Design of an Underwater Mine Countermeasure System

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***Abstract*—Mines are an effective method of blocking shipping lanes and restricting naval operations. The placing of mines in waterways can have a severely negative economic and environmental impact. The current mine clearance technology implemented by the U.S. Navy is very time consuming and expensive, and compared with the time and cost of placing of mines, highlight a weakness in the Navy's ability to effectively deal with mines. In this project, the design of a mine countermeasure system is analyzed, with the goal of finding the vehicle and sonar combination with the highest utility versus cost. Two existing sonar alternatives are considered, as well as five different vehicle alternatives combined with each sonar, adding up to a total of ten design alternatives. The vehicle alternatives include underwater, surface, and airborne vehicles towing the sonar through the water.**

***Index Terms*—Mine, Sonar, Inland waterways, Overt and Covert operations, Propulsion force, Lift power.**

I. CONTEXT

A. Importance of world 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]. 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.

The responsibility of clearing mines in the world's waterways often falls on the United States Navy. 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.

B. 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 the mine to be detonated at a more precise location or by some specific target. For example, mines can utilize acoustic sensors, pressure sensors, and a multitude of other techniques in order to become more precise [7]. Figure 1 shows mine designs for placement in different marine regions.

Figure 1: 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]. Figure 2 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.

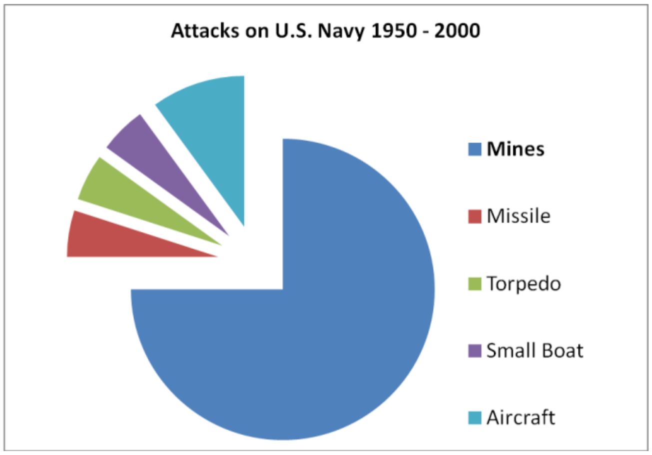


Figure 2: Number of attacks on U.S. Navy ships, by method of attack

C. 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 manned crew to operate the helicopter and sonar. The majority of the cost comes from manning and fuel for the helicopter.

D. 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.

II. Stakeholder Analysis

A. 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.

B. 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.

C. 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.

D. Stakeholder Tensions

Interactions among stakeholders expose the conflicts in their respective interests, and result in stakeholder tensions. These tensions are broken into Internal and External levels.

Internal tensions include tensions between system operators and system enforcers, with the system operators having concerns over operational safety, whereas the main objective of system enforcers is to decrease the time and cost of mine clearance. In addition, servicemen and system enforcers also experience internal tensions. Current training staff may not be able to effectively train the operators for the new system, and the new system may add significant burden to maintenance procedures.

External tensions include tensions between environmental groups and 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]. Other external tensions include tensions between taxpayers and system enforcers, with the taxpayers consistently seeking value of investment on the money they provide through taxes.

III. Problem and need Statements

A. Gap Analysis

Based on current technology, the system enforcers have two gaps to close. Figure 3 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 4) [27].

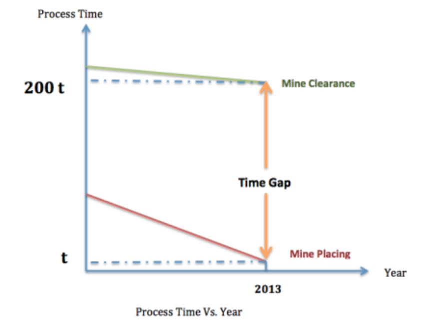


Figure 3: Time Gap

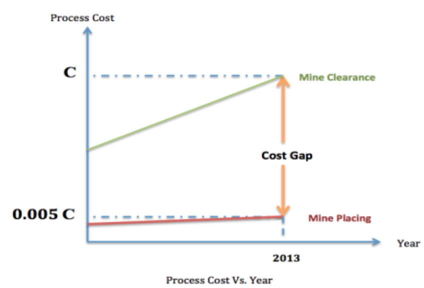


Figure 4: Cost Gap

B. 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.

C. 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.

IV. Concept of Operations

A. 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. 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.

B. Design Alternatives

Each system alternative will consist of two main components; a vehicle alternative, and a sonar alternative.

1. Sonar 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. 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. 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. All alternatives must be able to tow the AN/AQS-20A or T-SAS through the water.
2. Underwater Vehicle Alternatives: 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. It's 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].
3. Surface Vehicle Alternatives: 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 area 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].
4. Airborne Vehicle Alternatives: 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].

V. Simulation

All alternatives will be run through a simulation of mine detection over one square mile in the previously mentioned Chesapeake Bay area. An area of one square mile was chosen because it is the width of the shipping lanes, and therefore, is wide enough to allow ship traffic in two directions. If there was a situation where a suspected mine field was halting the movement of Navy ships, clearing a distance of one mile wide would be sufficient to allow passage in both directions. In addition, one square mile is a simplified baseline measurement that can be used as a conversion to project the clearance of a larger area if the situation exists. Figure 5 shows the pattern that the system will be traveling to cover the one square mile area.

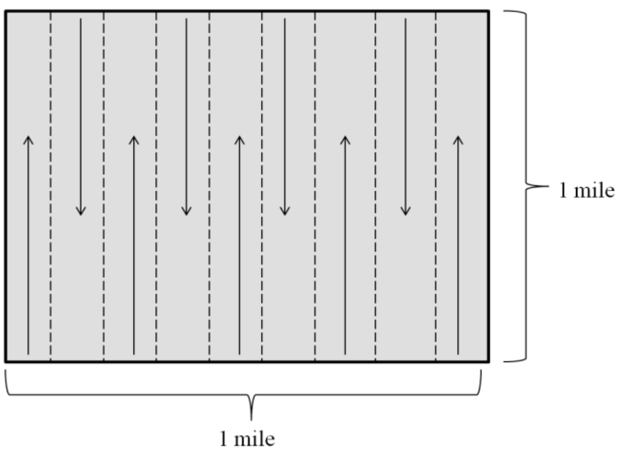


Figure 5: System travel pattern

Each system alternative will consist of one of the vehicle alternatives towing one of the sonar alternatives. Evaluating five vehicle alternatives and two different sonar alternatives totals ten different alternatives that will be run through the simulation. Table 1 shows the ten possible combinations that make up each system alternative.

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.

Table 1: Possible system combinations

		Inputs			Output	
		Sonar	Vehicle		Energy	Time
Alternatives	1	Raytheon	Airborne	Kmax		
	2			Fire Scout		
	3		Surface	Meggit		
	4			Textron		
	5		Submersible	RMMV		
	6	Thales	Airborne	Kmax		
	7			Fire Scout		
	8		Surface	Meggit		
	9			Textron		
	10		Submersible	RMMV		

The search area and underwater topography of the search area will be constant inputs. Figure 6 is a block diagram showing the planned simulation inputs and outputs.

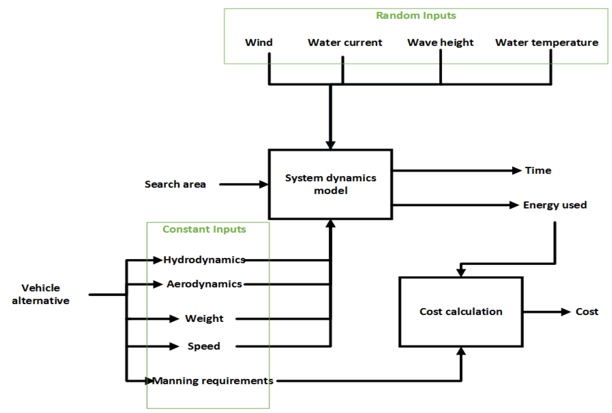


Figure 6: Simulation inputs/outputs

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 7, 8, and 9 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.

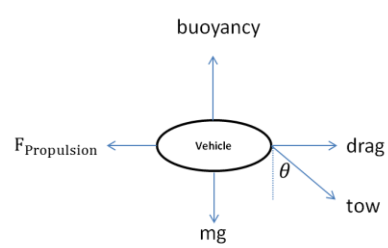


Figure 7: Forces acting on the underwater alternative

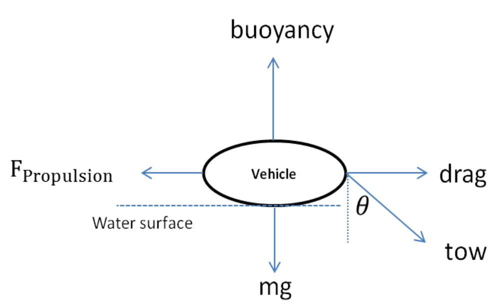


Figure 8: Forces acting on the surface alternative

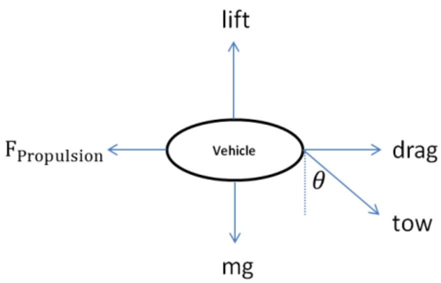


Figure 9: Forces acting on the airborne alternative

$$F_{Propulsion} = drag + (tow * \sin\theta) \quad (1)$$

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

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.

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

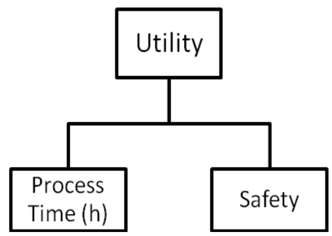
Lift power is multiplied by time to calculate the total energy used to keep the helicopter in the air as it travels through the one square mile search area. The energy needed for lift is then added to the energy used for propulsion to derive a total energy used. For the purpose of the simulation, we 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.

VI. 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 10 shows the preliminary value hierarchy. Figure 11 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 10: Value hierarchy



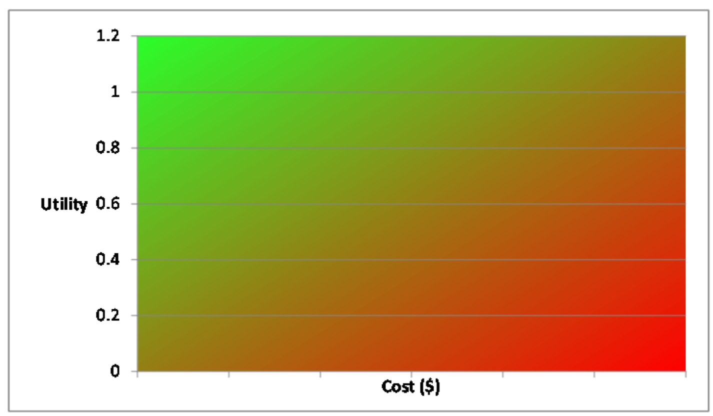


Figure 11: Cost versus utility analysis

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