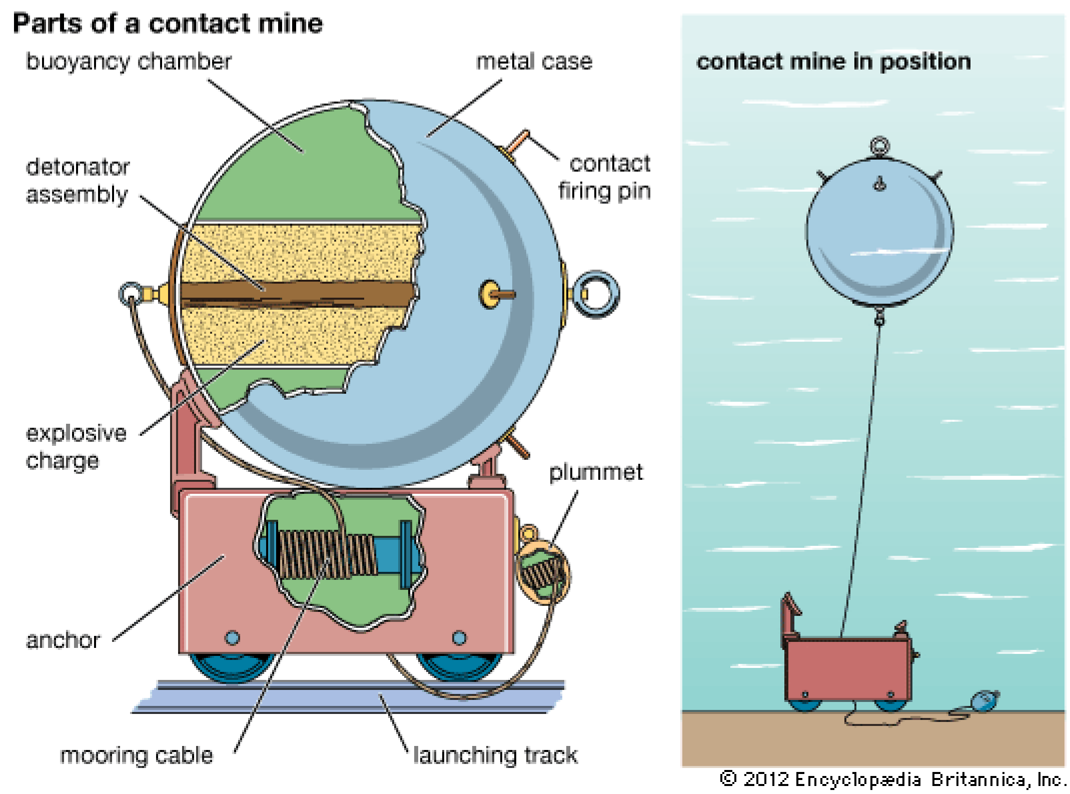


Figure 1.2: Contact Mine

The second and more complicated kind of sea mines are influence mines. These mines may have one or more initiation logics such as vibration, pressure and/or magnetism. Every ship class is unique and each engineering plant creates different mechanical vibrations. Different amounts and shapes of metal generate a different magnetic signature for each individual ship. Each ship's hull produces a different pressure line through the sea bottom. Thus, the influence mines can be tuned to a specific ship or specific ship classes. The unique properties of ships are called signatures, which designate them. These signatures are also vital for submarine operations. As a result, it is common for most nations to store the signatures of other navy ships by recording and updating them if necessary.

Offensive mining is able to lock all the ships of coastal nation to their ports. Mine clearance operations, even if it is applicable, are going to require huge amounts of time and effort. This timeframe will allow an invading nation to take further steps to their final military objective. Offensive mining can also be adopted by terrorist organizations to damage the freedom of navigation of other nations in their territorial waters or in international waters. Since it can be implemented with any kind of vessel, offensive mine threat is considerable for all nations.

Recent turmoil in the Middle East unfortunately resulted in some countries losing control of their military inventories, which created security concerns for their neighboring countries. For example, a second AH-1W Super Cobra helicopter of Turkish Armed Forces (TAF) was shot down with a 9K38 Igla SA-18 Grouse MANPADS (Man-Portable Air-Defense System) by a terrorist on 13 May 2016, killing two crew members [26]. Since the first Cobra helicopter was shot down 19 years before, the heat-guided missile was most likely pillaged from the Syrian military. It was reported on the news that between the years of 2012-2014 Syrian military depots (which contain portable air defense missiles) were plundered and weapons became available on the black market. That claim was first proven on 5 April 2016 when a Syrian SU-22 Fitter Aircraft was shot down by a member of a non-state organization with a missile (9K310 Igla-I) of the same type as the SA-18 missile [25]. Security concerns forced neighboring countries to allocate resources to keep the threat away from their land and waters.

For instance, Turkey has a border of 545 miles with Syria and 208 miles with Iraq. Both countries have had such internal conflicts, Turkey now has to take extra-ordinary precautions against threats posed by terrorist organizations in the northern parts of both Syria and Iraq. Along with land security concerns, there have been new concerns with sea territories. These concerns generate a need to reevaluate the concepts and policies that apply to Turkey’s sea territories in order to deal with the new security issues.

In addition to the threats from non-governmental organizations, threats from governmental organizations also need to be reevaluated. Border conflicts have occurred between countries in close proximity to Turkey in recent years (i.e. Russia-Ukraine, Azerbaijan-Armenia). These military conflicts also generate a need for reevaluation and review of concepts and policies, especially those applying to territorial waters.

1.1 Problem Statement

As noted earlier, offensive mining can easily be adopted to impair the freedom of navigation of a nation by individuals or organizations. Even the threat of mining promises to make a coastal nation halt naval activities and concentrate on mine clearance operations. Though territorial waters are surveyed regularly for possible mine threats, it is possible that a survey operation reveals offensive mine deployment without knowing the origin of the mines. Presence of mines in territorial waters can trigger a comprehensive set of mine clearance operations in the whole coastline of a country. That is because the coastline serves as the approach to ports, and it is vital for both domestic and international logistics.

With all aspects of offensive mining in mind, we will try to solve the problem of determining the reasonable number of mine clearance platforms necessary for a given geographical region. The sea around the Turkey will be used as a notional test site. Notional equipment (ship, SONAR's, UUV's, etc.) are based on average capabilities defined in Jane's Fighting Ships (2014-2015).

1.2 Motivation

The possession of over quarter million sea mines all around the world (including nuclear mines owned by North Korea) creates non-negligible security issues for navy ships. Thus, there have been relentless MCM efforts to overcome these security concerns. Mine clearance operations naturally take considerable time and effort. For that reason, the search for better mine clearance in less time is of interest to all nations. Yet, a search of the literature did not find any procedure to determine the number of required platforms for comprehensive mine clearance within a reasonable timeline.

There is no published procedure for more efficient mine clearance operations. However, there has been considerable work on better mine clearance platforms. For example, the LCS (Littoral Combat Ship) project of U.S. Navy is a well-known and widely followed project that has not been completed. When the funding for the LCS program between the fiscal years 2002-2011 is closely examined, it turns out that a single LCS type ship cost will be more than $470 million including development and procurement costs [7]. Unfortunately, the Remote Mine Hunting System (RMS) that is planned for the LCS program had several issues early in fiscal year 2015. For instance, the mean time between failures turns out to be 34.6 hours, rendering the system officially unreliable. Until the RMS mission module issues are resolved, operational tests cannot be completed [24, 22]. These results were followed by the U.S. Congress' decision to zero out the RMS budget for fiscal year of 2015. With all these issues, it is not likely that an MCM capable LCS will be available in the foreseeable future. Therefore, the current mine clearance ships (Avenger class, first commissioned in 1987) will remain the main MCM platform for U.S. Navy [24, 21].

The delay for acquisition of new MCM platforms brings the search for better procedures for MCM operations to the front. The expense of a single platform for mine clearance operations puts a high value on the solution of the problem defined earlier as to get best possible number of platforms for a selected MCM scenario. This research takes its core motivation from the facts stated above.

1.3 Scenario Assumptions

In order to determine the number of mine clearance platforms for reaching a desired mine clearance level at pre-determined sea areas within a reasonable time frame, a model will be developed with notional data sets. The reason for using notional data sets is that original data sets and parameters are classified. As a starting point, it will be assumed that there is a country under attack of offensive mining but enemy is unknown. Enemy forces can be state organizations and/or non-state organizations. Nature of the problem dictates to concentrate on mine clearance operations, thus further military steps of the attacking forces are out of concern for this research. The naval mine warfare is primary concern.

The objective of the attacking forces is to halt/destroy defending nation's use of sea. For this reason offensive mining against the coastal nation is adopted without being noticed while the deployment of the sea mines. Mining campaign is completed and no more mine deployment is going to take place. There is no information available for defending nation about the enemy nor its naval capabilities. However, it will be assumed that mine clearance units of defending nation is not going to receive any attacks from surface or from air. It will be assumed that there is only mine threat for the mine clearance units of defending nation.

It will also be assumed that the coastal nation explores the deployed mines within its territorial waters via survey operations. As a usual military approach, worst case scenario will be considered by the defending nation which proposes to consider the whole territorial waters as mined. In order to fully utilize its sea lands, the defending nation initiates comprehensive mine clearance operations to render the whole territorial waters safe. There is a reasonable mine clearance level that mutually accumulates to one with remaining mine risk. There is also reasonable timeline to complete all mine clearance operations in the whole sea lands. All the mine clearance units of the defending nation is considered to be active (in service) and they are also considered to be capable of doing their tasks at any part of the sea land as long as the limits permit. The defending nation does not start any other naval operations till all its sea land is declared to be sufficiently cleared from the deployed mines. Mine clearance units of defending nation is allocated dynamically, that is when a mine clearance operation is completed at any area, the units which were assigned to that area travel to next uncovered area till there is left no area uncovered. It is assumed that the defending nation has only surface MCM capabilities (no air MCM, no use of satellites for MCM, etc.) that is executed by two kinds of mine clearance vessels; 5 old type mine hunters, 6 new type mine hunters [19].

As stated before, sea lands of Turkey will be used a testing site and two kinds of mine clearance ships of Tu Navy will be used in the model as notional data set. The total number of vessels and their properties will be used as specified at Jane’s Fighting Ships Catalog 2014-2015 (ISBN: 9780710631015).

Chapter 2

Literature Review

By the nature of this research, the data set and parameters are classified. For that reason, it is not viable to reach a study that provides a solution to the problem of determining number of mine clearance vessels to be maintained. The problem, itself, has a quite number of aspects to be studied before developing a model to solve it. Environmental data, methods of clearance, and platforms used for clearance operations are only some major aspects of the problem.

Environmental data and its collection are diverse. Data is collected with satellites, ships, aircrafts, and other kinds of platforms. The collected data is stored on land and transferred to the units in need via all ways of communication possible. The environmental data of the seas is used not only by mine clearance units but the submarines and diver units. The widespread use of environmental data has enabled advanced data management and managing the environmental data is studied continuously. This paper is intended to develop models for given MCM scenarios and solving them. Thus environmental data management is not going to be a concern for this study. Reasonable notional environmental data will be used for the selected scenarios.

There are three types of MCM efforts; Air MCM, which is carried by aircrafts or satellites; Underwater MCM, which is carried by platoons with AUV's that are not hosted by MCM ships; and Surface MCM, which is carried by MCM ships. These three branches are not valid for all navies, but studying them will contribute to the perspective of this research.

There are several types of vessels being used by different navies for MCM purposes. In order to be consistent with the scenario assumptions, notional platforms with some real properties that are obtained from Jane's Fighting Ships 2014-2015 will be used.

Studying all the aspects of the mine clearance efforts is vital for developing a valid model for the given problem. Therefore we need to review several aspects of MCM efforts separately.

2.1 Remote Sensing for Detection of Submerged Mine-Like Objects

Active MCM efforts consist of two major branches; mine hunting and mine sweeping. Recent advances in defense technologies has enabled navies to optimize their effort in mine clearance operations at sea. Because mine hunting requires detection of mine threats before taking further steps through neutralization, it poses less risk to clearance units as well as providing better clearance levels. Mine clearance units face a mine explosion threat mostly while they are trying to detect mines. Using other forms of detection methods than sailing in the mine threat area is available for some navies and one of them is satellite spectral imagery. A study done by Sandersfield (2012) investigates the multispectral imagery for detecting submerged mine-like objects and supports the concept that commercial remote sensing is a viable option for MCM efforts. In this method, satellite spectral imagery is analyzed for the detection of submerged mine-like objects. Remote sensing is used to differentiate from changes in reflected, emitted or backscattered energy. It can be obtained by aircraft or space craft. It is also supported by the same research that commercial remote sensing is a viable option to support mine countermeasures. Further research is on the way for detecting mines remotely because naval mine technology is also a continuous area of study.

2.2 Unmanned Underwater Vehicle (UUV) Efforts in Mine Warfare

Underwater MCM efforts play big role in mine countermeasures. Today's MCM efforts mostly depend on humans as operators. A study done by Thompson (2015) suggests that UUVs will replace all other MCM assets. That change will naturally reduce the number of human operators. It is stated in the study that incorporating all international UUV assets would attain desired clearance levels within a reasonable time frame. The concept behind the study is that UUVs make search and platoons govern them. Success of the concept also highly depends on international partners. Though that study is interesting and promising, this paper is not intended to examine underwater MCM efforts separately.

Figure 2.1: UUV Platoon Certification with MK-18 Mod 1 UUV [4]

2.3 Littoral Combat Ship (LCS) for MCM Purposes

The need for replacing outdated mine clearance ships with up to date versions is apparent nowadays. A lot of projects have been launched in Europe and in the United States. The most remarkable project among those is the LCS project which has been launched in the last decade as two different types of ships. The first design is by Lockheed Martin® and the second design is by General Dynamics®. Unexpected delays in the project have continued and two ship have been commissioned (USN Freedom in 2008, USN Forth Worth in 2012) without the RMS mine hunting mission modules, even though the first design with all mission modules was supposed to be delivered by 2007.

A study done by Kertmen (2006) examines LCS potential for the Turkish Navy. The LCS design concept consists of two distinct parts, the ship itself and the mission packages it carries and deploys. The LCS's focused missions are mine warfare, anti-submarines warfare, and surface warfare. The majority of the capabilities come from mission packages. These packages are intended to be modular in that they will be interchangeable on the sea frame. Each mission package consists of systems made up of manned and unmanned vehicles and the subsystems. Additional crew will be needed to operate these systems. Each mission package is envisioned as being self-contained, interchangeable and will allow tailoring of LCS to meet specific threats.

An outline table of capabilities of LCS is presented below in Table 2.1 [7].

Table 2.1: Capabilities of U.S. Navy Future Combatant Ships

Missions		**LCS**	**DD(X)**	**CG(X)**
Deep Water Operations	**ASW**	Yes	Yes	Yes
	ASuW	No	Yes	Yes
	AAW	Yes	Yes	Yes
	Ship Interceptions	No	Yes	Yes
	Logistic support	No	Yes	Yes
	Aviation	Yes	Yes	Yes
Littoral Warfare Operations	**ASV**	Yes	No	No
	ASuW	Yes	Yes	Yes
	AAW	Yes	Yes	Yes
	MW	Yes	No	No
	Coastal Suppression	Yes	No	No
	Embarked Force	Yes	No	No
	Logistic support	Yes	Yes	Yes
	Aviation (inc. UAVs)	Yes	Yes	Yes

The initial intend of this study was not only to include two types of Tu Navy's MCM vessels but also to include the US Navy's recent project of littoral combat ship (LCS) in the ship analysis part of the study. The reason for not including the LCS in the analysis is not the unresolved RMS mine hunting module problem, but it is the major engine problems that 3 out of 4 ships have encountered at different time in a very short term.

Reportedly, for the third time in the year of 2016, one of the US Navy's $360 million littoral combat ship (lastly USS Freedom) was knocked out of action by mechanical problems when the sea water leaked into one of its two main diesel propulsion systems on July 11th [9]. Among those four littoral combat ships, it is only the USS Independence that did not have a major engine problem within a 12-month period ending in September 2016. The widespread major engine problems of the littoral combat ships ended up in the US Navy's decision to turn these first four ships into non-deploying test ships. The decision not only overhauled US Navy's force deployment strategy but also hampered the utilization of four newly constructed littoral combat ships which cost $360M each.

2.4 Optimizing MCM Efforts

The delays in the LCS project have naturally postponed the decommissioning of MCM-1 class ships of U.S. Navy. These ships were commissioned starting from 1983 to 1991 that makes them old enough to decommission. The maintenance of old ships is always expensive. That is because the parts used in them become rare on the market ending up in inflation of the costs of repair and maintain. Even though there is no released paper on how to replace MCM-1 class ships with LCSs, there is some research on how to do part harvesting which is a procedure of designating some ships as 'spares' in order to provide parts in need.

The only released publication close to deciding number and combination of MCM platforms (ship & helicopter) dates back to 1993. That research is done by Swallow. In the paper two distinct models are adopted to optimize minefield planning and clearance. In the first model, which is a tactical decision aid, there is a known mine threat area and MCM assets are supposed to clear minefields in the fewest number of days. Assumption of known mine threat area is not close to being valid for real cases. In the second model, there are many potential mine threats and the goal is to determine mine clearance times for a given mix of MCM assets. In the results of the study clearance rates of MH-53 helicopters is found to be twice that of the MCM-1 Avenger Type ships of U.S. Navy. In the analysis section of the study number of Explosive Ordnance Disposal (EOD) diver teams, MCM-1 ships, and MH-53 helicopters are used as input parameters to acquire the best combination of platforms.

Chapter 3

Modeling Approach

This chapter first provides a general outline of the problem. Later, Simio simulation software is introduced with the parts used in the model for this study. Lastly, open source information and its obtainment is explained with the assumptions made.

The MCM platform dynamic allocation and scheduling problem consists of three major aspects; **segments**, **tasks** and **assets**. The segments refer to mine threat sub-areas of the channels. Channels may be compromised of a single segment. The type of the mine threat can be ground or moored only. Being a ground or moored mine mostly has impact on the detection probabilities of mine sweeper ships. The vessel dataset of this study is solely consist of mine hunter ships which use SONAR transmissions to detect mines. For that reason, the type of the mine (i.e. moored or ground) has no big impact in this model. The tasks refer to the mine hunting operations performed by any MCM asset. Such tasks include detecting mines with SONARs and neutralizing them either by the AUVs of the ships or by EOD diver teams. There are sufficient number of AUVs and EOD teams on board of the each type of platform. Neutralization can be made with AUVs and/or with EOD teams. Allocating a MC platform means that the ship must be given a segment to clear from mines at a certain percentage (i.e. 95% clearance) in a certain amount of time (which may be affected by the ship’s operational cycle).

The only released study which is (partly) similar to this paper’s research interest in some aspects was done by Swallow (1993). But that study can’t be validated anymore due to the advances in mine clearance technology and other operational methods. For instance, AUVs and SONARs have been developed such that mine hunting has become primary over mine sweeping. New models with new parameters need to be studied and developed. In addition, improvements in computers and processors along with software have made it possible to solve huge models that was impossible to solve even 10 years ago. Thus, models which were to be shrunk and solved with big assumptions (i.e. known probability of the mine threats) need to be solved again with relaxed assumptions.

As presented earlier, Active Defensive MCM efforts consist of mine hunting/sweeping and neutralization efforts. These efforts are adopted via Air MCM, Underwater MCM and Surface MCM. As this research has chosen Turkey as a notional data set, MCM capabilities of Turkish Navy (Tu Navy) is considered as stated in Jane's Fighting Ships (2014-2015) catalog. Underwater MCM is carried by the AUV capabilities of surface ships. Air MCM, however, is not considered due to the problem size and time constraints of the study. At the time this research was initiated, the LCS ships were planned to be included in the model but the U.S. Navy's decision on September 2016 to decommission and turn all the LCS ships into test ships due to major engine problems, which made them officially unreliable, has lead us to exclude them from consideration [24].

3.1 Simio Simulation Software

3.1.1 Introduction of Simio

Simio is a simulation modeling framework based on intelligent objects. It also fully supports both discrete and continuous systems, along with large scale applications based on agent-modeling [26]. The intelligent objects can be built, sub-classed or can be created from scratch and these objects can be stored to use in other models. The core motivation for the writer to use Simio in this research is the enriched tools that the software has. For example, input parameters can be used for model variables and sensitivity analysis can be performed via KN (Kim and Nelson) Algorithm, which compares scenarios and iteratively runs additional replications to reduce the variability enough that the best alternative can be reliably determined, and OptQuest®, which enhances the analysis capability via removing some of the complexity by automatically searching for the optimal solution depending on what the objective is. In addition to its powerful approach for finding the optimal, Simio is also visually appealing by offering 3-D visualization which can either be downloaded from the web or can be extracted from the software.

3.1.2 Intelligent objects used in the model

Model Entity represents the mine deployment in the model. These entities seize or release the capacity of resources and they are also processed by other objects in the model such as server objects.

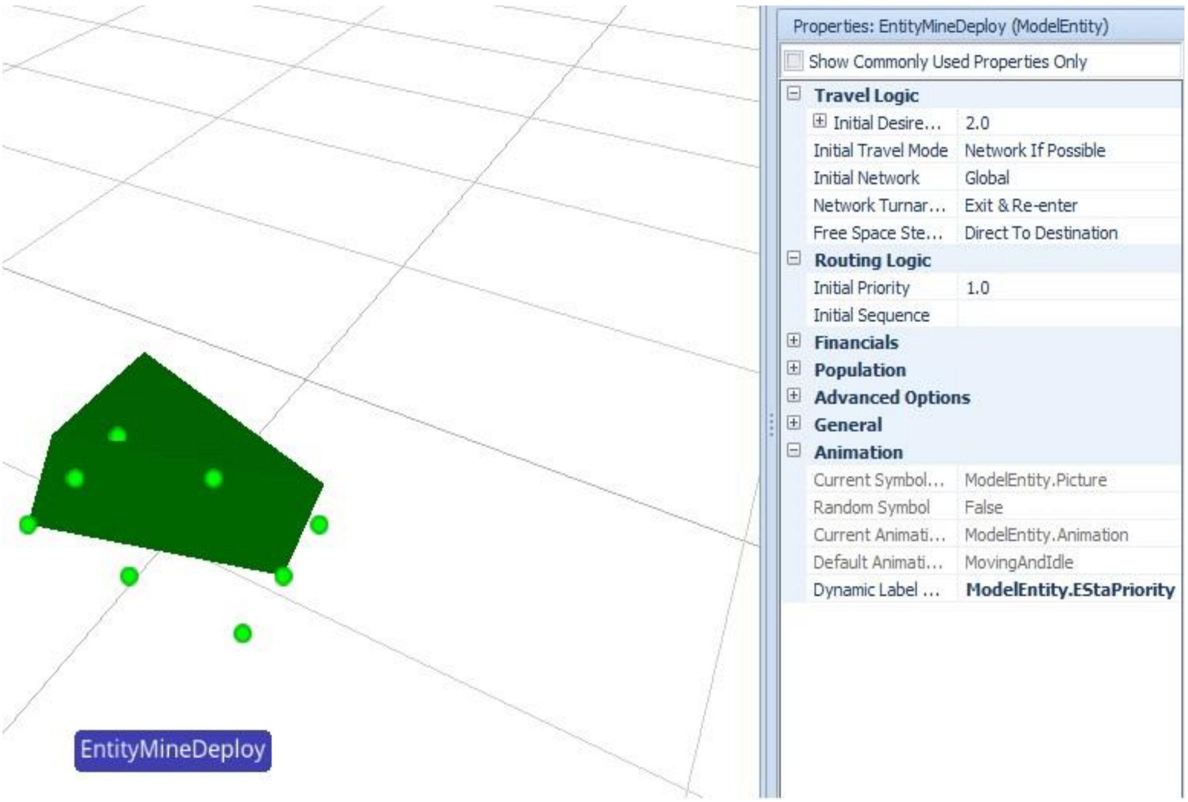


Figure 3.1: Model Entity Object in Simio (from the model)

Source objects introduce the model entities into the modeling canvas. Arrival modes, arrival rates, maximums arrivals and stopping conditions of the entities are defined through source objects.

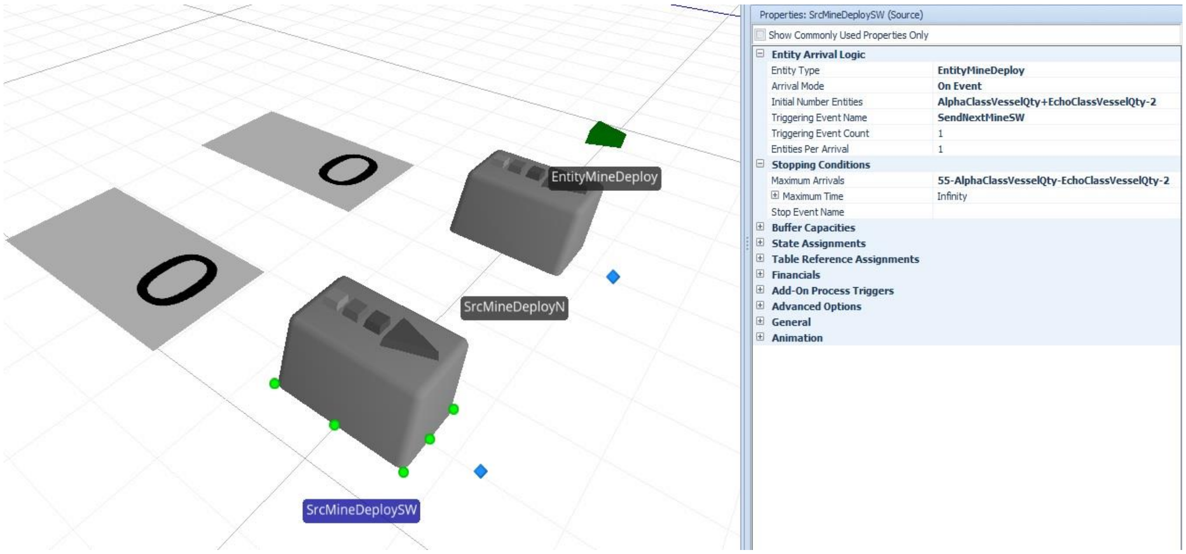


Figure 3.2: Source Objects in Simio (from the model)

Server objects are the ones that are frequently used for modeling processes, services etc. These objects can have capacity constraints, work schedules, reliability logics (failures) and secondary resource needs in order to begin processing. In the model, every segment of the channels are represented by server objects with processing times defined as a function of segment and ship parameters. It is important to note that these servers (segments) require secondary resources (ships) to begin processing (cleaning) the entities (mine deployments).

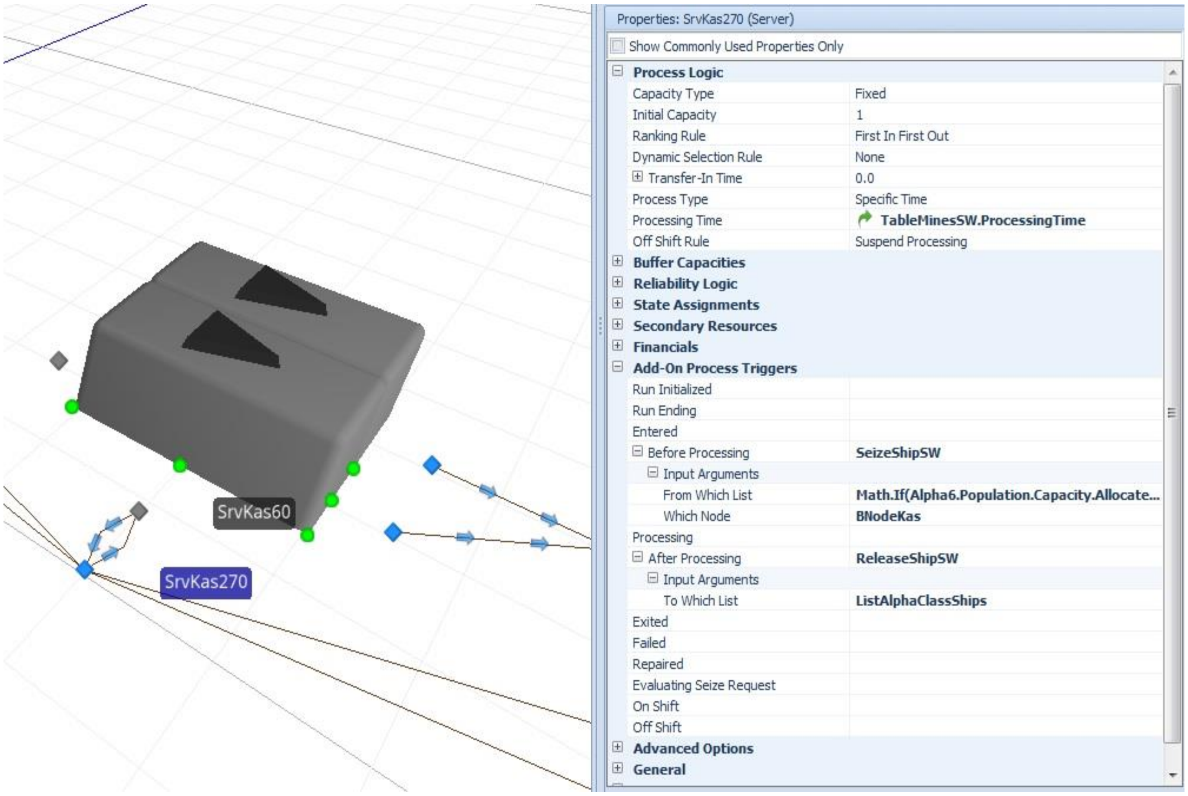


Figure 3.3: Server Objects in Simio (from the model)

Worker objects are one of the two moving transporter resources of Simio. The other transporter resource object is the vehicle object which can also move but it can't be seized for use as a secondary resource to process entities inside other objects. Because the MCM ships need to travel (move) between segments (server objects) and they also need to enter the segments (servers), neither the vehicle object nor the non-moving resource object can be used for modeling ships, but the workers can.

Figure 3.4: Worker Object (Ship) in Simio (from the model)

Basic Nodes enable the modeler to create network points, parking stations for transporters and entities as well as controlling their flow. In the model, basic nodes are used for creating parking stations and networks for workers (ships).

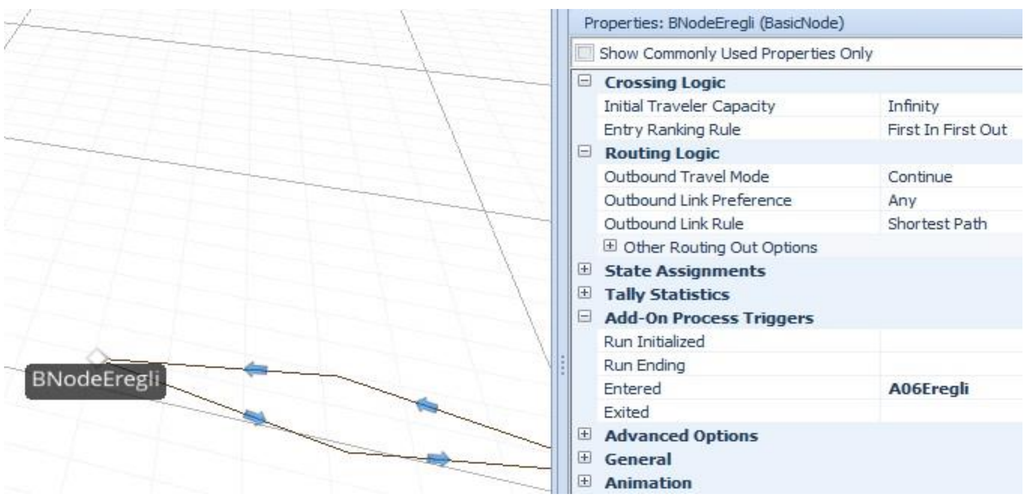


Figure 3.5: Basic Node Object in Simio (from the model)

Transfer Nodes are similar to basic nodes except that they can used for controlling destination of the transporters and entities. In the model, MCM ships need to wait for routes to be cleared. But only some the ships need to wait, others who are assigned to clear that route need to proceed and clear the route. For this reason, transfer nodes are used to select the task-assigned ships among others and to set their destination node as well.

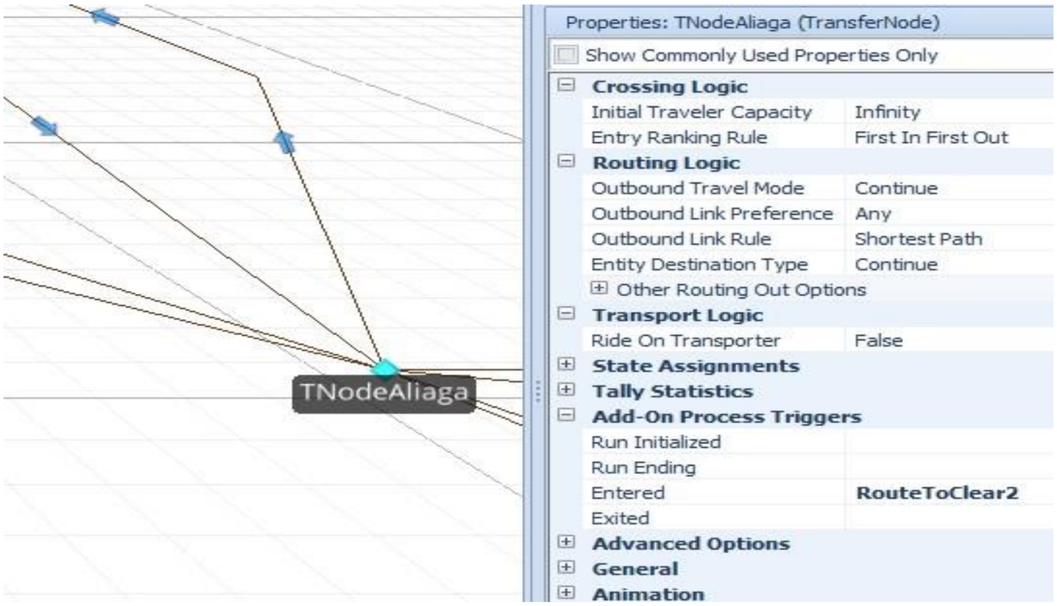


Figure 3.6: Transfer Node Object in Simio (from the model)

Connectors are one of the four link objects in Simio. The unique property of the connectors among other link objects is that connectors do not take up space or time. Thus, they are used in the model where the flow of entities and transporters should not consume any time or space.

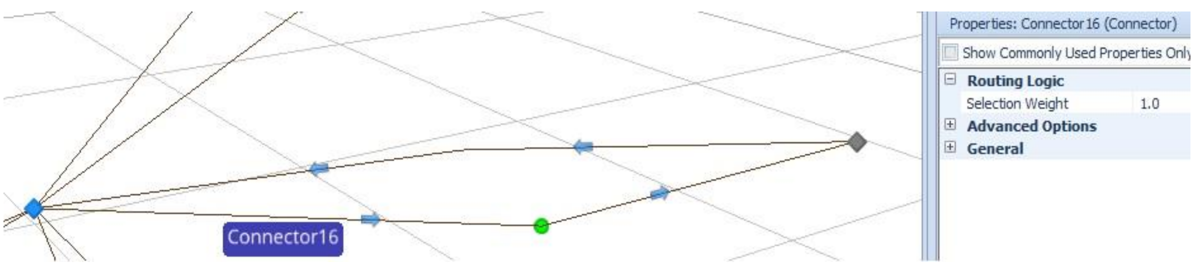


Figure 3.7: Connector Object in Simio (from the model)

Paths are other link objects of Simio. Simio has already defined distances as metric units and also in miles, including nautical miles which is definitely needed in the model. These paths can be bidirectional as well as unidirectional, but because bidirectional paths may block the flow of entities or transporters whenever two interface each other while heading to opposite directions, all the paths used in the model are unidirectional. The distance values of the paths are acquired from web based mapping tools as stated earlier.

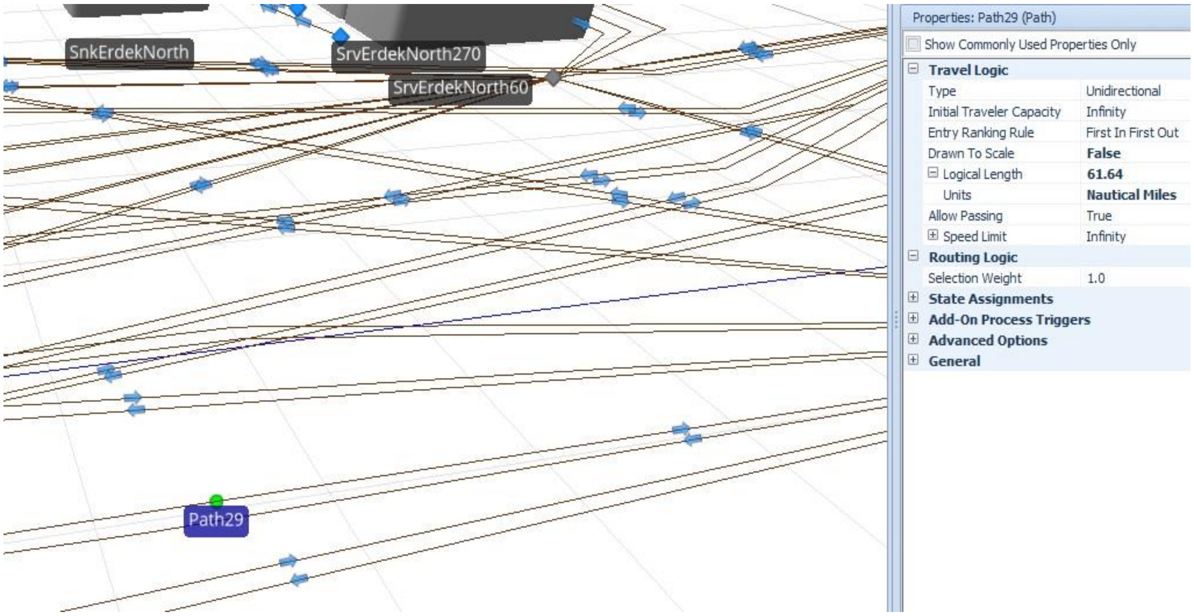


Figure 3.8: Path Objects in Simio (from the model)

Time Paths are the third kind of links that are used in the model. Time to travel can be defined either a unit time or an expression. When the time to travel is defined as epsilon, it is close to zero, which is just like connectors except that time paths have some add-on process triggers that are not defined in connector objects. In the model, time paths are used to make use of some add-on process triggers for routing purposes.

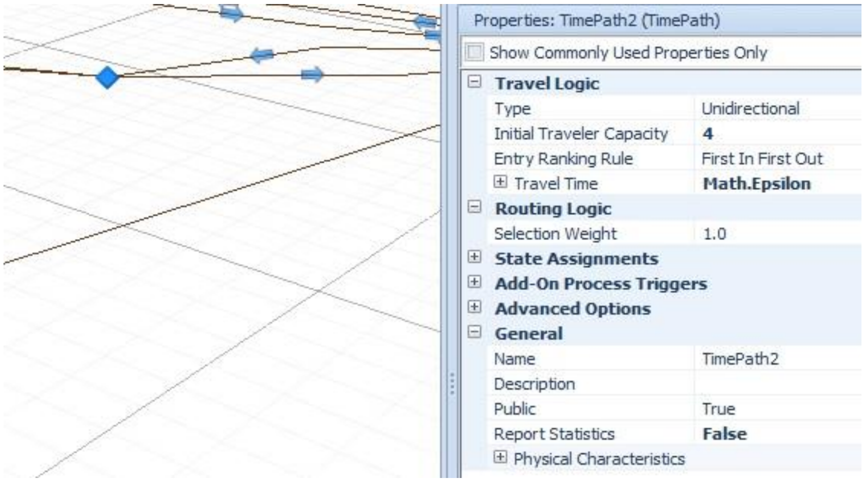


Figure 3.9: Time Path Objects in Simio (from the model)

Sinks are the objects where entities leave the system and destroyed. Sinks have certain advantages such as collecting statistics (i.e. time in system, number in system) and controlling the simulation run length. The reason for not using a single sink in the model is the need for firing events for every channel cleared, keeping independent and identical statistics for each channel and also controlling the next arrival of the entities.

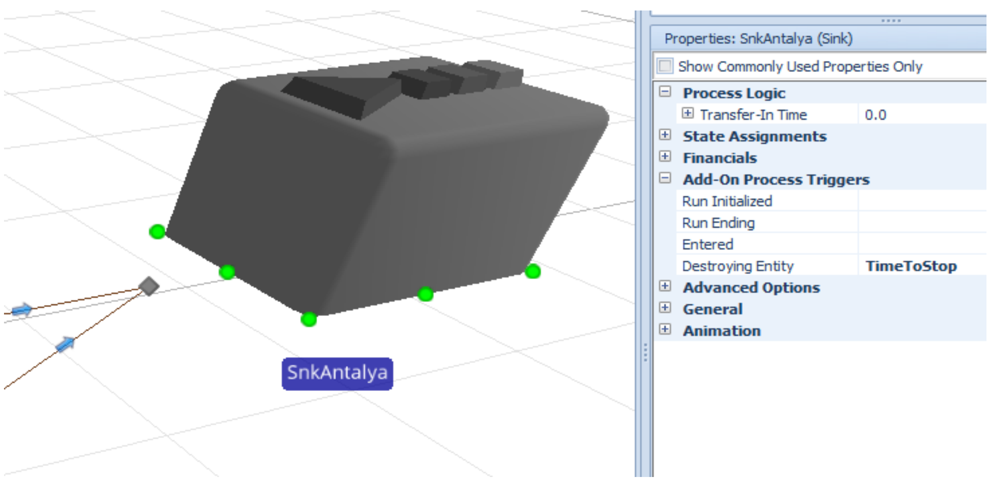


Figure 3.10: Sink Object in Simio (from the model)

3.1.3 Properties used in the model

Properties in Simio are very useful tools to make use of. The properties hold specific data types and these properties can be defined for each object in the model so that they can be referenced from the model. When any property is defined for an object it becomes the input parameter for that object with a default value which can be changed later in the model. The properties and their roles are explained as follows.

Number of Mine Deployment: This property is defined to allow multiple mine deployment within the same operation. It can be applied via source objects.

Velocity of Ship on Operation: This property is used to calculate the function that used in processing time of the server objects. Although the velocity at operation is fixed to a specific value, by defining that value as a property, the user has the velocity as an input parameter.

Mine Density: This property represents the (mine-like echo) MILEC contacts within a square nautical mile. The importance of this property is that it has a direct impact on the mine clearance efforts. The estimation of this property is provided by intelligence services and verified by the ship at the area with some classified procedures before the ship starts operation. For that reason, having this parameter defined as a property allows the user to input different estimated values to do the sensitivity analysis of the complete mine clearance operation time frame.

Time to Remove a Mine: This estimated property represents how much time (in hours) is spent by the MCM ship whenever a mine is encountered. This property is also included in the processing function of the servers so that different estimated values can be input and tested.

Channel Width: Although it was mentioned in the previous chapters that channel widths are fixed to be 600 yards, defining this width as a property in the model enables to input different values. Because this property is also included in the processing function of the servers, any change in the value has an instant impact on the model.

Effective SONAR Width: In the same way with channel width, effective SONAR width is stated as a fixed pre-determined value in the previous chapters, but having it defined as a property has no drawbacks but some advantages such as using different input values to do sensitivity analysis.

The calculation of the channel clearance time via input parameters is presented as follows.

$$ChannelClearanceTime = ChannelLength \otimes ChannelWidth \otimes ((\frac{1}{ShipVelocity \otimes EffectiveSONARWidth}) + \mathrm{MineDensity} \otimes \mathrm{TimeToRemoveMine})$$

Alpha/Echo Class Vessel Quantity: These quantities are mentioned with the numbers that are stated in Jane’s Fighting Ships catalog. Having defined these quantities as model properties allowed the writer to reach different completion times when other parameters remain unchanged.

Operation Cycle: The MCM ships need off-shift periods after operating for some amount of time so that the crew can rest and high pressure oil driven systems can cool down. The operation cycle and rest cycle sum to 48 hours. The operation cycle (On-Shift) is applied in the model as presented below (Figure 3.11).

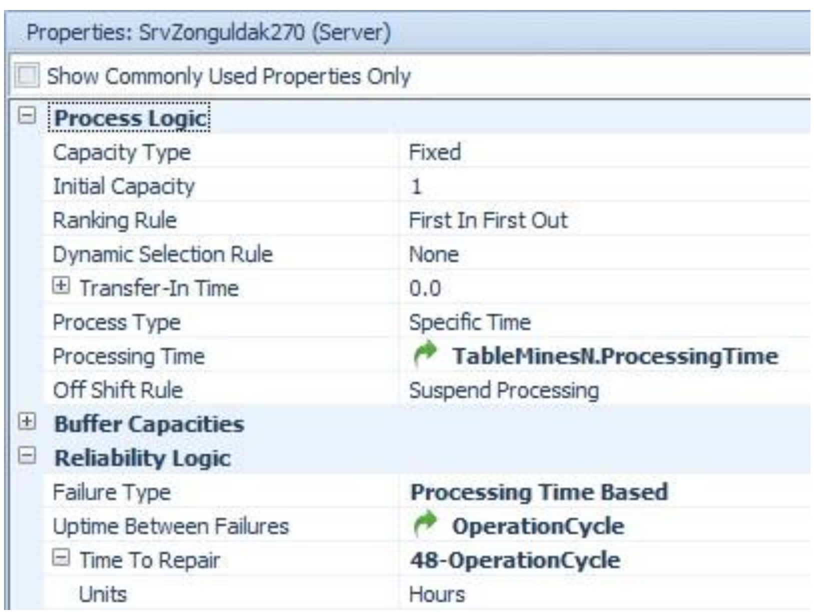


Figure 3.11: Operation Cycle Application via Reliability Logic (from the model)

3.1.4 State variables used in the model

Global and local state variable concepts of the computer engineering are adopted via model state variables and model entity state variables respectively in Simio. There are three model (global) state variables and a model entity state variable which is used for assigning priorities to the channels. Global state variables are reached from anywhere in the model, but model entity state variables are only available within model entities.

3.1.5 Events defined in the model

Simio enables users to define events in the models so that modeling becomes enhanced. Processes can be defined to be initiated whenever an event fired. This is adopted in the model of this research as well. Three types of events defined in the model for different modeling needs. First group is for forming teams need, second group is for governing the mine deployment in the north region and the last group is for governing the mine deployment to south-west region.

3.1.6 Functions, lists, tokens used in the model

The only function used in the model is for processing time of the server objects that models the mine clearance with properties stated in the previous sections of this chapter.

There are two kinds of lists defined and used in the model. The first kind is the node list which is used for controlling the paths of the MCM ships in the model. The second kind is the object list which holds the worker objects so that they are seized and released by the model entities via referring the name of the object list, i.e., List of Echo Class Ships.

Tokens execute the processes in a flow. They execute processes on behalf of the model. They also remove the need to create the same processes recurrently for different objects. Once they are defined, they can be used in multiple parts of the model. In the model, tokens are used for seizing and releasing ships and assigning priorities so that same processes with different parameters can be used within all objects.

Figure 3.12: Token Helped Seize Process Used for All North Segments (from the model)

3.1.7 Tables used in the model

One key feature of Simio that makes it very attractive is the use of tables. These tables work in accordance with Microsoft EXCEL actively. The EXCEL files can be read and written from Simio. Using tables, for that reason, provides big advantages to modelers. In the model two tables are used to read how many ships to assign on a task, how long the mine clearance needs to take, where the mine deployment is applied, and how the channel priorities are going to be. Adjusting these parameters from a table is far easier than adjusting each object.

Table 3.1: Table for South-West Region (from the model)

	Priorities	Channel Name	MCM Ship Needed	ProcessingTime (Hours)	Destination Node
1	1	ErdekNorth270	2	2.04*FuncProcessing/2	Input@SrvErdekNorth270
2	1	ErdekNorth60	2	20.45*FuncProcessing/2	Input@SrvErdekNorth60
3	2	ErdekWest270	2	12.34*FuncProcessing/2	Input@SrvErdekWest270
4	2	ErdekWest60	2	16.9*FuncProcessing/2	Input@SrvErdekWest60
5	3	GolcukBase270	2	9.19*FuncProcessing/2	Input@SrvGolcuk270
6	3	GolcukBase60	2	14.41*FuncProcessing/2	Input@SrvGolcuk60
7	7	CanakStraitNorth270	2	12.48*FuncProcessing/2	Input@SrvCanakStNorth270
8	8	CanakStraitMain60	2	81.18*FuncProcessing/2	Input@SrvCanakStrait60
9	9	IstShipyard270	2	5.47*FuncProcessing/2	Input@SrvIstShipyard270
10	9	IstShipyard60	2	1.28*FuncProcessing/2	Input@SrvIstShipyard60
11	10	YalovaPort270	2	0.59*FuncProcessing/2	Input@SrvYalova270
12	10	YalovaPort60	2	1.07*FuncProcessing/2	Input@SrvYalova60
13	11	MudanyaPort270	2	2.37*FuncProcessing/2	Input@SrvMudanya270
14	11	MudanyaPort60	2	12.88*FuncProcessing/2	Input@SrvMudanya60
15	12	BandirmaPort270	2	14.84*FuncProcessing/2	Input@SrvBandirma270
16	12	BandirmaPort60	2	12.94*FuncProcessing/2	Input@SrvBandirma60
17	13	TekirdagPort270	2	2.04*FuncProcessing/2	Input@SrvTekirdag270
18	13	TekirdagPort60	2	3.41*FuncProcessing/2	Input@SrvTekirdag60
19	14	Route1toClear270	2	89.64*FuncProcessing/2	Input@SrvRtToClear1_270

3.2 Model Definitions

The MCM scenario is defensive and the models in this study are developed on a defensive basis. The environment is the sea land of Turkey and the environmental information is supplied from open sources. The methods in the study, however, are a product of the literature and the author's three years of field experience. Even so, it should be kept in mind that any suggestion or analysis based on notional data may be misleading.

3.2.1 Region

In a mining campaign at sea, the goal of a defending nation is to open safe passage routes through the mine threat area. In this study, territorial waters of the interested country, Turkey, is divided into eight areas. These areas start from north-eastern part with one-digit ID numbers and end in the south-eastern part. It is important to note that these areas are not to be cleared but the channels resident in these areas are. The areas with ID numbers are shown below (Figure 3.13).

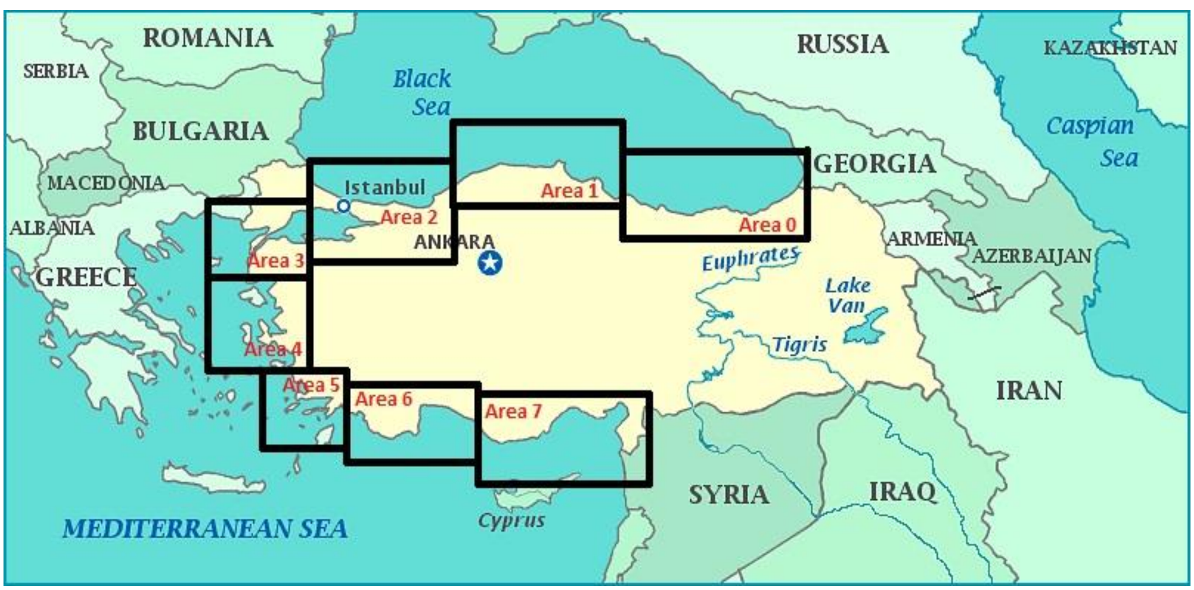


Figure 3.13: Determined Mine Threat Areas of Turkey [2]

In practice, every country has pre-determined channels within their territorial waters. These channels are fixed and their exact locations are classified. Although they may not be predicted precisely, a little information and a little work can easily approximate the exact location of these channels. The reason behind this close approximation is that these channels are built with respect to landmarks: important passage seaways, depths, safety to travel and so on. Keeping that in mind, our development of notional channels within each area are estimated between the important landmarks (i.e. ports, harbors, navy bases etc.) and the deep waters. The importance of the landmarks stems from the fact that the very first steps of a defending nation against hostile offensive mining are to open safe waterways for navy bases and to secure the sea lines of communications for trade and logistics via harbors. The landmarks are determined using maps provided on the free mapping tool websites. These maps show all landmarks including the military zones.

The safe passage routes and channels thru mine threat areas end at the point where depth exceeds the capability of a SONAR to detect bottom mines. The maximum depth (safety depth) to clear for our study is close to 270 meters which is the effective depth of TMS 2093 SONARs used in Alpha Class mine hunter ships of Tu Navy [25]. An example channel is provided below (Figure 3.14).

Figure 3.14: Sinop City Port Channel to Safe Depths (from the model)

The **channels** are supposed to be determined in peace time. These channels also need to be ordered regarding their primary importance for sea lines of communication. The channels are described with their length-width along with their locations. The characteristics of a channel are width, length (range), depth, seabed type and estimated probability of being mined. The only channel property which is a fixed number (in this study) is the channel width (c_w = 600 yards = 0.296 nm). Others may vary.

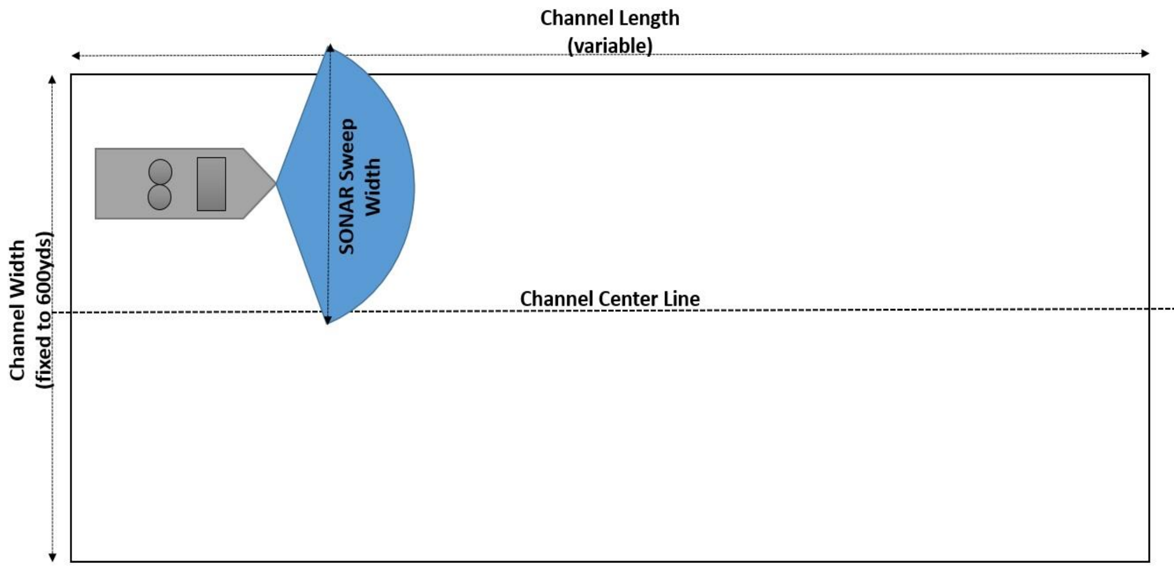


Figure 3.15: Channel Dimensions and SONAR Coverage.

In order to travel between the channels. The MCM ships need safe routes. As a reasonable approach, it is assumed (in this study) that routes on the sea depths of over 270 meters are safe. Travel routes at lesser depths need mine clearance before use. Because the operational and travel speeds of MCM ships are different, mine clearance operations on routes (before they can be used) will contribute to total completion time of the operations. The channels to clear, the routes to clear and the routes to travel are built using web-based mapping tools (i.e. www.map.openseamap.org). In order to determine the total area to perform mine clearance operations, length of channels/routes are multiplied by the fixed channel width (600 yards). Due to the fact that channels are expected to be scattered around the continent, travel times between channels play a big role on the completion time of clearing operations. To minimize travel distances, elaborate scheduling of the vessels becomes a primary concern. The estimated channels/routes to clear and distances are presented below (Table 3.2).

Table 3.2: Self-Determined Landmarks and Channels Information

DERIVED CHANNEL AND ROUTE DISTANCES TO PERFORM MINE CLEARANCE OPERATIONS					
ID	Name of the Port/Base	0-60m depth length (nm)	60-270m depth length (nm)	Total Distance (nm)	Areas
1	Port of Rize City	0.86	0.98	1.84	Area1
2	Port of Trabzon City	0.33	1.59	1.92	
3	Port of Giresun City	0.5	1.02	1.52	
4	Port of Ordu City	3.71	4.12	7.83	
5	Port of Fatsa City	0.49	1.45	1.94	
6	Port of Samsun City	3.65	3.07	1.989	Area2
7	Port of Sinop City	7.42	3.66	11.08	
8	Port of Amasra City	2.78	1.53	4.31	
9	Port of Zonguldak	1.57	1.44	3.01	Area3
10	Base of Eregli	3.08	4.29	7.37	
11	Port of Karaburun City	13.45	10.57	24.02	
12	Istanbul Strait North	0	10.11	10.11	
13	Istanbul Strait Main	20.37	0	20.37	
14	Istanbul Strait South	0	6.41	6.41	
15	Base of Golcuk	14.41	9.19	23.6	
16	Istanbul Naval Shipyard	1.28	5.47	6.75	
17	Port of Yalova City	1.07	0.59	1.66	
18	Port of Mudanya City	12.88	2.37	15.25	
19	Port of Bandirma City	12.94	14.84	27.78	
20	MCM Base of Erdek (North)	20.45	2.04	22.49	
21	MCM Base of Erdek (West)	16.9	12.34	29.24	
22	Port of Tekirdag City	3.41	2.04	5.45	
23	Canakkale Strait North	0	12.48	12.48	Area4
24	Canakkale Strait	81.18	0	81.18	
25	Port of Gokceada Island	14.83	0	14.83	
26	Route to Clear 1	0	89.64	89.64	Area5
27	Port of Aliaga Rafinery	1.22	11.35	12.57	
28	Route to Clear 2	0	11.18	11.18	
29	Base of Foca	1.46	9.12	10.58	
30	Route to Clear 3	0	0	0	
31	Port of Izmir City	37.64	9.12	46.76	
32	Route to Clear 4	0	83.02	83.02	
33	Port of Kusadasi City	2.51	3.6	6.11	
34	Route to Clear 5	0	73.17	73.17	Area6
35	Port of Bodrum City	2.13	3.57	5.7	
36	Route to Clear 6	0	83.04	83.04	
37	Base of Aksaz	10.01	10.97	20.98	
38	Port of Fethiye City	3.36	2.66	6.02	
39	Port of Kas City	0.69	1.2	1.89	Area7
40	Port of Antalya City	0.3	1.82	2.12	
41	Port of Alanya City	1.17	1.09	2.26	
42	Port of Tasucu City	10.64	5.34	15.98	Area8
43	Base of Mersin	6.27	6.47	12.74	
44	Route to Clear 7	0	43.12	43.12	
45	Route to Clear 8	25.47	0	25.47	
46	Port of Yumurtalik Rafinery	18.96	0	18.96	
47	Base of Iskenderun	13.26	0	13.26	
48	Port of Cyprus Island	1.6	4.75	6.35	
	Totals	374.25	565.83	935.349	

The routes between channels are drawn in a way that they do not interfere with territorial waters of neighboring countries. Travelling on the routes located in the territorial waters of other countries' waters is prohibited. Thus, this adds to the completion times for transit as courses orbit a lot to avoid interference. For the geographical region of this study, the time added due to orbits is significant because the Aegean Sea between Turkey and Greece has a large number of islands. An estimated course for a ship avoiding interference with the Greek territorial waters is shown below (Figure 3.16).

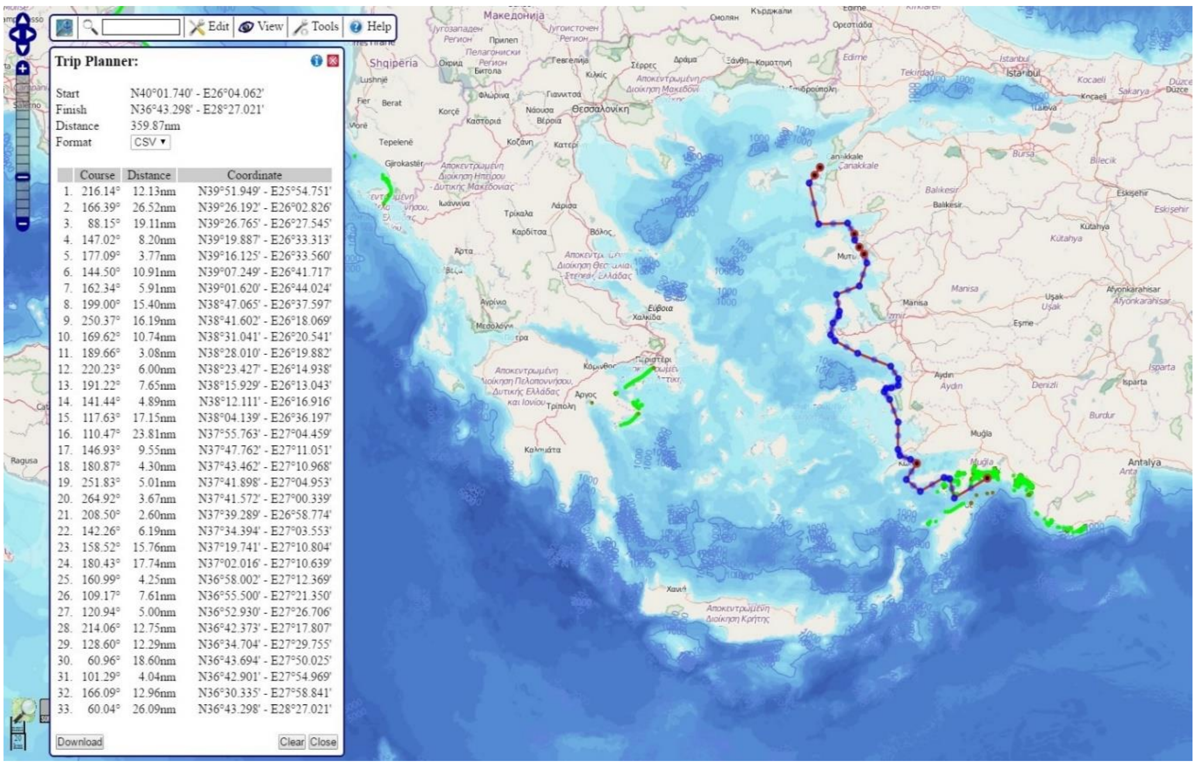


Figure 3.16: A Route from North to South Respecting Neighboring Country's Sea Lands

Channels are also dispersed over whole territorial waters. Because the depths vary, **segments** are determined within the channels and they are assigned to different kinds of MCM ships, either to an Alpha class or to an Echo class. Multiple segments can be allocated to a single MCM unit and vice versa. There can be restrictions on assigning MCM units to clear a segment. For example, Echo Class Mine Hunter Coastal (MHC) ships of Tu Navy have hull-mounted SONARs which enable them to detect only the mines deployed not deeper than the maximum effective depth for ground mines. The **seabed**

type is important because it effects the SONAR echo which may make detection difficult. If it is rock then detection is less probable. If it is too soft and the probability soil burial is high, it may be covered and a SONAR echo would not reflect the contact. The best known method for detecting difficult targets under water (i.e. buried mines) is using sea mammals which have bio-sonars and higher diving capabilities than humans [27]. But for the data set of this study there are no such sea mammal units, and there is no need because the areas of interest have low likelihood of burial.

Figure 3.17: Moored and Bottom Mine Reconnaissance and Clearance by Sea Mammals [10]

The disadvantage of complete burial and impeding rocky seabed type is expected to be exploited by an enemy. Thus, it is clear that the **probability of being mined** will be different for each segment of the dataset. This probability can be estimated, but it only has impact on the order that the channels need to be considered. Basically it will imply the primary order of a mine endangered channel to be cleared by MCM units. Factors that constitute the probability of mining would be necessary and sufficient to give the sense of determining the order to follow and they are explained as follows.

Use by the Defending Navy: In order to prevent a defending nation from taking further actions, the sea routes that are estimated to be used by a defending nation's navy would be under sincere consideration of an enemy.

Traffic Density of the Channel: Although an enemy would not like to engage other nations than the defending one, it would still try to deploy mines to impair the logistics sea lines of the defending land that are critically important to sustain defense.

Sea Bed Type of the Channel: Sea bed type plays a big role in detecting mines. Extreme kinds of the sea beds (i.e. rocky or too soft/absorbing) impedes mine detection efforts. This may be exploited by an enemy if there are routes passing over detection-difficult sea bed regions.

Distance of the Channel from the Defending Land: Mine laying is fairly easy but it still should be carried in a covert way. The channels located away from the observation of the defenders have higher likelihood of being mined. In addition, being detected by the defending nation while mine laying could require an enemy to make drastic changes in their plans.

Clutters, Sea Current: A SONAR signal is transmitted from bow line of the ship in order to hit an object and return. Along with clutter (sea animals, particles etc.) the current of the sea plays a role in detection, diving and AUV efforts. Thus, the areas with high sea current have a higher probability of being mined than other areas with low or no sea current.

Distance from the Enemy's Reach: The longer the distance, the lesser the attraction rule applies when an enemy's reach to a channel is considered.

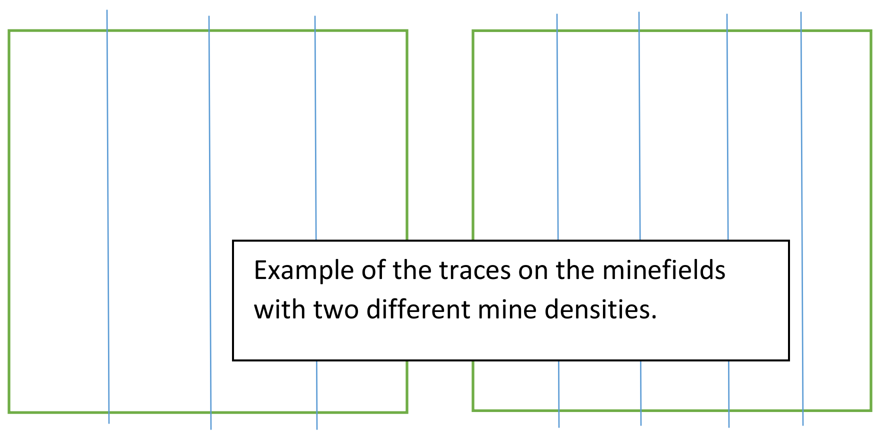
In a mine clearance operations at sea, traces are determined and plotted on maps to be followed by MCM platforms. In order to plot the traces on the mine threat area **mine density**, mine per nautical miles (NM) square, is estimated. The procedure for this estimation is NATO confidential but the estimated values are not. In this estimation process there can be two types of prediction errors. Estimated mine density may be greater than the true value. This type of error (Type-I) results in more

MCM efforts than needed by requiring more traces of the minefield. Overlaps of the SONAR sweeps are tolerated so as not to skip any mines.

Table 3.3: Types of Errors in Estimating Mine Density

Estimating low while the true value is low **Hit**	Estimating high while the true value is low **Type-I Error**
Estimating low while the true value is high **Type-II Error**	Estimating high while the true value is high **Hit**

It is also possible to estimate the mine density less than the true value. This type (Type-II) of estimation error is not desired because it will increase the gaps between traces raising the probability of skipping a mine (which can prove fatal).



Figures 3.18-19: Traces for Mine Density=3 mines/nm^2, Mine Density = 5 mines/nm^2

3.2.2 Mine threats

Naval mines have undergone continuous evolution since they were first used centuries ago. Recent advances in the naval mines has made it difficult to classify them. But, classification is still necessary to introduce them to readers of this paper. Naval mines can basically be classified by their position at sea after deployment, and by their activation method. Yet, there are still some kinds of naval mines which cannot be placed in one of these groups. These special mines are presented in this study as unusual mines. Every kind of mine can be different in size, which makes them unequally detectable.

MINES[29]

Position at Sea	Detonation Logic	Unusual Mines
Drifting Mines	Contact Mines	Bouquet Mines
Moored Mines	Influence Mines (i.e. magnetic)	Anti-Sweep Mines
Ascending Mines	Selective (Smart) Mines	Homing/Rising Mines
Oscillating Mines (Rise & Ebb)	Limpet (Detachable) Mines	Mobile Mines
Daisy-Chained Mines		Nuclear Mines
Ground/Bottom Mines		Dummy Mines

Figure 3.20: Mine Types

Damage caused by naval mines can also vary. They may cause direct damage after an explosion. Direct damage usually is caused by contact or limpet mines. The bubble jet effect is another kind of damage caused by naval mines. This kind of damage occurs when a mine detonates in the water a short distance from the target platform.

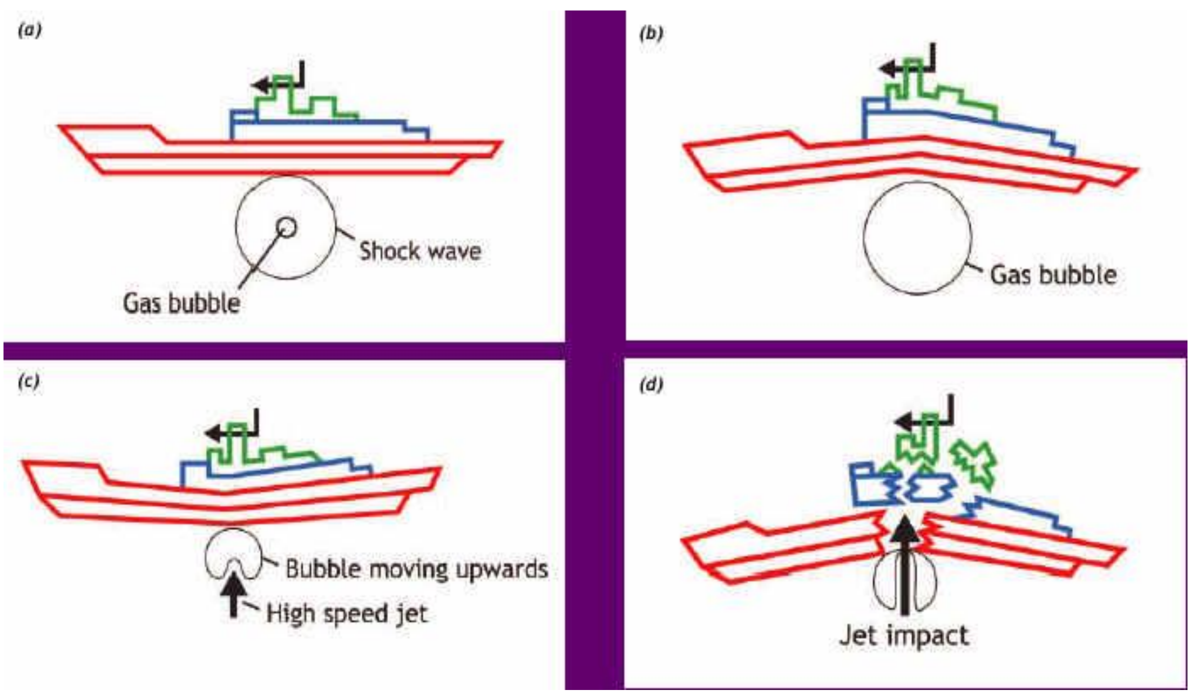


Figure 3.21: The Bubble Jet Effect [23]

The last kind of damage is the shock effect. This effect is the most dangerous for navy platforms because when a mine explodes at a distance from the ship, it causes the whole ship to resonate. The common consequences of this resonation are ripping machines off their beds and tossing everything on board around.

3.2.3 MCM assets

According to the scenario, the sea land of Turkey undergoes comprehensive mine clearance by the MCM platforms of the Tu Navy. These platforms are, as stated in JFS, 6 Alpha Class MHC ships, 5 Echo Class MHC ships and 8 mine sweeping ships. At the Turkish Naval Forces Command's website however, there are 4 mine sweeping ships. The remaining mine sweeper ships are well past their expected lifetime, and there is a widespread trend for adopting mine hunter ships rather than mine sweepers. For that reason, only mine hunter ships of the inventory are included in this paper.

Figure 3.22: Detection with TMS 2093 Variable Depth SONAR (VDS) [9]

The main difference between the Alpha and Echo class MHC ships is the SONAR's operational position on the ship, which puts a constraint on the maximum detection depth of the mines. The Alpha class MHC ships have Thales® TMS 2093 Variable Depth Sonar (VDS) which enables them to detect mines located deeper than the Echo Class MHC ships do with hull-mounted SONARs. The Echo Class MHC ships with hull-mounted SONARs have a restricted depth range. The difference between the two kinds of ships plays a primary role on the assignments of tasks to the MHC ships.

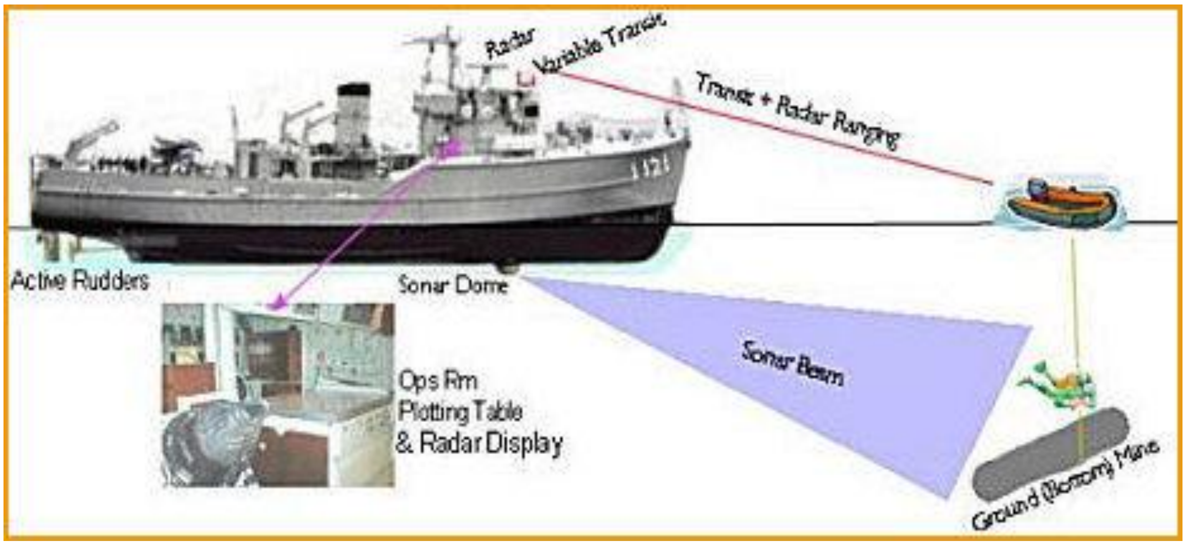


Figure 3.23: Detection and Neutralization with Hull-Mounted SONAR [20]

Aside from the SONAR based differences, the Alpha and Echo Class MHC ships share properties in common such as speeds, operation cycles, crews etc. Unless stated specifically, it is assumed that the Alpha and Echo Class MHC ships have the properties in common. The common notional properties of the two kinds of MHC ships used in this research are extracted from JFS and are listed below.

- Effective SONAR Cover Width = 350 yards = 0.173 nm
- Maximum Effective SONAR Range (at stop) = 450 yards = 0.222 nm
- Operational Speed = 3 knots (kts, nm/hr)
- Economic/Travel Speed = 10 kts
- Maximum/Emergency Speed = 14 kts
- Cover area per pass = 3 nm/hr x 0.173 nm = 0.519 nm^2

3.2.4 Modeling logics

In the model every server object represents a search segment with a depth indicator tag which is either 60 meters or 270 meters (i.e. SrvErdek270). The categorization stems from the fact that Echo Class MCM ships have a detection depth constraint due to having hull-mounted SONARs. The server objects have processing times which are a function with different parameters as presented earlier in this chapter. The required off-shift periods of the MCM ships are represented by reliability logics of the server objects that are based on processing times. Whenever the server objects processes more that the on-shift period, they fail for a specified amount of time. Because the ships execute mine clearance operations, server objects need to wait for secondary resources which are worker objects before starting operations. This is applied in the model via secondary resource needs of the server objects. Every segment requests secondary resources from its designated worker object lists, i.e. segments in the north request from north group and segments in the west/south request from their worker object list.

The MCM ships are simulated by worker objects in the model. They choose the next segment with respect to priorities assigned as presented earlier in this chapter. The match between the workers and the segments is done by “the closest distance available”. If there is none available, selection is made by sequence of the workers in the object list. The two ships in the north worker object list are called for other areas only after they complete their clearance operation in the north. This logic is applied by using a combined list of worker objects. The travel speeds (nautical miles/hour) are applied via the travel speeds of the worker objects. Operational speeds are fixed and embedded in the processing function for each segment.

Routes that need mine clearance before use are simulated by server objects are well. Travel distances, on the other hand, are modeled by the path objects in Simio.

It is also important to note that ships need to form teams before starting mine clearance in a channel. The reason is that either 60 m. or 270 m. segments can be located at the entrance of the channel. This forming team rule is adopted in the model via basic nodes. The condition for team forming is tested within each basic node which are entrance and exit points of the segments. The testing process for Erdek Channel (north) is shown below (Figure 3.24).

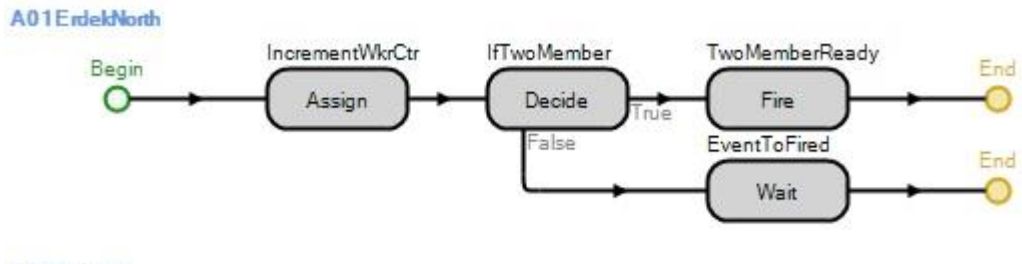


Figure 3.24: Team Forming Condition Testing Process (from the model)

Allowing only the assigned MCM ships to enter and blocking other ships to enter the routes that need mine clearance before use constraint is applied within transfer node objects.

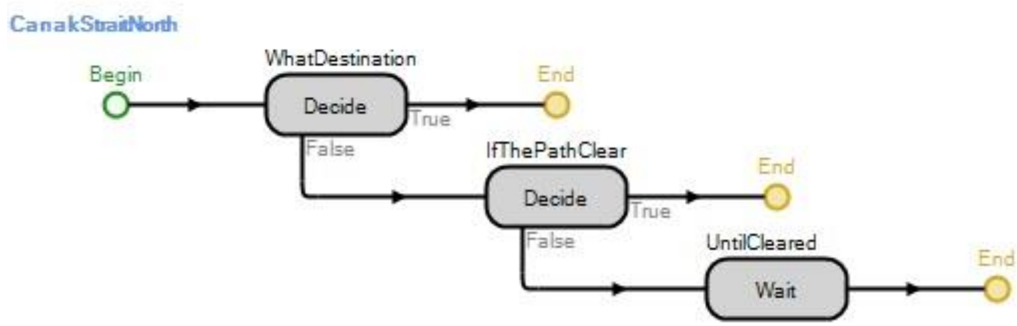


Figure 3.25: Allowing On-Duty Ships and Blocking Transit Ships Process (from the model)

In order to control and stop the simulation run, sink objects and processes are used for each channel. Whenever the last entity leaves the system that means all mine clearance operations are completed, then the simulation run is stopped.

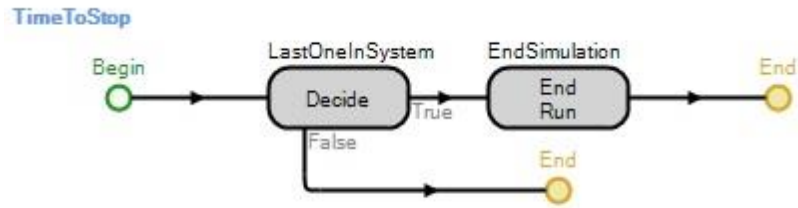


Figure 3.26: Ending Simulation Run Process (from the model)

3.2.5. Modeling assumptions

1. The model scenario is based on the worst case, which is a common sense approach for defense area studies. In the model, it is assumed that every channel needs mine clearance operations because mine existence has been reported at one of the channels.

2. Multiple mine deployments to the same channel is not allowed as the defending nation will be alert to prevent further deployments.

3. Because the maximum depth to detect mines is 270 meters, routes that pass over this depth are considered to be safe. It is important to note that whatever the mine's explosive charge is, the maximum depth for a mine to damage a surface ship is around 60 meters. For that reason, the assumption of safe routes is valid.

4. The channel clearance priorities (orders) are pre-determined considering the geographical and tactical factors for defending nation.

5. Sea and weather states are favorable for mine clearance operations all the time.

6. Because segment widths are fixed to 600 yards and SONAR sweep widths are fixed to 350 yards, no more than two mine clearance ships are allowed to work in the same segment.

7. Assignments of clearance operations for the ships is controlled from the headquarters on land and assignment criteria is "closest available". Thus, utilization of identical ships may vary.

8. MCM ships are identical within the same classes (Alpha or Echo class). The sole main difference between the classes is the maximum mine detection depth. The reason for difference originates from the SONAR locations. For Alpha class mine hunter ships it is a variable depth SONAR (VDS), for Echo class mine hunter ships the SONAR is hull-mounted.

9. Replenishment of fuel and human needs is provided at sea. As a result, there is no need to leave an operation and go to a harbor.

10. Because all the navy ships are built with system-device spares, reliability of the mine clearance units is continuous.

11. At the start, all MCM vessels are ready for operation and they are located at a single specific harbor.

12. Because the MCM ships are constructed such that they do not activate mines that other vessels activate, it is assumed that there is no threat posed by sea mines to the MCM ships.

13. As all the channels are located within territorial waters close to land with depths less than 270 meters, it is assumed that the MCM ships are fully protected from any kind of attack by other forces.

14. The number of MCM vessels remains the same throughout the operation. Due to the lengths of mine threat areas, two of the total number of ships are primarily responsible for the Black Sea. When these MCM ships are finished with tasks in the Black Sea, they can be called for tasks in other areas with the rest of the MCM vessels.

15. In order to start operations in a channel with two segments, first teams of 2 or 4 ships need to be formed. Team members do not start clearance until the last member of the team arrives. Whenever one the team member has completed the task assigned, it can depart independently for the next task assignment.

16. When two MCM vessels are assigned to work within the same segment, assumptions below are made:

- They independently work without affecting each other's operation.
- Diver teams are not bothered by SONAR transmissions of other vessels.
- Travel times from the end point to the starting point of the segment are ignored.

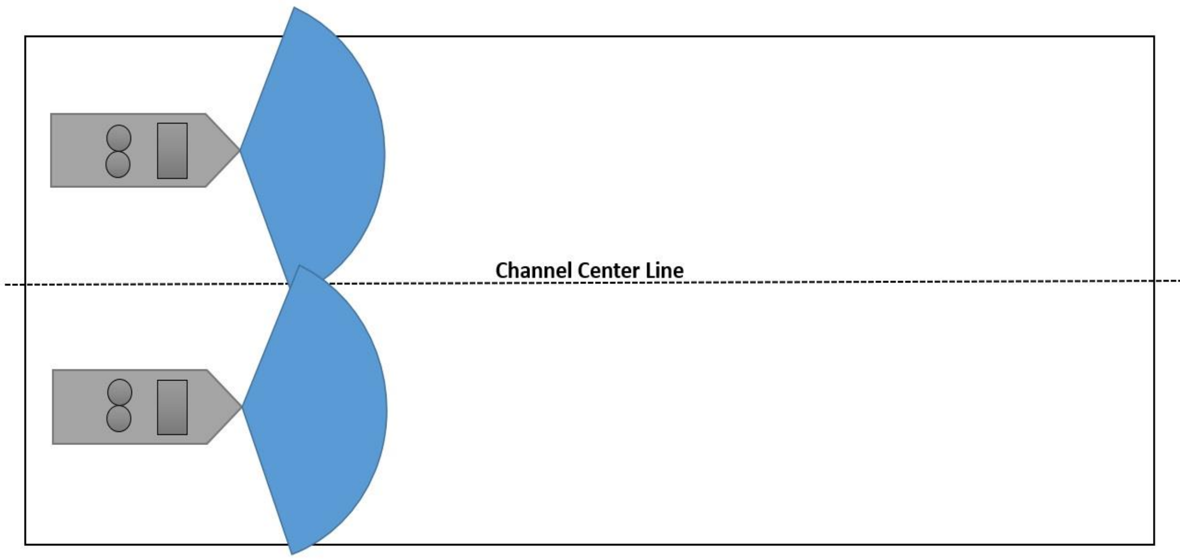


Figure 3.27: Two Ships Working in a Segment

17. Off-shift periods of the ships, which is represented via failure of the server objects in the simulation, is after 36 hours of continuous operation.

Chapter 4
Model Development

The model of MCM vessels dynamic allocation and scheduling is developed with the estimated parameters, existing literature, and personal field experience logic, as well as reasonable simplifying assumptions. The parameter values are applied to model via intelligent objects of the Simio software.

4.1 Initial Model

In order to approach the problem of this study, an initial model is developed. Then it is improved step by step. The improvement is done by running the model and observing the results. The initial model has the characteristics as presented below.

- Assignment of ships to segments is done at the beginning of the simulation, and is kept until completion. In other words, allocation of the ships are not dynamic, but static.
- The ships are not divided into mission groups such as north group and south-west group. This means a vessel may travel a long distance between two assigned segments.
- Channels priorities (order to clear) are determined in consideration of the factors that play a role in the calculation of mining probability as stated in Chapter 3.
- Every segment is cleared by a single mine clearance vessel.
- The input parameter values used in the initial model are;

  Number of Mine Deployments: 1 throughout the simulation

  Velocity of Ships on Operation: 3 knots (Nautical Miles per Hour)

  Mine Density: 0.5 Mines per Nautical Miles Square

  Time to Remove a Detected Mine: 1 Hour per Mine

  Channel Width: 600 yards

  Effective SONAR Width: 350 yards

  Number of Alpha Class MCM Vessels: 6

Number of Echo Class MCM Vessels: 5

The channels that are located at three different seas and their priorities are as shown below (Table 4.1).

Table 4.1: Channels Information

Priority	Channel	#of Ships	Priority	Channel	#of Ships
1	Erdek North	1	25	Yumurtalik port	1
2	Erdek West	1	26	Zonguldak port	1
3	Golcuk Base	1	27	Tasucu port	1
4	Ist Strait South	1	28	Bandirma port	1
5	Ist Strait Main	1	29	G.Ada port	1
6	Ist Strait North	1	30	Mudanya port	1
7	Canak Strait North	1	31	Yalova port	1
8	Canak Strait Main	1	32	Tekirdag port	1
9	Route 1	1	33	Amasra port	1
10	Route 2	1	34	Sinop port	1
11	Route 3	1	35	Samsun port	1
12	Route 4	1	36	Fatsa port	1
13	Route 5	1	37	Ordu port	1
14	Route 6	1	38	Giresun port	1
15	Aksaz Base	1	39	Trabzon port	1
16	Foca Base	1	40	Rize port	1
17	Eregli Base	1	41	Karaburun port	1
18	Mersin Base	1	42	Kusadasi port	1
19	Route 7	1	43	Bodrum port	1
20	Route 8	1	44	Fethiye port	1
21	Iskenderun Base	1	45	Kas port	1
22	Istanbul Shipyard	1	46	Antalya port	1
23	Izmir port	1	47	Alanya port	1
24	Aliaga port	1	48	Cyprus port	1

The completion time of this model resulted in **741.5 hours** (30.9 days) which appears to be fairly high in terms of early military actions. Thus, improvement in the methodology is needed.

In order to visualize the Turkey's territorial waters that host the channels of this study, a map is provided below. (See Figure 4.1)

Figure 4.1: Map of Turkey with Coastal City Port and Channel Names [6] (See Table 4.1 Above)

4.2 Model Improvements

In the initial model, channel priorities are determined regarding the factors which play role in calculation of the probability of mining. An observation made based on the simulation run is that there are idle ships which are waiting inside the Marmara Sea, while at the same time there are some channels which wait to be cleared in the Marmara Sea too. Thus, an approach is adopted to assign the channels in the Marmara Sea to the idle ships so as to improve the utilization of the MCM vessels. Now that they spend less time waiting as idle. Because only the assigned MCM vessels proceed to clear the route while others wait, utilizing the waiting MCM vessels may contribute to minimizing the completion time of clearance operations.

The utilization is adopted only in the Marmara Sea which has two straits connecting it to the Black Sea and the Aegean Sea. As the assigned MCM vessels operate in the straits, others need to wait until the straits are cleared before passing thru. Instead of keeping these waiting ships idle, channels with low priorities located in Marmara Sea are assigned to these idle ships.

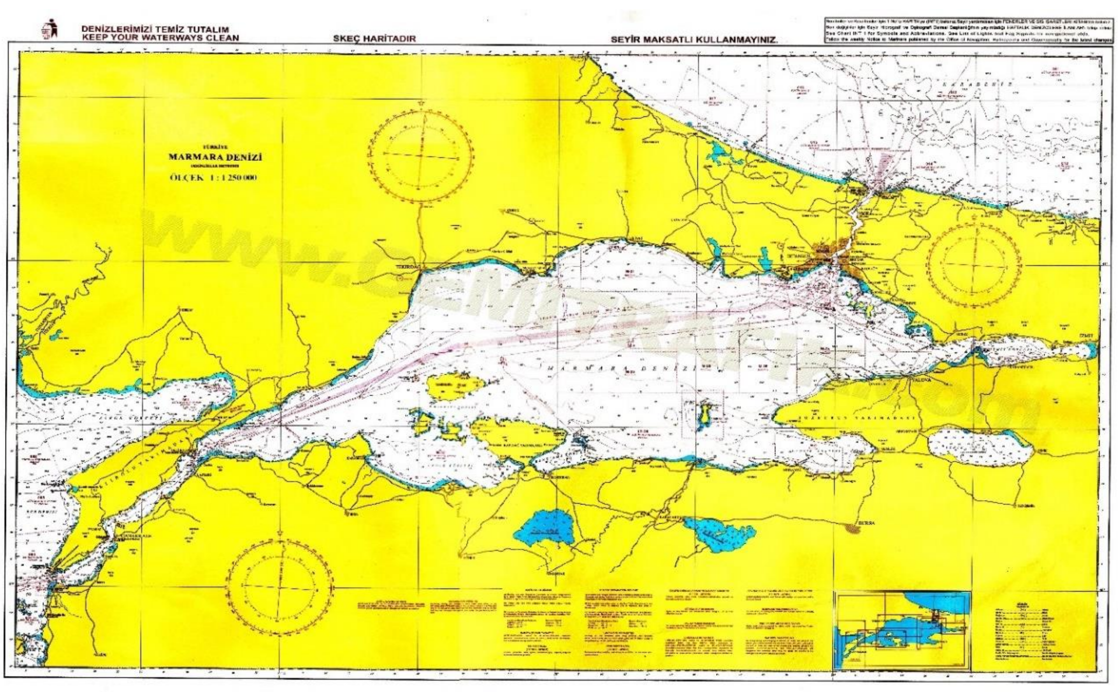


Figure 4.2: The Marmara Sea Connects the Aegean Sea (Left) and the Black Sea (Upper Right)

Another observation made from the first simulation is that instead of assigning one vessel per segment, two vessels can be assigned to a segment. In total there are four different scenarios to test, two different options for utilization (utilize or not utilize) and two different options for the number of vessel assignments for each segment (one or two vessels). A drawback of assigning two vessels to a segment is that team forming may take some time and if the segment is small (can be cleared in a small period of time) then travel time to that segment may be greater than the clearance time that makes the extra unit assignment futile. So the more ships/less time premise may not be necessarily valid. To answer these questions, four different cases are modeled, keeping the other parameters unchanged.

Case 1: Not utilizing waiting vessels and one vessel per each segment. That resulted in a completion time of 741.5 hours (30.89 days) (i.e., the initial model).

Case 2: Not utilizing waiting vessels and two vessels per segment. That resulted in a completion time of 885.53 hours (37 days).

Case 3: Utilizing waiting vessels and one vessel per segment. That resulted in a completion time of 749.58 hours (31.23 days).

Case 4: Utilizing waiting vessels and two vessels per segment. That resulted in a completion time of 706.94 hours (29.46 days).

The results of the four cases imply increasing the number of vessels assigned to the segments and utilization of idle ships may contribute to earlier completion. Another observation made from the model runs is that as the model allocates the MCM vessels to the segments once at the beginning of the operation, there are vessels that travel huge distances between two consecutive tasks. To solve this issue, two approaches are adopted. First, the MCM vessels are divided into two groups depending on the workload anticipated. Groups created are the north group and the south-west group with 1 Alpha and 1 Echo, and 5 Alpha's and 4 Echo's respectively. Second, every channel is evaluated individually before deciding how many vessels need to be assigned (see Tables 4.3 and 4.4). The scenario is still within the Marmara Sea. The Vessels groups and segments within the channels information for the groups with priority values (orders) are as shown in Tables 4.2, 4.3 and 4.4 below.

Table 4.2: Groups of MCM Vessels

North Group Vessels	Alpha-6 and Echo-5
South-West Group Vessels	Alpha 1,2,3,4,5 and Echo 1,2,3,4

Table 4.3: Segments of the Channels (see Table 4.1) and Vessel Information for South-West Group of Vessels

Priority	Segment	#of Ships	Priority	Segment	#of Ships
1	ErdekNorth270	2	21	IzmirPort60	2
1	ErdekNorth60	2	22	Route5ToClear270	2
2	ErdekWest270	2	23	KusadasiPort270	2
2	ErdekWest60	2	23	KusadasiPort60	2
3	GolcukBase270	2	24	Route6ToClear270	2
3	GolcukBase60	2	25	BodrumPort270	2
7	CanakStraitNorth270	2	25	BodrumPort60	2
8	CanakStraitMain60	2	26	AksazBase270	2
9	IstShipyard270	2	26	AksazBase60	2
9	IstShipyard60	2	28	MersinBase270	1
10	YalovaPort270	2	28	MersinBase60	1
10	YalovaPort60	2	29	Route7ToClear270	2
11	MudanyaPort270	2	30	Route8ToClear60	2
11	MudanyaPort60	2	31	IskenderunBase60	2
12	BandirmaPort270	2	32	YumurtalikPort60	2
12	BandirmaPort60	2	34	TasucuPort270	1
13	TekirdagPort270	2	34	TasucuPort60	1
13	TekirdagPort60	2	44	FethiyePort270	1
14	Route1toClear270	2	44	FethiyePort60	1
15	GokceadaPort60	2	45	KasPort270	1
16	Route2ToClear270	2	45	KasPort60	1
17	AliagaPort270	2	46	AntalyaPort270	1
17	AliagaPort60	2	46	AntalyaPort60	1
18	Route3ToClear270	2	47	AlanyaPort270	1
19	Route4ToClear270	2	47	AlanyaPort60	1
20	FocaBase270	2	48	CyprusPort270	1
20	FocaBase60	2	48	CyprusPort60	1
21	IzmirPort270	2			

Table 4.4: Segments of the Channels (see Table 4.1) and Vessel Information for North Group of Vessels

Priority	Segment	#of Ships	Priority	Segment	#of Ships
4	IstStraitSouth270	1	38	Fatsaport60	1
5	IstStraitMain60	2	38	FatsaPort270	1
6	IstStraitNorth270	1	39	OrduPort60	1
27	EregliBase60	1	39	OrduPort270	1
27	EregliBase270	1	40	GiresunPort60	1
33	ZonguldakPort60	1	40	GiresunPort270	1
33	ZonguldakPort270	1	41	TrabzonPort60	1
35	AmasraPort60	1	41	TrabzonPort270	1
35	AmasraPort270	1	42	RizePort60	1
36	SinopPort60	1	42	RizePort270	1
36	SinopPort270	1	43	KaraburunPort60	1
37	SamsunPort60	1	43	KaraburunPort270	1
37	SamsunPort270	1	43	KaraburunPort60	1
38	Fatsaport60	1	43	KaraburunPort270	1

In Tables 4.3 and 4.4, the numbers 60 and 270 after names of the channels stand for depths and they refer to different segments within the same channel. As there is only one type from each MCM vessel class in the north group, assignments are restricted to one. Even with one vessel per MCM class, it is observed in the model that north group vessels finish their tasks before the south-west group and the model is designed such that inter assignments of vessels (assigning a ship from another group) between groups are enabled.

The resulting completion time of this approach has decreased enormously (**287.66 hours,** close to 12 days). This points out how sensitive completion time is to the scheduling. This model represents the real life scenarios except for the off-shift periods needed to rest the crew and cool down the oil driven systems on board. As a last development step, off-shift periods are implemented in the model and naturally the completion time increases a little, resulting in **306.11 hours** (12.75 days).

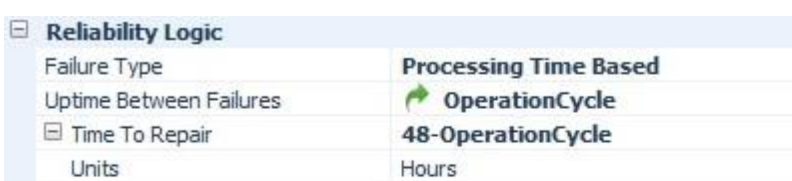


Figure 4.3: Application of Off-Shift Periods of the MCM Vessels (from the model)

4.3 Response of the Model to Channel Priority Changes

Aside from the testing of vessel assignments, priority assignment is also tested to determine the response of the model to channel priority changes. To see how the model reacts, three different channel priorities are used. Based on geographical issues, within the 48 channels, less than 10 of the channels' priority order have been changed in two models to observe the effect on the completion time. The base model run (see Tables 4.3 and 4.4) has a completion time of 306.11 hours (close to 13 days). The second model has channel priority changes in the Black and Mediterranean seas (See Appendix A.1) has a completion time of 385.69 hours. The third model, which is based on a first come, first served policy, and neglects important port channels (See appendix A.2), has a completion time of 302.86 hours. These results show that assigning priority does have a direct impact on mine clearance completion time as the travel times are crucial within the geographical data set. However, priorities are set based on military priorities rather than potential efficiencies.

4.4 Analyzing the Response of the Model to Number of Vessels Change

The previous section has studied how to schedule the MCM ships and how the priorities may be determined. This section examines how the mine clearance operation completion time changes as a function of the number of MCM vessels. The Design of Experiment tool in Simio provides quick results for different input parameters. The base model, which is built with the vessel information provided from the Jane's Fighting Ships catalog, is built with 6 Alpha and 5 Echo class mine hunter vessels. Different input values are tested and results are provided below (Table 4.5).

Table 4.5: Number of Each Type of MCM Vessels and Corresponding Completion Times

Alpha Class MCM Ships	Echo Class MCM Ships	Completion Time (Hours)
5	4	377.11
6	4	377.11
5	5	306.11
6	5	306.11
7	5	303.30
6	6	302.32
7	6	299.51

The results in Table 4.5 shows how much time is needed to complete the mine clearance operations at all channels when the properties (except the number of each class MCM vessels) are fixed such that MCM vessel operational speed is 3 knots, time to remove a detected mine is 1 hour, the channel widths are 600 yards, SONAR cover width is 350 yards and vessels' operational cycle is 36 hours in a 48 hours period. As the main difference between the Alpha Class and Echo vessels is the detection depth, these ship classes mainly represent where more units are needed, i.e., at 0-60 meter depth segments or at depths over 60 meters which are cleared by only the Alpha Class MCM vessels. One thing to note is that Alpha Class vessels can work all segments that Echo Class vessels work. Echo Class MCM vessels are restricted by their hull-mounted SONARs to lower depths. Thus, if the model suggests the need for more Echo Class Vessels, they can also be regarded as Alpha Class vessels. But the contrary is not true (Echo class can't substitute for Alpha class).

One interpretation that might be concluded from results in Table 4.5 is that an increase or a decrease in the number of Alpha class MCM vessels has little direct impact relative to the impact of the number of Echo Class MCM vessels. This implies that utilizing more units at shallower depth segments would help to decrease the operation completion time. It is important to note that these results are acquired using notional input parameters. Thus any conclusion drawn for real life application may be misleading.

Chapter 5

Design of Experiments and Results

In order to solve the problem of "Dynamic Allocation and Scheduling of MCM Vessels for Comprehensive Naval Mine Warfare," a notional data set is created and the writer's field experience is used with the support of literature to develop methods. The data set is created from unclassified open source information that is used to approximate real values.

The model built in Simio is intended to be generic so that notional data can be varied, tested or replaced. The methods adopted in the model also can be modified, enriched or restricted depending the needs of the user. The input parameters, which are the core elements in building a model, have been defined as model properties which can be controlled and varied at one place to be effective all over the model. These input parameters are given estimated values by the writer to develop base scenario which is enriched later in the model with the tools provided by Simio software. The base model's input parameters and their values are as shown below.

Number of Mine Deployments: 1 (throughout the simulation run)

Velocity of Ships on Operation: 3 knots (nautical miles per hour)

Mine Density: 0.5 mines per nautical miles square

Time to Remove a Detected Mine: 1 hour per mine

Channel Width: 600 yards

Effective SONAR Width: 350 yards

Operation Cycle of MCM Ships (On-Shift): 36 hours per 48-hour period

Number of Alpha Class MCM Vessels: 6

Number of Echo Class MCM Vessels: 5

All the parameters are kept same but the number of ships are changed and tested in the previous chapter. This chapter tests the sensitivity of the input parameters which are the most vulnerable to variation. These input parameters are Velocity of Ships on Operation, Mine Density and

Time to Remove a Detected Mine. The design of experiments and results are shown below (Table 5.1).

Table 5.1: Design of Experiments and Resulting Completion Times

Scenario	Mine Density (mine per nm^2)	Time to Remove A Detected Mine (in hours)	Velocity of Ships on Operation (knots)	Completion Time (in hours)
1	0.5	1	2.5	349.97
2	0.5	1	3	306.11
3	0.5	1	3.5	287.64
4	0.5	1.5	2.5	407.17
5	0.5	1.5	3	322.88
6	0.5	1.5	3.5	304.41
7	0.5	2	2.5	420.51
8	0.5	2	3	358.49
9	0.5	2	3.5	321.19
10	1	1	2.5	420.51
11	1	1	3	358.49
12	1	1	3.5	321.19
13	1	1.5	2.5	412.20
14	1	1.5	3	440.98
15	1	1.5	3.5	413.93
16	1	2	2.5	443.05
17	1	2	3	419.27
18	1	2	3.5	457.59
19	1.5	1	2.5	412.20
20	1.5	1	3	440.98
21	1.5	1	3.5	413.93
22	1.5	1.5	2.5	458.48
23	1.5	1.5	3	434.70
24	1.5	1.5	3.5	417.71
25	1.5	2	2.5	584.75
26	1.5	2	3	480.98
27	1.5	2	3.5	463.99

Nu	(Alpha,Echo)	Completion Time
1	(0,0)	306.108
2	(0,1)	302.323
3	(0,2)	291.267
4	(0,3)	284.88
5	(0,4)	268.51
6	(0,5)	268.51
7	(1,0)	303.3
8	(1,1)	299.515
9	(1,2)	288.765
10	(1,3)	274.923
11	(1,4)	275.904
12	(1,5)	266.342
13	(2,2)	288.765
14	(3,0)	277.02
15	(3,1)	299.515
16	(3,2)	273.568
17	(3,3)	273.568
18	(3,4)	272.337
19	(3,5)	230.279
20	(4,0)	303.3
21	(4,1)	299.515
22	(4,4)	280.386
23	(4,5)	272.932
24	(5,0)	278.659
25	(5,1)	278.002
26	(5,4)	270.06
27	(5,5)	257.858

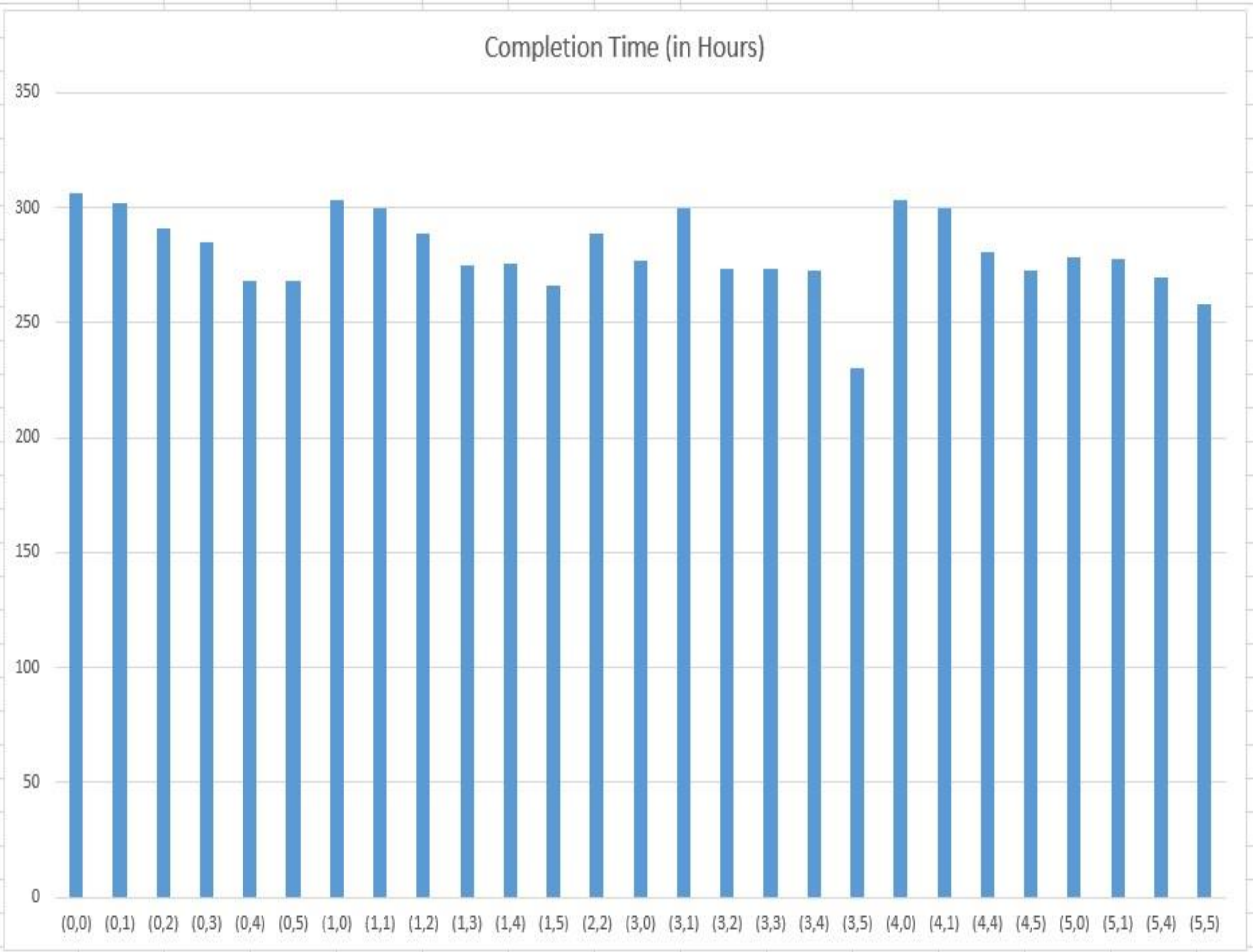


Figure 5.1: Additional MCM Vessels for Each Kind to Current Inventory and Results

The resulting chart shown in Figure 5.1 above is a graphical representation of how the completion time of the mine clearance operation change with the corresponding numbers of each of the MCM class vessels. Each class can be regarded here as the depth segments, Echo class MCM vessels stand for swallower depths and Alpha class MCM vessels stand for deeper segments. It is important to note, again, that Alpha class MCM vessels can substitute for Echo class vessels but the contrary is not true. From the chart in Figure 5.1 it is observed that the minimum value of 230.28 hours is possible with 3 Alpha class and 5 Echo class vessels.

Chapter 6

Conclusions and Recommendations

This thesis develops models in Simio in order to address questions that are expected to arise in a comprehensive naval mine clearance operation. The models are developed with a notional data set which also includes data from open sources. The methods are built using experiments in Simio and the writer's field experience. Although it would be misleading to draw any real conclusions from the model based on notional data, the model provides decision alternatives that can be tested replacing notional data with actual values. The questions addressed by the model in this thesis are:

- How would performance change if simple scheduling (if idle MCM vessels are utilized for clearing secondary channels in the Marmara Sea) is applied?
- How would performance change when assigning one vessel per segment versus two vessels per segment?
- How sensitive is performance to channel priority changes?
- How would performance change if mine density, vessel speed and/or time to clear a mine changes?
- How many additional vessels are needed at shallower depth segments (number of Echo class vessels) and also at deeper segments (number of Alpha class vessels)?
- What are the statistics for the segments and for the MCM vessels?

This study contributes to naval mine warfare efforts in two ways. First, it encourages modeling and simulating mine clearance operations with enriched software so that parameters can be input and quick results are acquired. Second, it allows user to tailor their MCM force to maximize mine clearing performance based on geographical and threat considerations.

6.1 Potential Applications

6.1.1 Determining the optimum combination of MCM helicopters and vessels

In the study, the MCM vessels are defined with their properties (i.e. speeds, SONAR characteristics). This study does not contain Air MCM (i.e. MH Helicopters) but it could be easily included. Landing base and air routes also would need to be defined so as to approximate real life scenarios.

6.1.2 Modeling mine clearance of a foreign navy

This model is maintained at the unclassified level using open source information about geography and platforms. The contribution of the writer's field experience also conforms to the unclassified level. Even so, the model represents real life scenarios fairly closely. Adopting simulation modeling for mine counter measures, could give early estimates of an enemy's mine clearance efforts in case of a need to approach hostile waters.\

6.1.3 Modeling service or product delivery systems

The nature of the problem of this study is similar to those systems that have trucks routing all over the service network to deliver service or products with respect to some constraints and policies. Thus, the model developed in this study can be modified in the way to represent these kind of delivery systems.

6.2 Topics for Further Research

The scope of this study is to analyze a comprehensive naval mine clearance effort of a selected test site. The complexity of the problem would grow when the costs and human factors (i.e. operator's experience, decision maker's bias) are involved. Even though the model would be more representative including these factors, it would reach beyond the point of this study's intent. For that reason, this paper leaves including these factors for further researchers.

Aside from the above factors, further platforms, i.e., satellites, mine clearance platoons, and new type mine clearance vessels, can also be included with their properties to enrich the model and the analysis as well.

REFERENCES

[1] CHIPS, The department of the Navy's Information Technology Magazine (2016). *Rear Adm. Timothy C. Gallaudet Talks METOC and Information Dominance.* Retrieved August 7, 2016 from http://www.doncio.navy.mil/CHIPS/ArticleDetails.aspx?id=5573.

[2] Image Retrieved July 14, 2016 from http://www.yourchildlearns.com/online-atlas/turkey-map.htm.

[3] Image Retrieved August 18, 2016 from www.dialabull.net

[4] Image Retrieved August 18, 2016 from www.forecastinternational.com

[5] Image Retrieved November 11, 2016 from https://www.thalesgroup.com/sites/default/files/medias/documents/MP%203290%20SONAR%202093.pdf.

[6] Image Retrieved December 4, 2016 from http://www.mapsofworld.com/turkey/.

[7] Kertmen, A. (2006). *Evaluation of the Littoral Combat Ship (LCS) Potential for Turkish Navy*. Naval Postgraduate School Department of Information Sciences, Monterey.

[8] Khan, S. (2010*). Iranian Mining of the Strait of Hormuz – Plausibility and Key Considerations*. (Special Report No. 4). Institute of Near East & Gulf Military Analysis

[9] Lendon B.& Cohen Z. *Third Breakdown in Year for $360M US Navy Combat Ships* Retrieved September 12, 2016 from http://www.cnn.com/2016/08/29/politics/us-navy-littoral-combat-ship-breakdowns/index.html.

[10] Mine Warfare Association (2005). *Naval Special Clearance Team One Briefing*. Panama City, Florida. Retrieved August 3, 2016 from http://www.minwara.org/wp-content/uploads/23-NSCT-ONE-MINWARA-05-Brief.pdf.

[11] NATO Standardization Agency. (2002). *Multinational Maritime Tactical Instructions & Procedures, Volume 1.* US Navy Warfare Library Publications.

[12] Needham, J. (1987). *Science & Civilization in China, Volume 5: Chemistry and Chemical Technology, Part 7: Military Technology: The Gunpowder Epic*. Cambridge [England] Press, page 203-205.

[13] Ocean Studies Board, National Research Council Staff, Division on Earth and Life Studies, 2000. *Oceanography & Mine Warfare*, National Academies Press, page 12.

[14] Program Executive Office Littoral and Mine Warfare (2009). *21st century U.S. Navy mine warfare - Ensuring Global Access & Commerce.* Retrieved from Bowe (2015).

[15] Rabiroff, J. (2011). US Military Enters New Generation of Sea Mine Warfare. Retrieved July 14, 2016 from http://www.stripes.com/news/.

[16] Retrieved November 12, 2016 from http://www.simio.com/about-simio/.

[17] Retrieved November 15, 2016 http://www.public.navy.mil/spawar/Pacific/71500/Pages/faqs.aspx.

[18] Sandersfield, M. R. (2012). *Detection of Subpixel Submerged Mine-Like Targets in Worldview-2 Multispectral Imagery*. Naval Postgraduate School Monterey Department of Information Science.

[19] Saunders S. (2015). *IHS Jane's Fighting Ships 2014-2015*. Information Handling Services Publications.

[20] Seck H.H. *Navy Takes 1st Four Littoral Combat Ships out of Deployment Rotation* Retrieved September 12, 2016 from http://www.military.com/daily-news/2016/09/09/navy-takes-four-littoral-combat-ships-out-deployment-rotation.html?ESRC=dod_160909.nl.

[21] Seligman L. (2014). *Cuts to LCS Mission Module Program Will Increase Costs, Delay Fielding*. Retrieved 15 July, 2016 from http://insidedefense.com/inside-navy/cuts-lcs-mission-modules-program-will-increase-costs-delay-fielding

[22] Seligman, L. (2015). *Challenges Persist for LCS Remote Mine Hunting System in Recent Tests*. Retrieved July 15, 2016 from http://insidedefense.com/inside-navy/challenges-persist-lcs-remote-minehunting-system-recent-tests.

[23] Seng Y.K. (2006). *Devastating Bubble Power*. Retrieved August 3, 2016 from http://www.eng.nus.edu.sg/EResnews/0306/rd/rd_12.html.

[24] Thompson, A.R. (2015). *Evaluating the combined UUV efforts in a Large-scale Mine Warfare Environment.* Naval Postgraduate School Department of Operations Research, Monterey.

[25] The Aviationist. (2016). Syrian Su-22 Fitter Shot Down by Rebels Over Aleppo. Retrieved June 17, 2016 from https://theaviationist.com/2016/04/05/syrian-su-22-fitter-shot-down-by-rebels-over-aleppo/.

[26] The Washington Post. (2016). Kurdish Militants Reportedly Shoot Down Turkish Security Forces Helicopter. Retrieved June 17, 2016 from https://www.washingtonpost.com/news/worldviews/wp/2016/05/14/kurdish-militants-just-challenged-turkish-air-power-in-a-major-way/.

[27] The US Naval Institute. (2016). *Essay: Navy, Air Force Reviving Offensive Mining with New Quickstrikes*. Retrieved July 14, 2016 from https://news.usni.org/2016/04/26/essay-navy-air-force-reviving-offensive-mining-with-new-quickstrikes.

[28] US Joint Chief of Staff. (2011). *Barriers, Obstacles, & Mine Warfare for Joint Operations*. Joint Publication 3-15.4.

[29] Wikipedia The Free Encyclopedia (2016). Retrieved August 3, 2016 from www.en.wikipedia.org.

Note: Program Executive Office Littoral and Mine Warfare is restricted to ".mil" web sites, thus unable reach but referring the research that used them (See [14] above).

APPENDICES

APPENDIX A.1: Channel Priorities for Section 4.3

Table A.1: Channel Priorities for Second Case

South West Region			North Region		
Priority	Channel	#of Ships	Priority	Channel	#of Ships
1	Erdek North	2	4	Ist. Strait South	1
2	Erdek West	2	5	Ist. Strait Main	2
3	Golcuk Base	2	6	Ist.Strait North	1
7	Canak Strait North	2	27	Karaburun Port	1
8	Canak Strait Main	2	33	Eregli Base	1
9	Ist. Shipyard	2	35	Zonguldak Port	1
10	Yalova Port	2	36	Amasra Port	1
11	Mudanya Port	2	37	Sinop Port	1
12	Bandirma Port	2	38	Samsun Port	1
13	Tekirdag Port	2	39	Fatsa Port	1
14	Route1 to Clear	2	40	Ordu Port	1
15	Gokceada Port	2	41	Giresun Port	1
16	Route2 To Clear	2	42	Trabzon Port	1
17	Aliaga Port	2	43	Rize Port	1
18	Route3 to Clear	2			
19	Route4 to Clear	2			
20	Foca Base	2			
21	Izmir Port	2			
22	Route5 to Clear	2			
23	Kusadasi Port	2			
24	Route6 to Clear	2			
26	Aksaz Base	2			
28	Mersin Base	1			
29	Route7 to Clear	2			
30	Route8 to Clear	2			
31	Iskenderun Base	2			
32	Yumurtalik Port	2			
34	Tasucu Port	1			
44	Cyprus Port	1			
45	Alanya Port	1			
46	Antalya Port	1			
47	Kas Port	1			
48	FethiyePort	1			

APPENDIX A.2: Channel Priorities for Section 4.3

Table A.2: Channel Priorities for Third Case

South West Region			North Region		
Priority	Channel	#of Ships	Priority	Channel	#of Ships
1	Erdek North	2	4	Ist. Strait South	1
2	Erdek West	2	5	Ist. Strait Main	2
3	Golcuk Base	2	6	Ist.Strait North	1
7	Canak. Strait North	2	27	Eregli Base	1
9	Ist. Shipyard	2	33	Zonguldak Port	1
10	Yalova Port	2	35	Amasra Port	1
11	Mudanya Port	2	36	Sinop Port	1
12	Bandirma Port	2	37	Samsun Port	1
13	Tekirdag Port	2	38	Fatsa Port	1
14	Route1 to Clear	2	39	Ordu Port	1
15	Gokceada Port	2	40	Giresun Port	1
16	Route2 to Clear	2	41	Trabzon Port	1
17	Aliaga Port	2	42	Rize Port	1
18	Route3 to Clear	2	43	Karaburun Port	1
19	Route4 to Clear	2			
20	Foca Base	2			
21	Izmir Port	2			
22	Route5 to Clear	2			
23	Kusadasi Port	2			
24	Route6 to Clear	2			
25	Bodrum Port	2			
26	Aksaz Base	2			
28	Fethiye Port	1			
29	Kas Port	1			
30	Antalya Port	1			
31	Alanya Port	1			
44	Tasucu Port	1			
45	Mersin Base	1			
46	Cyprus Port	1			
47	Route7 to Clear	2			
47	Route8 to Clear	2			
48	Iskenderun Base	2			
48	Yumurtalik Port	2			

APPENDIX B: Graphical Representation of the Model

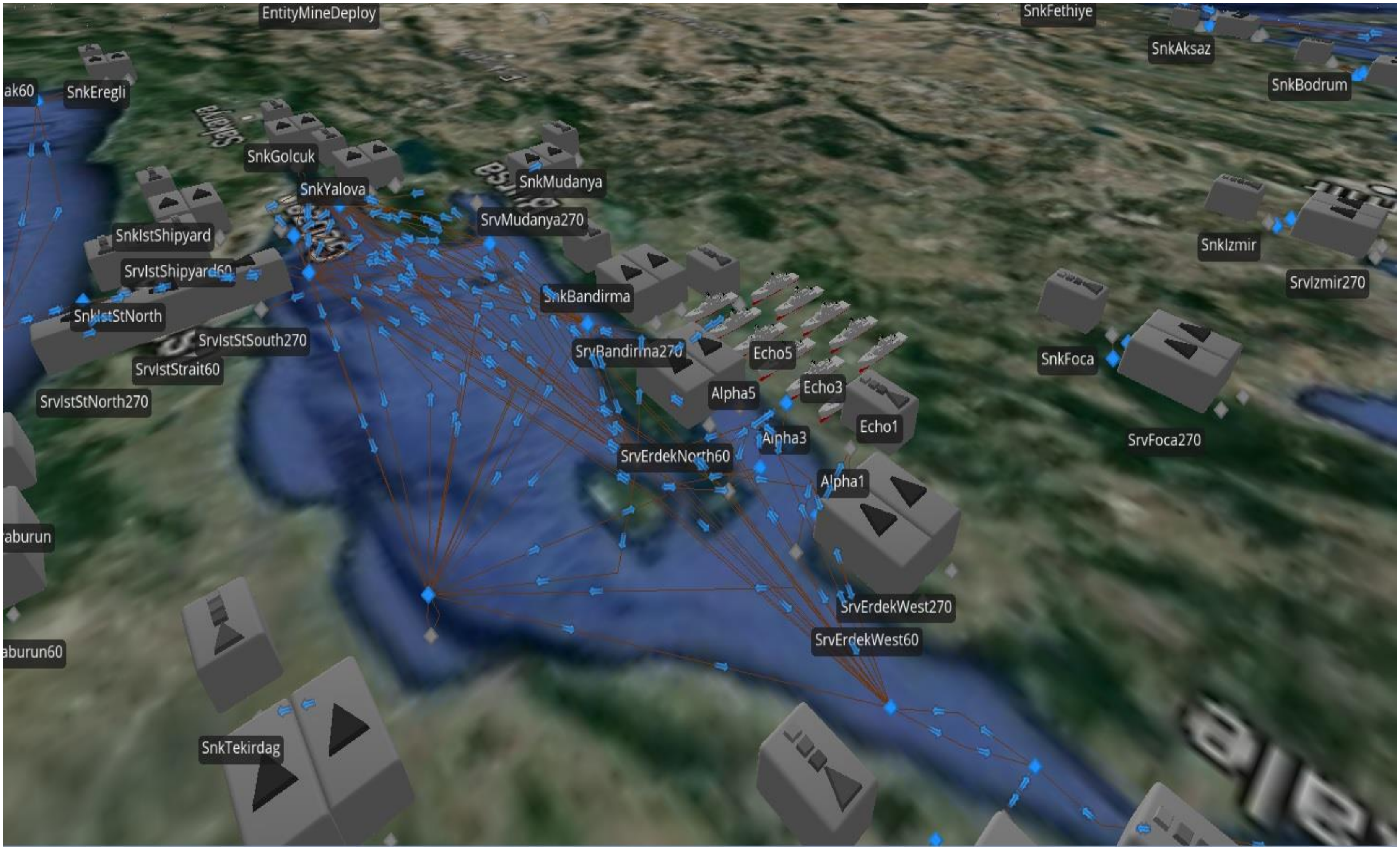


Figure B.1: Canvas of the Model Built