

# Design of an Underwater Mine Countermeasure System

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## Proposal Final Report

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## 1.0 Context

### 1.1 Importance of the world's waterways

Water is a vital resource to all life on earth. Humans tend to settle near areas with reliable access to waterways because maritime travel is an essential part of modern life. 80% of humans live within 60 miles of coastal waters and 90% of global commerce is conducted by sea [34]. The port cities that facilitate this commercial movement are generally accessed by travel through inland waterways that provide a link to the open ocean. These waterways create a bottleneck for ship traffic. Due to the heavy traffic and shallow water, these inland waterways can be targets for attacks to disrupt the economy or military operations.

As an example of such an area, the mouth of the Chesapeake Bay is an inland waterway that is of great importance to the United States, both commercially and militarily. All ship traffic traveling into or out of the Chesapeake Bay must pass over one of two shipping lanes that cross over the Chesapeake Bay Bridge-Tunnel. Each shipping lane is one mile wide [35]. Traffic passing through the mouth of the Chesapeake Bay includes:

- Shipping traffic traveling to and from the port of Hampton Roads, Virginia (third largest port on the East Coast of the United States) [17].
- Shipping traffic traveling to and from the port of Baltimore, Maryland (fourth largest port on the East Coast of the United States) [17].
- Shipping traffic traveling to and from smaller ports within the Chesapeake Bay such as Richmond, Virginia and Annapolis, Maryland.
- United States Navy ships traveling to and from Navy bases in the Hampton Roads area. Norfolk Naval Station and Joint Expeditionary Base Little Creek-Fort Story are homeports to 69 United States Navy ships [18].
- Numerous other fishing and recreational boats.

In addition to the heavy volume of traffic passing through a narrow choke point at the mouth of the Chesapeake Bay, the shallow depth is an ideal setting for mines to cause damage to ships. In the hypothetical situation where an enemy wanted to disrupt the economy of the United States and the operations of the U.S. Navy, and was capable of placing mines in U.S. waters, the mouth of the Chesapeake Bay would be a prime target. It is for this reason that this area will be used for the system simulation later in this report. Figure 2 shows the underwater topography of the area of focus including the North and South shipping lanes over the two tunnel sections of the Chesapeake Bay Bridge-Tunnel. Figure 3 is a close look at the chart of the Thimble Shoal Channel which passes over the south tunnel of the Chesapeake Bay Bridge-Tunnel.

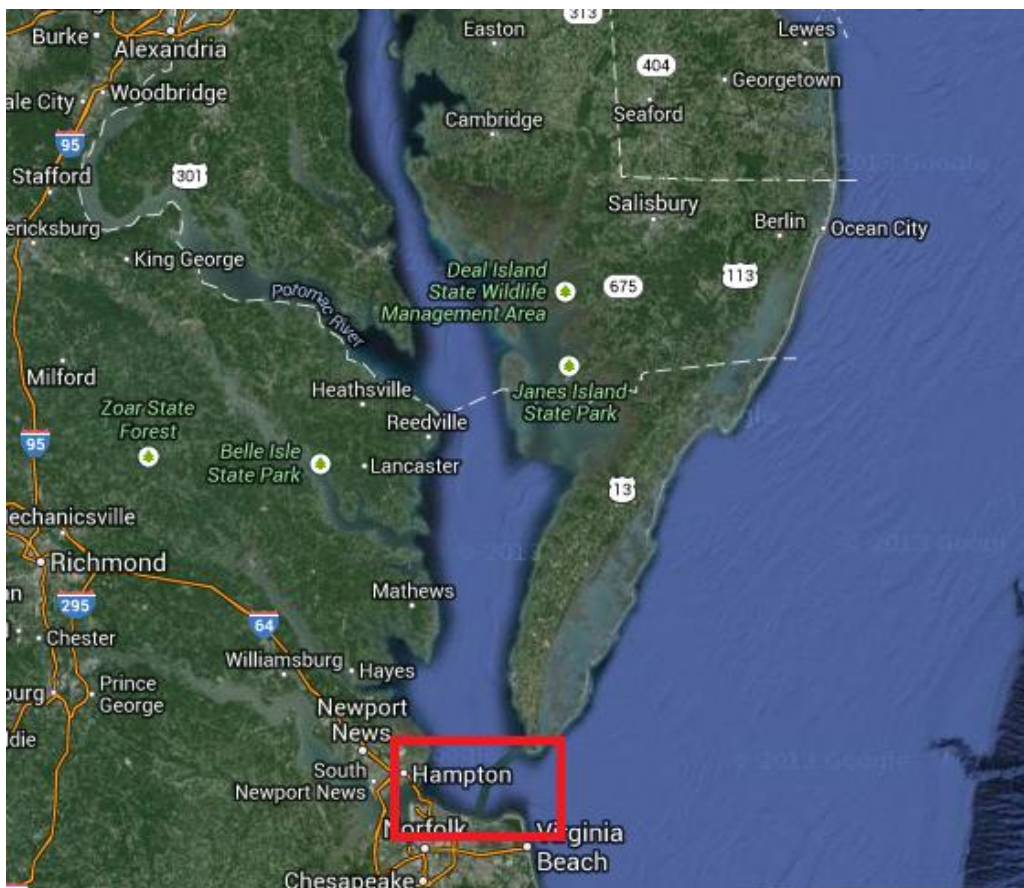


Figure 1: Chesapeake Bay (Google Maps)



Figure 2 [19]



Figure 3 [19]

## 1.2 History

The mission of the Navy is to maintain, train and equip combat-ready naval forces capable of winning wars, deterring aggression and maintaining freedom of the seas. Thus, to complete this mission, it is critical that these waterways remain clear for the safe conduct of military operations. A great example of how mines can hinder naval operations occurred during the Korean War. Wonsan Harbor was mined and the U.S. Navy was unable to get to shore to



achieve its mission objective. After the mission, 2 ships had sunk, more than 200 sailors lost their lives, and the shore landing was delayed by five days. The events at Wonsan Harbor opened the Navy's eyes to the effect that mine warfare can have on a fleet in an inland waterway.

Admiral Forrest P. Sherman, U.S. Navy Chief of Naval Operations at the time, summarized the situation well by saying "when you can't go where you want to, when you want to, you haven't got command of the sea" [2].

### 1.3 Current mine technology

In order to understand how to best detect underwater mines, they must first be understood. Mines are designed to be as undetectable and deadly as possible and, as such, can vary greatly in terms of their designs. Mines can float on top of a body of water, rest on the sea floor, or be moored to the sea floor. Mines can also be fitted with technology for detecting certain signals that allow them to be detonated at a more precise location or by a specific target. For example, during World War II, mines were fitted with magnetic sensors in order to detect steel-hulled ships. Since the 1940's mines have become even more technologically advanced by utilizing acoustic sensors, pressure sensors, and a multitude of other techniques in order to become more precise [7]. Figure 4 shows mine designs for placement in different marine regions.

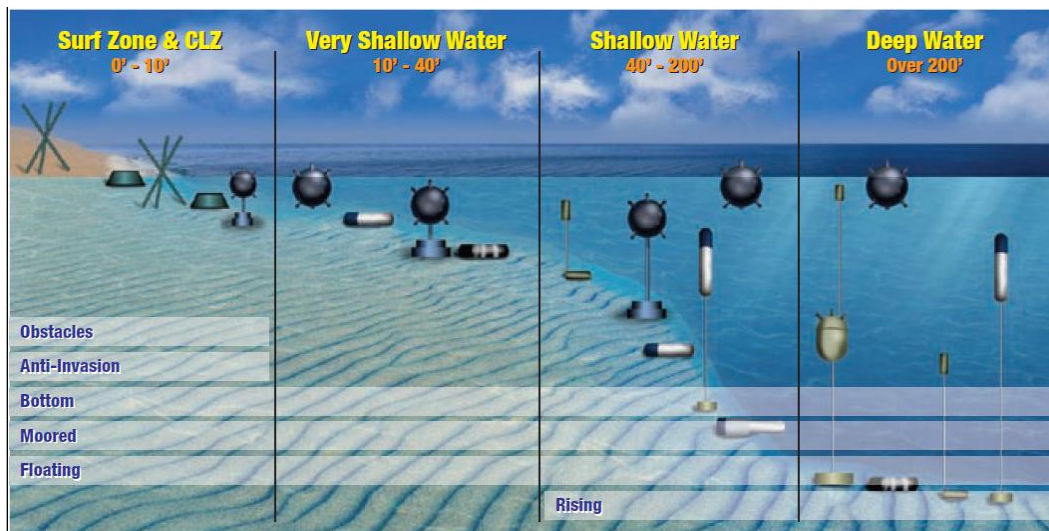


Figure 4: Mine warfare regions [21]

The reason that mines can be used as such an effective means to block waterways stems from the asymmetry involved in the process to place a mine field versus the process to clear one. Clearing a minefield can take up to 200 times longer and cost up to 200 times more than laying a

minefield [27]. They are difficult to detect and can cause hundreds of thousands of dollars in damage to marine vessels. In 1988, the USS Samuel B. Roberts struck an Iranian M-08/39 mine [3]. The mine cost an estimated \$1,500 and the explosion caused approximately \$89.5 million in damage to the ship [4]. In 1984, magnetic sea mines damaged 19 ships in the Red Sea while a minesweeping mission involving U.S, British, and French ships was largely unsuccessful in clearing the mines [5]. In 1991 during the Gulf War, the USS Princeton struck a moored mine which caused \$24 million in damage [6].

Figure 5 shows that since the end of World War II, U.S. Navy ships have experienced three times more attacks by mines than all other types of attacks combined. All of the above examples demonstrate the extent of damage that mines can cause and the difficulty and importance of detecting and eliminating them.

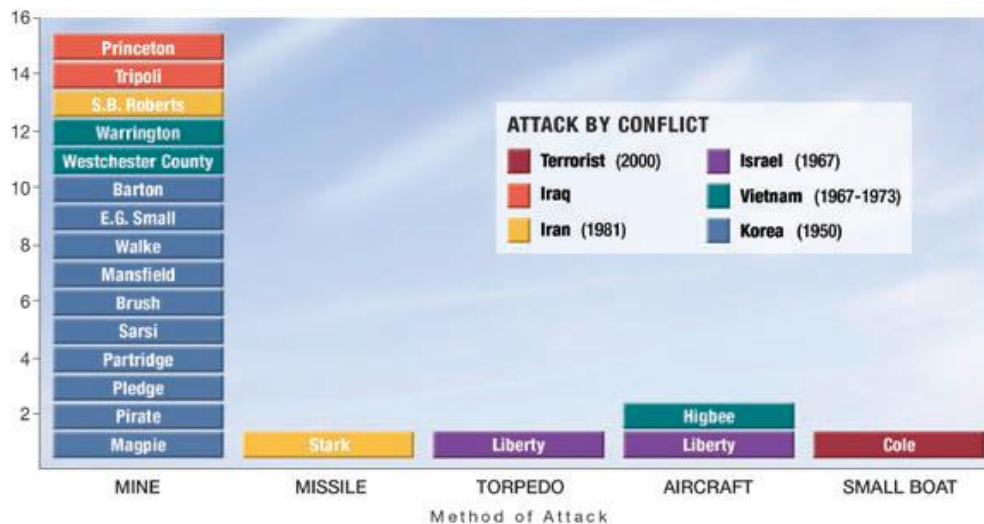


Figure 5: Attacks on U.S. Navy ships since World War II [21]

In addition to the negative effects mines can have on the military, they can also cause serious economic damage. Mines can be used to disrupt shipping lanes or in ports so that the products in transit cannot reach their destination. A labor dispute involving workers at the port of Los Angeles and Long Beach in 2012 can be used as an example of how devastating the threat of mines can be to the economy. The strike shut down the port for eight days and cost the American economy about \$1 billion each day [1]. Even just a threat of mines in any given waterway is likely to shut down the area, and cause negative economic effects similar those experienced during the strike.



Underwater mines can also create an environmental problem. This is due to the fact that they do not decompose until long after they are deployed. Thus, the mines that are laid in any given conflict remain there after the conflict is over and have the potential to cause tremendous damage. As the economy and culture of each country becomes more globally oriented, an efficient mine countermeasure becomes increasingly necessary.

#### **1.4 Current mine clearing techniques**

Mine clearance systems that are most commonly in use by the U.S. Navy today are time consuming and expensive. An MH-60S helicopter flies to the site of the mine field and deploys a sonar to be towed by the helicopter through the water over the minefield. The helicopter then returns to base and the collected data is examined for signs of mine-like objects. The helicopter makes a second pass over the mine field to eliminate the mines, and finally makes a third pass to verify that the mines are destroyed [7]. This process requires three distinct flights of the helicopter and a three man crew to operate the helicopter and sonar. The majority of the cost comes from manning and fuel for the helicopter.

The threat of underwater mines and other obstacles coupled with the fact that they are difficult and costly to find has led the U.S. to develop alternate techniques that may seem somewhat farfetched. In 1988, the U.S. Navy began using marine mammals such as bottlenose dolphins and sea lions to detect and neutralize mines, recover torpedoes, and defend divers. The mammals have proved to be more effective than their human counterparts in some situations and they are the only mine detection method that can locate buried bottom mines with reliability [21].

#### **1.5 Project scope**

Determining the actual time and cost required to clear any given mine field is difficult because there are so many variables that can affect the situation. These factors include the size of the mine field, type of mines, whether or not the enemy is trying to stop the operation (covert or overt operation), the natural environment of the minefield, and the type of sensors being used. In order to narrow the scope of this project, the aforementioned factors have been limited due to time constraints. The simulation will examine a vehicle and sonar system operating in a 1 square mile area in the mouth of the Chesapeake Bay, the mission is overt, the system will search for moored mines in the water column, and the objective is to clear a path as rapidly as possible.

Although the scope of the project is narrowed, the idea is that when the simulation is complete, it can be run with different inputs to simulate different situations that were not necessarily used in this project.

## 2.0 Stakeholder Analysis

Table 1 displays the stakeholders of the system, examples of groups representing each set, and their objectives on this matter. The stakeholders are broken into three classes of primary, secondary, and tertiary. System Operators are considered the primary stakeholders. Designers and manufacturers, system enforcers, beneficiaries, and minelayers are considered secondary stakeholders. Servicemen, taxpayers, and environmental groups are considered the tertiary stakeholders.

Table 1: Stakeholders

| Class      | Title                              | Examples  | Objectives  |
|------------|------------------------------------|---|---|
| Primary    | <b>System Operators</b>            | e.g. sailors, pilots  | Operational safety  |
| Secondary  | <b>Designers and Manufacturers</b> | e.g. Raytheon Integrated Defense Systems                    | Provide a cost effective solution to warfighters, grow market share |
|            | <b>System Enforcers</b>            | U.S. Navy   | Clear underwater mines in a safe, timely and cost effective manner  |
|            |                                    | Department of Defense                                       | Maintain freedom of movement in waterways                           |
|            | <b>Beneficiaries</b>               | Military Traffic  | Conduct missions in a safe and timely manner                        |
|            |                                    | Commercial Traffic  | Safe transportation through waterways                               |
|            | <b>Minelayers</b>                  | Enemies   | Deny freedom of action to U.S. Navy forces                          |
| Terrorists |                                    | Cause chaos, seek media attention and worldwide recognition |   |

|                 |                             |                    |  |
|-----------------|-----------------------------|--------------------|--|
| <b>Tertiary</b> | <b>Servicemen</b>           | System Trainers    | Adapt to new procedures                |
|                 |                             | System Maintainers |  |
|                 | <b>Taxpayers</b>            | Congress           | National security, value of investment |
|                 |                             | People             |  |
|                 | <b>Environmental Groups</b> | e.g. EPA, NRDC     | Protection of environment              |

## 2.1 Primary Stakeholders

The primary stakeholders of the system are system operators, whose safety is at stake. Examples of system operators include those in charge of the vehicles involved in the mine clearance process; such as sailors and pilots. The major objective for system operators is to have their operational safety increased.

## 2.2 Secondary Stakeholders

Designers and manufacturers include the groups that design the entire system, as well as the manufacturers of all the applied components. Components include the vehicles involved in the process (such as boats or helicopters), the mine detection unit (sonar), the mine clearance unit (neutralizer), and all other physical and virtual components involved in the system. An example of designers and manufacturers is Raytheon Integrated Defense Systems. Raytheon Company is a technology and innovation leader specializing in defense, security, and civil markets throughout the world, with over 68,000 employees worldwide. Integrated Defense Systems (IDS) is one of four major business branches of Raytheon. Raytheon IDS specializes in air and missile defense, large land and sea based radars, and systems for managing command, control, communications, computers and intelligence. It also produces air traffic management systems, sonar, torpedoes and electronic systems for ships [9]. In this project, the objective of designers and manufacturers is to grow their market share, and they do so by providing a cost effective solution to warfighters.

The next group that is considered a secondary stakeholder is the system enforcers, who include the U.S. Navy and the Department of Defense. As a part of homeland defense, the U.S. Navy, which functions under the supervision of the Department of Defense, implements mine clearance systems to clear waterways that are suspected to have mines. With an estimated 323,225 on active duty, 285 deployable battle force ships, and over 3700 aircraft, the U.S.

Navy's mission is to maintain, train and equip combat-ready Naval forces capable of winning wars, deterring aggression and maintaining freedom of movement in oceans and waterways throughout the world [10]. For this project, the Navy is the customer and would be purchasing the mine clearance system from the designers and manufacturers. The Navy's objective is to clear underwater mines in a safe, timely and cost effective manner. Headquartered at the Pentagon, the mission of the Department of Defense (DOD) is to provide the military forces needed to deter war and to protect the security of the country [11]. DOD stands a level above the Navy and ensures freedom of movement in the water for military, commercial, and other purposes. In addition, the DOD requires the proposed system to be interoperable with the existing defense and tracking systems [12].

Beneficiaries are the users of the waterways. They benefit from the free and safe movement throughout the waterways of the world, which is provided by the system enforcers. Beneficiaries include the ship traffic through the water, such as military and commercial ships. The military traffic's objective is to conduct missions in a safe and timely fashion, while the commercial traffic seeks safe transportation through the waterways.

The final group that is a secondary stakeholder is the minelayers. Having invested in storing mines under the water, the minelayers are countered through using the mine countermeasure systems. Minelayers may include strategic enemy countries, as well as terrorist groups. Enemies seek to deny freedom of action to the U.S. Navy forces, and laying mines can be a very effective means of achieving this objective. Terrorist groups carry out planned attacks to cause widespread chaos, seek the attention of media, and obtain worldwide recognition.

## **2.3 Tertiary Stakeholders**

System servicemen are those employees of the system enforcers who are indirectly affected by the move to a new system. Servicemen include system trainers and maintainers, who will be facing new training and maintenance tasks. The objective of the servicemen is to adapt to the new procedures.

United States taxpayers seek national security from the government and are therefore affected by the decisions of the people in charge. On the other hand, taxpayers continuously have concerns over maximizing investment value, and are consequently affected in this project.

Taxpayers include the congress, who make decisions on where money is spent, and people, who pay the taxes.

Environmental groups form the final section of tertiary stakeholders. Environmental groups such as the Natural Resources Defense Council (NRDC) and the Environmental Protection Agency (EPA) have similar objectives and seek to protect humans, animals, and the environment against harms. Founded in 1970, NRDC is a non-profit group consisting of 1.4 million members and activists backed by the expertise of more than 350 lawyers, scientists and other professionals. NRDC is rated as the nation's most effective environmental action group, with the mission of protecting the earth, its people, plants and animals, and the systems on which all life depends [13]. EPA was also established in 1970, is a federal agency that conducts research, sets standards, and enforces actions to protect the environment [23]. In this project, environmental groups hold concerns over sea water quality and underwater species, ensuring they are guarded against pollution, damage or other negative effects.

## 2.4 Stakeholder Interactions

Figure 6 displays an overview of the interactions among the stakeholders through the system. System operators, who are the primary stakeholders, are shown in the center, working directly with the system. The secondary stakeholders are those whose interactions affect the entire system. The minelayers start the cycle of interactions by laying mines in the water, disrupting the movement of beneficiaries. This event creates a need for action to system enforcers, who identify the need for a new system to more efficiently counter the minelayers. Designers and manufacturers create the system, and the system clears the mines. On the other hand, the system presents several indirect impacts on a set of other groups; the tertiary stakeholders. These impacts include new procedures assigned to the servicemen, the cost associated with the system to the taxpayers, and the environmental impacts to the environmental groups. As a result of each impact, the respective tertiary group reacts with new concerns. Servicemen have concerns over the new procedures. Taxpayers have concerns over the value of investment. Finally, the environmental groups will have concerns over the impact of the system on the underwater environment. All these concerns relate back to the system enforcers, who are using the system, and form a series of conflicts and tensions.



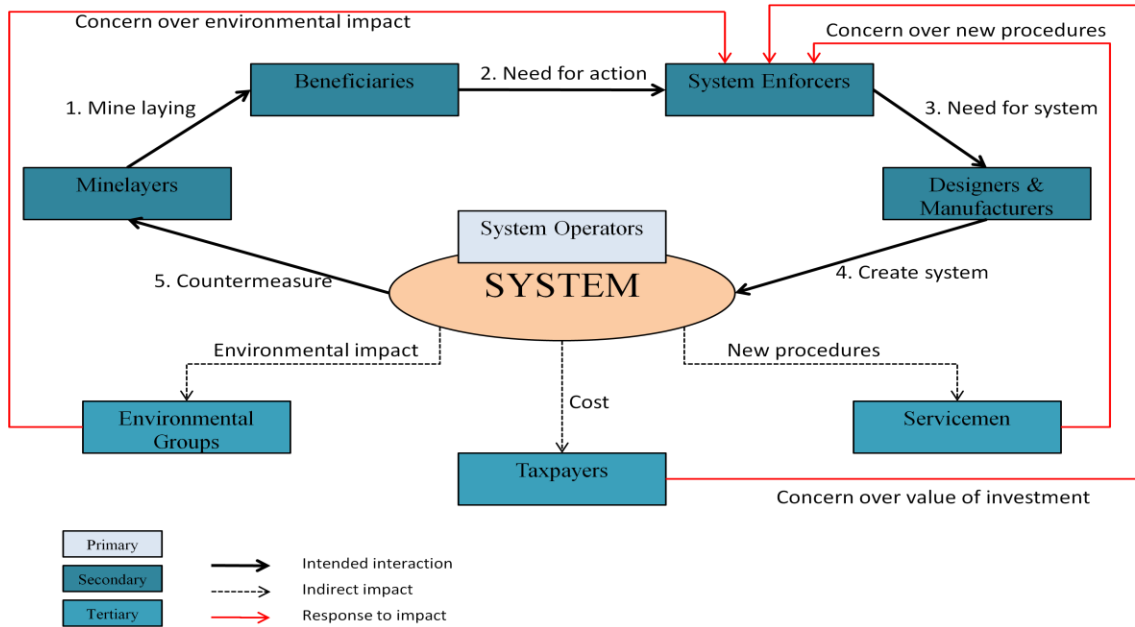


Figure 6: Stakeholder Interactions Diagram

## 2.5 Stakeholder Tensions

### 2.5.1 Internal Tensions

- System Operators vs. System Enforcers: System operators have concerns over operational safety, whereas the main objective of system enforcers is to decrease the time and cost of mine clearance.
- Servicemen vs. System Enforcers: Current training staff may not be able to effectively train the operators for the new system. In addition, the new system may add significant burden to maintenance procedures.

### 2.5.2 External Tensions

- Environmental Groups vs. System Enforcers: Sound waves produced by the sonar employed by the Navy have previously been lethal to marine animals on several occasions. NRDC has been a leader in the battle to regulate sonar use

and protect underwater species from its harmful effects. In 2008, a case filed by the NRDC against the Navy, was heard by the U.S. Supreme Court [14].

- b. Taxpayers vs. System Enforcers: Taxpayers consistently seek value of investment on the money they provide through taxes. The utility of the system must justify its cost.

### 3.0 Problem and Need Statements

#### 3.1 Gap Analysis

Based on current technology, the system enforcers have two gaps to close. Figure 7 shows the process time gap between mine placing and mine clearance. Using current technology, it takes up to 200 times more for the system enforcers to clear the mines than it takes the minelayers to place them. In addition, current mine clearance process is extremely expensive compared to what it takes to lay a minefield; which can be as low as only 0.5% the cost of mine clearance process (Figure 8) [27].

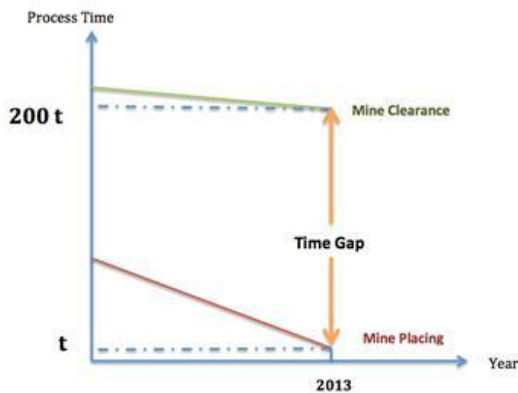


Figure 7: Time Gap

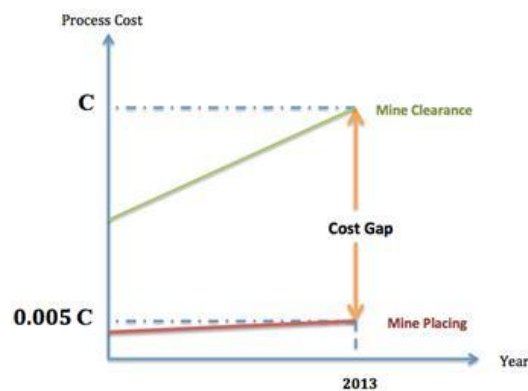


Figure 8: Cost Gap

As a consequence, the threat of underwater mines is increasing because they are easy to build and difficult to detect and neutralize.

### 3.2 Problem Statement

Underwater mines are a very effective method of blocking shipping lanes, restricting naval operations. They are a challenge to identify, classify, and neutralize. This threat can have severe negative effects on the world economy and the ability of the world's Navies to conduct necessary operations. Because of the capabilities and worldwide influence of the United States, the responsibility of clearing mines to assure freedom of movement on the world's waterways often falls on the U.S. Navy. As explained in the gap analysis section, today's technology to clear waterways of mines is slow and costly when compared to what it takes minelayers to store the mines in the waterways. Underwater mines also pose negative environmental impacts, by exposing the underwater species and the natural environment to the danger of explosion.

### 3.3 Need Statement

There is a need for the U.S Navy to improve the effectiveness of mine clearance systems. The U.S. Navy needs to reduce the operational cost of mine clearance to allow them to perform more mine clearance missions at a time. The rate of detection and neutralization needs to improve to prevent the threat of underwater mines from increasing. Furthermore, there is a need to remove the safety risk of personnel in a mine clearance operation.

Making the investment of time and money now, will end up saving time and money in the future if an event occurs where the U.S. Navy needs to clear an area of underwater mines. The current investment will also reduce the negative economic impact that underwater mines can cause to the U.S. or world economy [1]. An effective mine countermeasure system will also prevent a situation like the previously mentioned Korean War incident where Navy ships and personnel could not reach land.

### 3.4 Win-Win

- I. Reducing the time of mine clearance process contributes to better defense of the country, and in doing so, achieves higher national security. As mentioned in the stakeholders section, national security is an objective sought by the taxpayers.
- II. The taxpayers are also concerned over the value of investment. The new system requires initial investment, but it should decrease the long term costs of encountering mines. By more efficiently clearing the underwater mines, the Navy would avoid

blocking of shipping lanes that would greatly damage the economy. Therefore, in the long term, the initial investment would be justified and the value of investment would be achieved.

- III. The new system needs to find a way to remove the safety risk of system operators to address the concerns of the primary stakeholders.
- IV. As mentioned in the Stakeholder Analysis section, NRDC has had concerns about the use of sonar and its damaging consequences for underwater species. However, taking no action against underwater mines poses a significantly greater risk to underwater species than sonar does. Additionally, the Navy has been employing marine animals such as dolphins and sea lions to be used in the mine detection process [24]. This phenomenon has the animal engaged in a dangerous situation, and as a consequence, alerts the environmental groups and those protecting animal rights. The Navy has expressed an interest in reducing the role of animals, but has failed to promise removing that role entirely [25]. The new system needs to remove the animal from the system entirely, and make a win-win possible for the Navy and environmental groups.

## **4.0 System Requirements**

- The system operators shall be protected from mine explosions.
- The system shall detect underwater moored mines.
- The system shall cover XX square miles is XX hours.
- The system shall be transportable on current Navy ships.

## **5.0 Concept of Operations**

### **5.1 Limitations**

When designing a mine countermeasure system there are some important limitations that should be noted. Any system that is looking for objects underwater is limited to the currently available sonar technology. Other technologies that are traditionally used to find objects at a distance are not effective underwater. Sonar has a much longer range than either radar or optical

instruments (cameras) due to the physical nature of the way light waves, radio waves and sound waves move through water. For this reason, the system being designed must use sonar to detect underwater mines.

One other constraint that we face is a time constraint. For any system that we choose to design, we must be able to plan, design, and evaluate the system with four people in just two semesters worth of work. In order to finish the system design within the allowed time, we must narrow the complexity of the system. To overcome the time constraint, we came to the conclusion that we cannot design a new sonar system, or a new vehicle propulsion system. For these reasons, we will be using sonar systems and vehicle systems that are already in production. More information on the sonar and vehicle systems that are considered for use in the system can be found in the following section.

## 5.2 Design Alternatives

### 5.2.1 Sonar alternatives

There are several different sonar systems with varying capabilities available for use. To start the design, however, we will evaluate two alternatives. The first alternative, the Raytheon AN/AQS-20A Minehunting Sonar System, is considered the standard in mine hunting technology by the U.S. Navy [20]. The system does not have propulsion capabilities and therefore must be towed through the water. The AN/AQS-20A simultaneously uses a combination of five different sonar systems while moving through the water to get a picture of both the sea floor beneath the vehicle, and the water column in front of it.



Figure 9: AN/AQS-20A Minehunting Sonar System [20]



The second sonar alternative that we will be considering is the Thales Towed Synthetic Aperture Sonar (T-SAS). The T-SAS is currently used by several foreign navies. A synthetic aperture sonar typically has a higher resolution output for the sonar operator, however the Thales T-SAS is equipped with only two side scan sonars [32]. This is a disadvantage compared to the side scan and forward looking sonar combination that the AN/AQS-20A employs.



Figure 10: Thales Towed Synthetic Aperture Sonar (T-SAS) [32]

There are other sonar systems in the form of a hydrodynamic towable body, as well as sonar systems that would need to be built into a towable body that could eventually be used in our mine countermeasure system. For the sake of this system design, we will limit our evaluation to just the Raytheon and Thales sonar alternatives.

To begin the design of the unmanned autonomous mine clearance system, we will take a broad approach and evaluate three very basic alternatives. All alternatives must be able to tow the AN/AQS-20A or T-SAS through the water.

### 5.2.2 Underwater alternative

The underwater alternative will consist of an underwater vehicle that is capable of towing either of the two sonar alternatives through the water. The underwater alternative that we will consider for this project is the Lockheed Martin Remote Multi-Mission Vehicle (RMMV). The RMMV is designed to be deployed with the U.S. Navy's Littoral Combat Ship (LCS). The RMMV is powered by a diesel engine and has a snorkel that extends beyond the surface of the

water. Its capabilities include the ability to stay in water for up to 24 hours, tow sonar through the water, and autonomously travel pre-programmed routes [28].

### **5.2.3 Surface alternative**

The surface will consist of an unmanned surface craft towing the underwater sonar. The two surface alternatives that will be evaluated for this system design are the Meggitt Hammerhead and the Textron Fleet-Class Common Unmanned Surface Vessel. Similar to the underwater alternative, both surface alternatives are able to tow heavy loads, and travel along pre-programmed routes through the use of their GPS systems. The Meggitt Hammerhead is able to tow up to 500 pounds while traveling at 35 knots, and has more than eight hours of endurance [33]. The Textron unmanned boat is much larger and can carry heavier loads. It can haul up to 5,000 pounds while traveling at 10 knots, and has a range of 1,200 miles [26].

### **5.2.4 Airborne alternative**

The airborne alternative will consist of an unmanned helicopter towing the underwater sonar. There are two unmanned helicopters available that will be evaluated for use, the U.S. Navy's Fire Scout and the U.S. Marine Corp's K-Max. Both unmanned helicopters are currently being used by the U.S. military. Similar to the underwater and the surface alternatives, the unmanned helicopter can carry heavy loads, travel through preprogrammed GPS positions, and communicate with human observers through conventional radio communications. The Fire Scout can lift up to 2,650 pounds and stay in the air for up to eight hours, while the heavy duty K-Max can lift up to 6,000 pounds and has a flight endurance of more than two and half hours [29],[30].

## **6.0 Method of Analysis/Simulation**

### **6.1 Simulation**



The goal of each simulation is to determine the time it takes for each alternative to clear the area of mines, and how much energy was used. Random inputs that will affect the simulation will be wind, water temperature, water current, and wave size. Each random input will affect the hydrodynamics and aerodynamics of the system in different ways, depending on the vehicle alternative. The search area and underwater topography of the search area will be constant inputs. Figure 12 is a block diagram showing the planned simulation inputs and outputs.

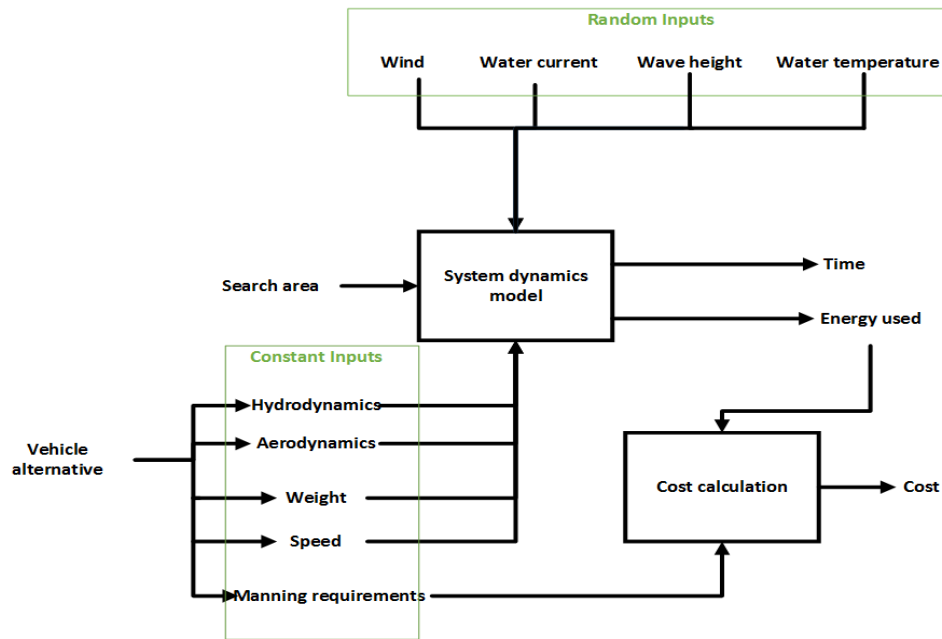


Figure 12: Simulation inputs/outputs

The systems dynamics model will be made using free body diagrams for each system alternative. The free body diagrams show all the forces acting on the vehicle component of the system while it moves through space. Figures 13, 14, and 15 are the free body diagrams for the underwater, surface, and airborne alternatives, respectively. Equation (1) is the equation used to calculate propulsion force for all vehicle alternatives. Equation (2) is the equation used to calculate drag for each vehicle alternative and for the towed sonar.

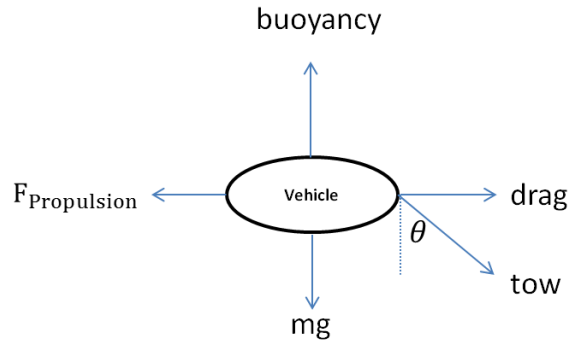


Figure 13: Forces acting on the underwater alternative

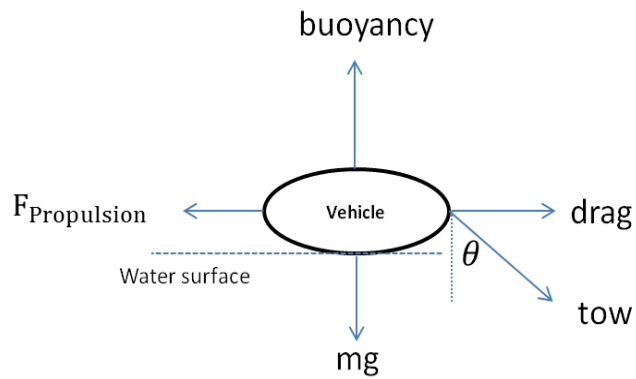


Figure 14: Forces acting on the surface alternative

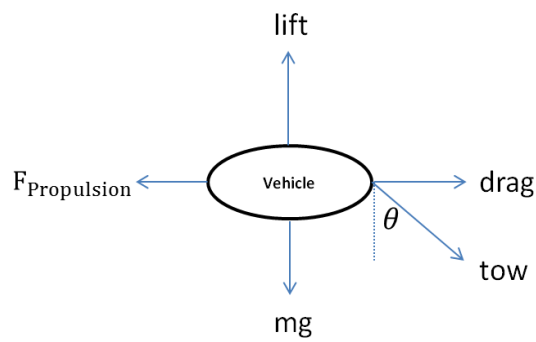


Figure 15: Forces acting on the airborne alternative

$$\mathbf{F}_{\text{Propulsion}} = \mathbf{drag} + (\mathbf{tow} * \sin\theta) \tag{1}$$



$$\mathbf{drag} = \frac{1}{2} * \rho * C * A * v^2 \quad (2)$$

As the system moves through space, the propulsion force must overcome the force of drag on the vehicle body and on the body of the sonar that it is towing. After propulsion force is calculated, it is multiplied by distance to come up with the total energy used. Since the system will be traveling at a constant velocity for the majority of the one square mile area, we are assuming that the extra forces due to acceleration are negligible. When the simulation has been run, the total energy needed for the system to travel through the one square mile area will be calculated.

The airborne alternative will require additional energy to keep the helicopter in the air. The helicopter must create enough lift to overcome the force of gravity and the weight of the sonar body that it is towing through the water. Equation (3) is the equation used to calculate lift power.

$$\mathbf{Lift Power} = \mathbf{mg} + (\mathbf{tow} * \mathbf{cos}\theta) \sqrt{\frac{\mathbf{mg} + (\mathbf{tow} * \mathbf{cos}\theta)}{2\rho\pi r^2}} \quad (3)$$

Lift power is multiplied by time to calculate the total energy used to keep the helicopter in the air as it travels through the one square mile search area. The energy needed for lift is then added to the energy used for propulsion to derive a total energy used. For the purpose of the simulation, we are assuming that the angle at which the sonar tow cable trails the vehicle will remain constant for all vehicle alternatives.

From the output of the simulation, the required energy will be multiplied by energy density of the fuel to calculate the total volume of fuel needed. Volume of fuel can then be converted into total cost based on current fuel costs. An important thing to consider when calculating fuel cost is extra fuel that is consumed beyond what is used to for propulsion. This extra fuel can be to power subsystems, such as electronics or hydraulics, or due to heat and friction losses. To account for the extra fuel consumption in the simulation, a figure of merit will be used. Figure of merit is similar to an efficiency factor. The energy used to propel the system is divided by the figure of merit, resulting in an actual quantity of energy that is consumed. Each vehicle alternative will have a unique figure of merit. Energy cost will be added to cost of manning, acquisition cost, and lifecycle cost in the cost model to determine an overall cost for the system.

## 7.0 Work Breakdown Structure and Project Plan

Figure 16 shows the Work Breakdown Structure for completion of this project. Orange boxes show tasks that are on the critical path.

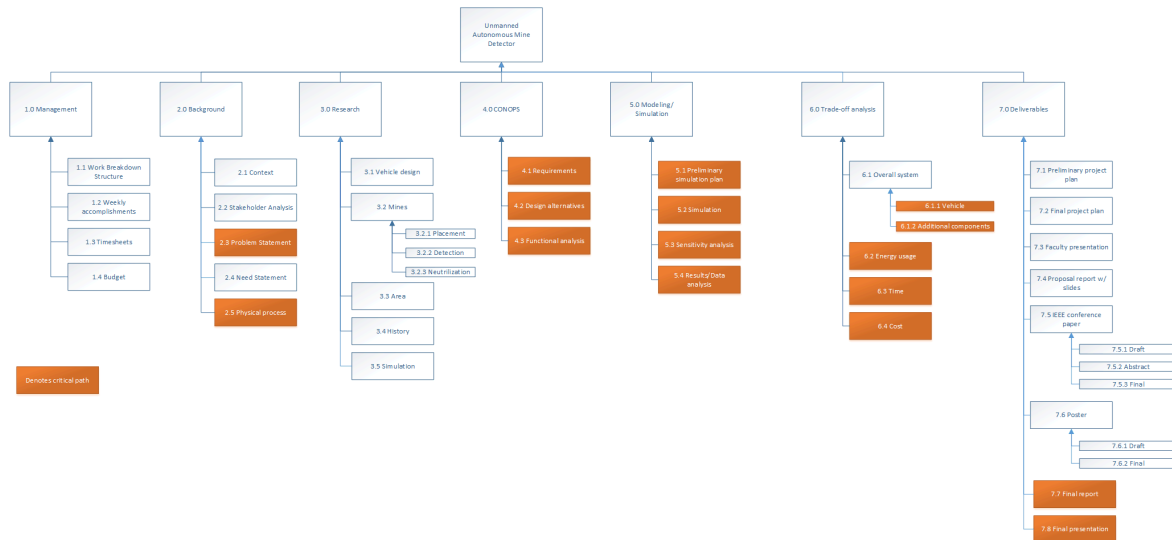


Figure 16: Work Breakdown Structure

### 7.1 Critical Path and milestones

Figure 17 displays the timeline of the tasks on the work breakdown structure. The tasks colored in red are those on the critical path. The accomplishment of these tasks on time is crucial to completion of the project in a timely and professional manner. These tasks include the problem statement, explanation of physical processes, requirements, design alternatives, functional analysis, preliminary simulation plan and simulation, sensitivity analysis, data analysis, trade off analysis, final report and final presentation.

Major milestones for the project include the faculty presentation, final proposal submission, IEEE conference paper abstract and final report.

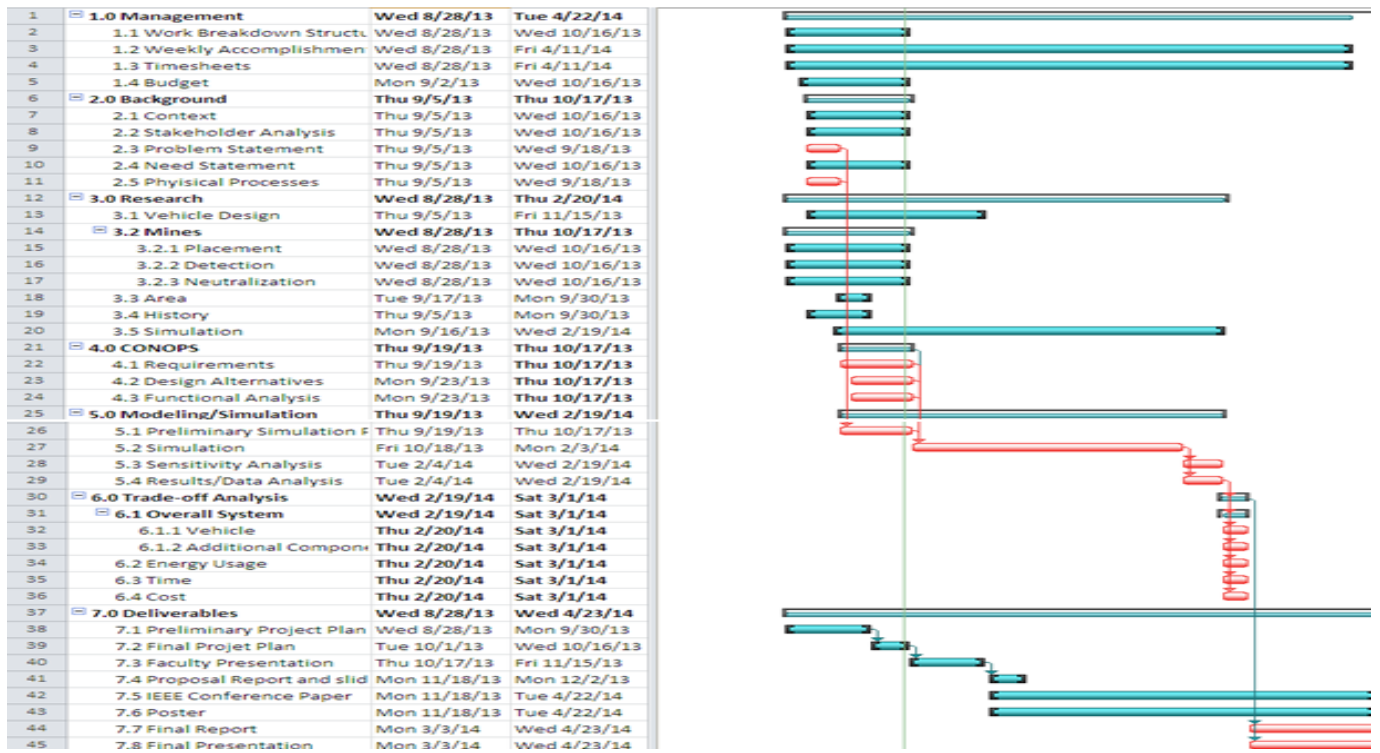


Figure 17: Project Plan

## 8.0 Budget

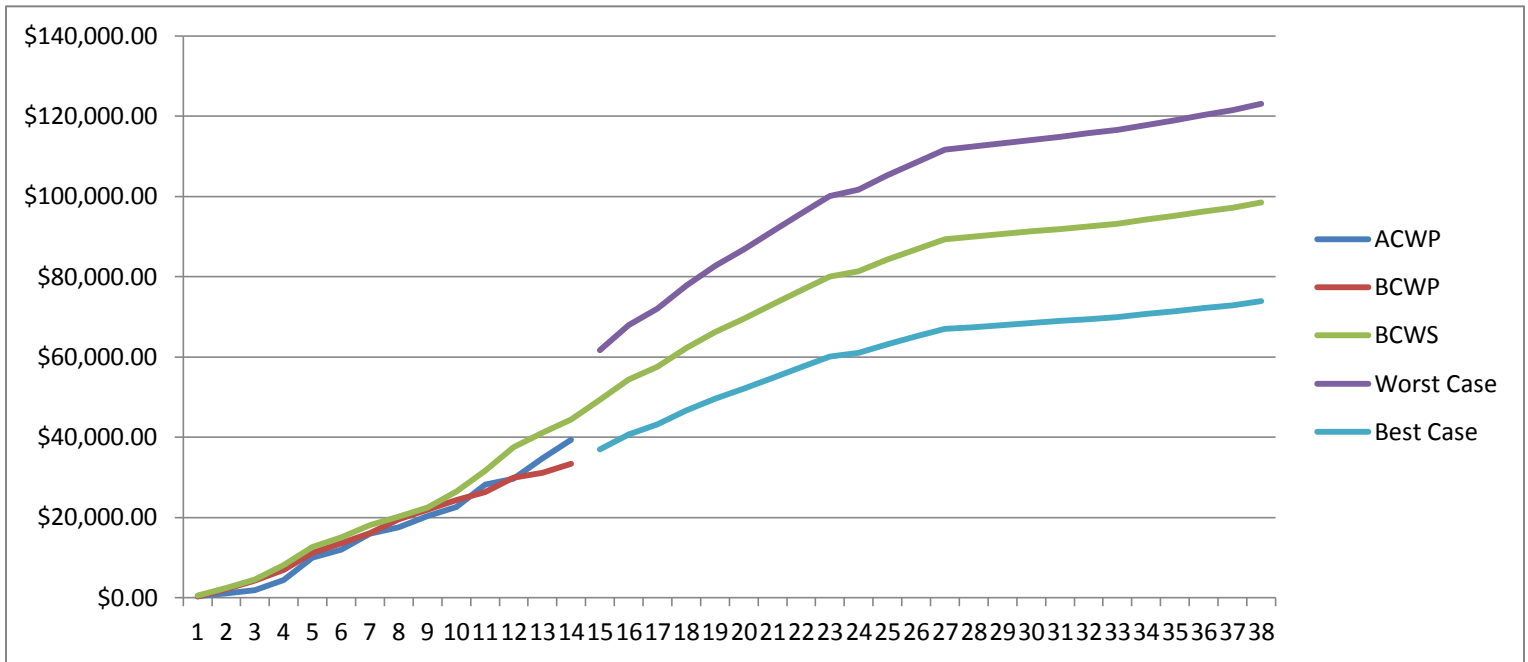


Figure 18: Budget

The budget is based on at \$33/hr salary for each team member (\$68,640/year) plus a 2.0 mark up factor.

## 9.0 Risks and Mitigation

Table 3: Risks and Mitigations

| Risk   | Mitigation  |
|--|---|
| <p><b>Simulation:</b></p> <ul style="list-style-type: none"> <li>• Critical task because many other tasks depend on it.</li> <li>• Failure to complete on time could delay the whole project.</li> </ul> | <ul style="list-style-type: none"> <li>• Start early and budget extra time for simulation.</li> <li>• Perform thorough research prior to simulation design.</li> <li>• Work through winter break</li> </ul> |
| <p><b>Background information:</b></p> <ul style="list-style-type: none"> <li>• Mines and countermeasure systems often contain classified information.</li> </ul>   | <ul style="list-style-type: none"> <li>• Work closely with sponsor for ways to access data.</li> <li>• Use open source data and sensible assumptions</li> </ul>   |
| <p><b>Stakeholders:</b></p> <ul style="list-style-type: none"> <li>• Satisfying all objectives of a stakeholder may be infeasible.</li> </ul>  | <ul style="list-style-type: none"> <li>• Better achieve stakeholder’s feasible objectives.</li> <li>• Justify why solution is best available.</li> </ul>  |
| <p><b>Communication with sponsor:</b></p> <ul style="list-style-type: none"> <li>• Sponsor is busy and sometimes difficult to reach.</li> </ul>  | <ul style="list-style-type: none"> <li>• Allow ample time for response.</li> <li>• Perform extended research.</li> </ul>  |

## 10.0 Future work

Future work over the winter break and into next semester will include, adding the sonar equation and a detection probability into the simulation, adding current technology into the simulation as a baseline assessment, further development of value hierarchy, derivation of attribute weights, utility versus cost analysis, and tradeoff analysis. Figure 19 shows the preliminary value hierarchy. Figure 20 shows what the utility versus cost analysis will look like. Each of the 10 system alternatives will fall somewhere on this graph. The optimal alternative will be near the green portion of the graph with high utility and low cost.

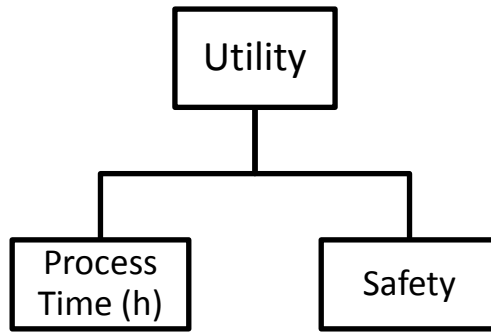


Figure 19: Value hierarchy

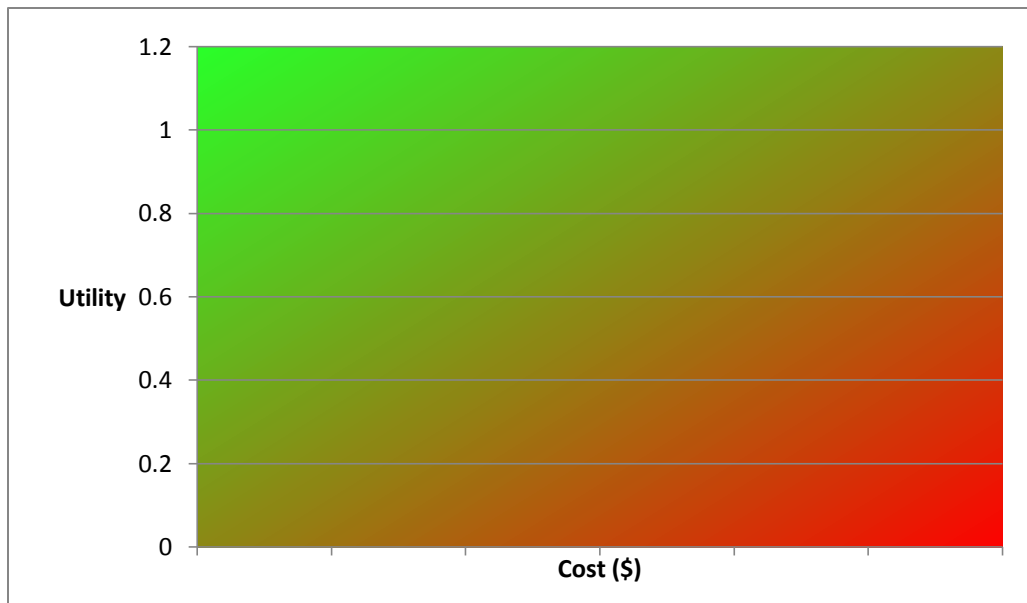


Figure 20: Cost versus utility analysis

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