# Design of a Marine Debris Removal System

Thomas Chrissley, Morgan Yang, Connor Maloy, Anthony Mason
George Mason University, tchrissl, myang9, cmaloy2, amason13@gmu.edu

***Abstract* - The amount of human generated debris entering the oceans was recorded at eight billion kilograms (kg) in 2010, and has been rising exponentially by 10% each year. The most common pollutant is plastic which composes about 80% of the debris. Plastic takes approximately 500 years to decompose, and in that time, it is harming wildlife while collecting in the ocean's circular currents called gyres. The Subtropical Convergence Zone, stretching between California and China, contains the largest of the five major gyres, the North Pacific Subtropical Gyre, which is located between California and Hawaii. The estimated cost of environmental damage from human generated debris is about three billion dollars. Seven design alternatives are evaluated: autonomous vacuum (AV), vessel with nets (VN), barge with unmanned aerial vehicles (B-UAV), artificial floating island (AFI), artificial floating island with sail (AFI-S), artificial floating island with motor (AFI-M), and barge with autonomous surface vehicles (B-ASV). Using a multi-attribute utility function, the best alternative was determined per weights associated with performance, technology readiness level (TRL), and risk. The design alternatives are ranked as follows: AV at 8.461, AFI-M at 7.188, AFI-S at 6.849, B-UAV at 6.571, AFI at 6.221, VN at 4.288, and B-ASV at 2.287. The weight that significantly changes the value of the design alternatives is performance. With a change in the weighs, the optimal solution changes from the AV to the AFI-M. The most viable option is the AV; one AV would clean up the Subtropical Convergence Zone in approximately 5700 years while 5700 AVs would clean up the debris in one year.**

*Index Terms* – Gyre, Human generated debris, North Pacific Subtropical Gyre, Plastic, Subtropical Convergence Zone.

## CONTEXT

Marine debris is defined as any persistent solid material that is manufactured or processed and directly or indirectly, intentionally or unintentionally, disposed of or abandoned into the marine environment [1]. There are seven major types of debris in the ocean: plastic, metal, glass, paper, cloth, rubber, and wood [2]. The biggest impacts of marine debris are wildlife harm, habitat destruction, economic loss, and vessel damage [2]. This debris collects in ocean gyres, which are systems of circular ocean currents formed by the forces of the earth and wind [2]. There are five major gyres, the North Pacific Subtropical, South Pacific Subtropical, North Atlantic, South Atlantic, Indian Ocean Subtropical, and the largest is the North Pacific Subtropical Gyre [2]. The North Pacific Tropical Gyre, also called Great Pacific Garbage Patch (GPGP) is located between California and Hawaii. It is made up of four main currents, the North Pacific, California, North Equatorial, and Kuroshio currents [2] which also creates the Subtropical Convergence Zone (SCZ). The Subtropical Convergence Zone is estimated to be seven million square miles in surface area [3], which is approximately 3.8 billion football fields side by side.

The debris is affecting every system that is associated with the ocean. The marine transportation and fishing industries are the largest affected. Marine debris is adding excess cost to the marine transportation industry from vessel damage and navigation hazards. Varying in size, debris can be difficult to see in the ocean. If a vessel were to hit a large piece, it could damage the hull structure of the vessel or risk possible blocked intake and entanglement of the propeller [3]. These repairs are very costly; up to $1,000,000 depending on the type of ship and damages incurred [4]. For the fishing industry, entanglement, ghost-fishing, and ingestion of debris greatly affect the population and health of marine wildlife [3]. A continual reduction in wildlife results in less of that wildlife available and healthy enough for fishing. This decrease in wildlife directly correlates to a decrease in profit as well as an increase in cost [3].

## STAKEHOLDERS

The marine debris issue is a "tragedy of the commons," being that everyone contributes to the problem yet no one is willing to contribute to the cleanup. Given that the SCZ is located in international waters, nobody wants to take responsibility for the debris, so organizations and individuals will be reluctant to provide necessary funding. There are five main stakeholders for the Marine Debris Removal System (MDRS): non-profit organizations (i.e. Rozalia Project), fishing industry, military, marine transportation, and competing companies. All of the stakeholders want clearer waters to support their overall goals. The risk that each stakeholder faces is the loss of profit and increased costs from the debris affecting their objective. The increased costs include vessel damage or lower quality fish, reducing the profit that stakeholders would be able to make.

## PROBLEM STATEMENT

### *I. Gap Analysis*

Marine debris is harming the marine wildlife through habitat damage, entanglement, ghost-fishing, ingestion, and alien/invasive species transport. The marine transportation, military, and fishing industries are also negatively impacted through economic loss, vessel damage, and navigation hazards. This leads to additional costs and reduced profits. Marine debris is associated with a cost of $1.2 billion to the 21 Asia-Pacific Economic Cooperation members [5].

### *II. Need Statement*

To mitigate the harmful effects of marine debris on the marine wildlife, the debris must be removed from the ocean before irreversible damage is done to the planet. There is a need for a removal system that can traverse the ocean collecting the marine debris efficiently and safely.

## SYSTEM REQUIREMENTS AND DESIGN

### *I. Concept of Operations*

The concept of operations is to deploy a vessel(s) in the vicinity of the marine debris such that it can collect the debris efficiently. The debris must then be retrieved and disposed of or repurposed.

### *II. System Requirements*

The mission requirements are the following:

1. MDRS shall focus on the surface debris – everything within 3 meters deep.
2. MDRS shall produce no extra debris.
3. MDRS shall not harm any pre-existing ecosystem.
4. MDRS shall remove 175,000,000 kg per year.

### *III. Functional Requirements*

MDRS is defined by four functions: deploy, collect, retrieve, and dispose. The deploy function positions MDRS in a location within the SCZ. The collection function removes the marine debris from the marine environment into a collection area. The retrieval function empties the debris from MDRS to transport in back to land. Finally, the dispose function recycles or disposes of the debris.

## SYSTEM DESIGN IMPLEMENTATION

This section describes the technology alternatives available for each of the four functions.

### *I. Deploy*

- Fossil fuel propulsion provides fastest mobility and power. Fuel is required to be replenished regularly on shore and is expensive. Burning fuel emits emissions into the ocean as well as the atmosphere.
- Electric propulsion provides mobility but has limited power output. Electric power is renewable and rechargeable through solar panels and/or wind turbines on the vessel. No harmful emissions.
- Current-driven propulsion means that the vessel is solely dependent on being carried by the ocean currents. Very limited mobility and no emissions or power source needed.
- Wind and current propulsion provides some mobility and some power. Higher mobility and speed is limited by wind speeds. No emissions.

### *II. Collect*

- The vacuum sucks in water as well as the debris. The system will separate the debris from the water, moving the debris to the storage area and draining the water back into the ocean.
- The conveyor belts move at a constant rate bring the debris from the ocean directly to the storage area. The belt with have scoops on it to maximize the amount of debris that is removed at a time.
- Nets, depending on the design alternative, will vary in size. Nets do not catch water but are limited on the size of the debris that they can pick up due to mesh size.

### *III. Retrieve*

- The barge will be a base of operations for a design alternative. Each barge must be modified to accommodate the different requirements of the design alternatives (i.e. charging stations). The barge will not require a crew to operate the design alternative.
- The vessel will be used for variety of different purposes (i.e. deploy and collect). The vessel must have a crew and is limited by fuel. The vessel that will be used is a “Capesize” style ship for the capacity and operational costs.

### *IV. Dispose*

- Landfills are the most available way to dispose of the debris. There is a cost of $50 per ton for the disposal.
- Recycling consists of a sorting process that will find eligible debris (i.e. plastics) for repurposing.
- Incinerators are available for burning specific materials to produce energy. A sorting process is required so that debris containing harmful toxins will not be burned.

## DESIGN ALTERNATIVES

Based on the functional requirements and available technologies, seven design alternatives are considered. Alternatives I-IV use technologies that already exist, while alternatives V-VII are concepts developed for this project.

### *I. Barge with Autonomous Surface Vehicles (B-ASV)*

A fleet of autonomous surface vehicles (ASV) will bring debris to a centralized location (barge). Each ASV traps the debris as it floats over debris along the surface and compacts it into a storage area at the bottom of the vessel. The travel routes are determined through a geo-fencing capability, where each ASV within the fleet will have its own designated work area. These vehicles run on battery that is recharged at the barge when it dumps off debris. The barge is powered by solar panels for the purpose of charging the vehicles. Each ASV initially costs $75,000 with an annual operational cost of $3,750. Each can hold up to 500 kg of debris, with a capability of removing up 15 kg of debris per day. The ASV have a lifecycle of 5 years and due to the limited capacity and size of the ASV, a fleet of 50 is used.

TABLE I
TECHNOLOGIES FOR B-ASV

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Solar powered motor | Vacuum | Barge | Landfill, recycling, incinerator |

### *II. Barge with Unmanned Aerial Vehicles (B-UAV)*

A fleet of unmanned aerial vehicles (UAV) will be used with a barge as a base of operations. Each UAV flies out from the barge and scans the area for debris that is floating on the surface of the ocean. Once the UAV retrieves the debris via a low hanging net, it returns to the vessel where it places the debris in a collection area. The UAVs use geo-fencing to keep them close to the vessel and divide the working area to avoid in-air collisions. After the UAV has delivered the debris, it returns to a station where it charges, and once the charge is full it goes back out to gather more debris. The charging method used by the UAVs is solar power. Each UAV initially costs $5,600 with an operational cost of $280 per year. Each can hold up to 20 kg of debris with one trip. One UAV can make 3 flights per day and due to the limited capacity and the size of the UAV, a fleet of 100 is used. The lifecycle of the UAV is 1 year.

TABLE II
TECHNOLOGIES FOR B-UAV

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Solar powered motor | UAV with net | Barge | Landfill, recycling, incinerator |

### *III. Vessel with Nets (VN)*

A VN is a simple ship that has two nets, one on each side. The nets will be able to collect most of the debris in the marine environment as the ship goes along its course. The only debris that would be able to bypass the nets would be microplastics, tiny particles of degraded plastic that is typically ingested by fish. Once the vessel collection is full or runs low on fuel, the vessel needs to return to port to refuel and dispose of the debris. The initial cost of the net depends on the size that is generated by the model, and the price per square meter of netting is $0.30. The operation cost is a factor of the labor and fuel that is needed to run the vessel, which is $10,950,000 per year.

TABLE III
TECHNOLOGIES FOR VN

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Fossil fuel powered ship | Net | Ship | Landfill, recycling, incinerator |

### *IV. Autonomous Vacuum (AV)*

The AV will travel around the area and suck in water and debris, and then filters out the water. This alternative does not require an additional vessel for collection, only for deployment and retrieval. The debris is then moved to the back of the vessel to a collection area. The vessel is self-sustained by having solar panels and wind turbines in order to power the AV. The initial cost of the AV is $3,000,000 with an annual operation cost of $30,000. The capacity of the AV is 136,000 kg and a lifecycle of 8 years.

TABLE IV
TECHNOLOGIES FOR AV

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Solar and wind powered motor | Vacuum | AV | Landfill, recycling, incinerator |

### *V. Artificial Floating Island (AFI)*

The concept of the AFI is to use the ocean surface currents to drift with the debris, following the same path. This alternative does not require an additional vessel for collection, only for deployment and retrieval. The AFI has conveyor belts on each side at an incline in order to bring the debris out of the water and into the center of the AFI where it will be stored. The initial cost of the AFI is $500,000 with an annual operational cost of $5,000. The lifecycle of the system is 8 years.

TABLE V
TECHNOLOGIES FOR AFI

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Current driven | Conveyor belts | AFI | Landfill, recycling, |

| | | | |
|---|---|---|---|
| | | | incinerator |

### VI. Artificial Floating Island with Sail (AFI-S)

The AFI-S is designed to use the surface winds along with the currents to move with the debris. This alternative does not require an additional vessel for collection, only for deployment and retrieval. The AFI-S has the same features as the previously mentioned AFI, the only modification is the sail it has on top to catch wind. Being able to catch the wind will allow the AFI-S to travel at faster speed than the original AFI, improving the rate of removal. The initial cost of the AFI is $550,000 with an annual operational cost of $5,500. The lifecycle of the AFI-S is 8 years.

TABLE VI

TECHNOLOGIES FOR AFI-S

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Current driven and wind powered motor | Conveyor belts | AFI-S | Landfill, recycling, incinerator |

### VII. Artificial Floating Island with Motor (AFI-M)

The AFI-M is designed to use the ocean surface currents, but also use a motor to power through the areas of the SCZ and collect debris. This alternative does not require an additional vessel for collection, only for deployment and retrieval. The AFI-M has the same features as the previously mentioned AFI, except for the motor. The control on the motor will allow the system to change speed depending on location of AFI-M in the SCZ. The system will travel at a faster speed when the debris density is lower as there is less debris for it to collect. When the system is in higher density areas, it will either lower the speed or the motor will turn off to increase the amount that is collected. The initial cost of the AFI-M is $600,000 with an annual operational cost of $6,000. The lifecycle for the system is 8 years.

TABLE VII

TECHNOLOGIES FOR AFI-M

| Propulsion | Collection | Storage | Disposal |
|---|---|---|---|
| Current driven and electric powered motor | Conveyor belts | AFI-M | Landfill, recycling, incinerator |

## METHOD OF ANALYSIS

### I. Simulations

The objective of the simulation is to estimate the time, cost and efficiency of each design alternative. The input of the simulation is the amount of debris that will be in the marine environment at a given time. The density of the debris, being the volume and area of the debris and how it is spread out throughout the ocean, is second input. The uncontrollable variables are the drift rate of the ocean currents. The currents are dynamic in the way that they are constantly changing speed and direction. The outputs from the simulation are the amount of debris that is collected, the time to collect, and the cost of operation for each alternative.

### II. Simulation Parameters and Variables

The parameters for the simulations are the following: speed of the vessel, debris collection method, operation time, charge time, hourly cost, and non-recurring costs. The speed of the vessel is dependent on the design alternative and varies from stationary to 15 knots. The debris collection is how the design alternative collects debris and is able to store the debris until it is emptied. The operation time and downtime are dependent on the rate of removal and the capacity of the alternative. The operation time is the time that the alternative is able to be collecting and storing debris, while the downtime is when the alternative needs to be emptied, serviced, moved, or refueled. The hourly cost is highly dependent on the alternatives, all require some level of labor cost but vary depending on the time that the vessel is needed. The non-recurring costs are the initial costs for each alternative and any other associated purchase costs including charging stations and vessels.

### III. Assumptions

The AFI is based on the assumption of the Cheerio Effect. The Cheerio Effect is a phenomenon that explains how objects that usually float will attract to one another and form a cluster [6]. The ocean surface current speed depends on the wind stress created on the surface of the ocean. The wind data is gathered from two different buoys that are the closest to the SCZ and have the historical data. Ocean current speed in calculated from the following equation:

$$V_0 = T/\sqrt{2}\mu\rho\omega \sin\varphi \qquad (1)$$

Another assumption is that the ocean currents will bring the AFI to the GPGP, as there is an assumption for the distribution of the marine debris that is found within the SCZ. The distribution is that 90% of the garbage patch is a low concentration area while the other 10% is a high concentration area, which is assumed to be the GPGP.

### IV. Simulation Implementation

The implementation of the simulations returns the results: the amount of debris collected, time to collect, and the overall cost to remove the debris. From running the simulation, the results show which design alternative is the best option in terms of time, cost, and/or both. For testing, the weight of the input was the same value in order to compare the cost and time for each of the design alternatives. After comparing the time and cost, the best design alternative is chosen based on the optimal cost and time needed to remove that amount of debris. The following equations are used to calculate the rate of removal for the B-UAV and the VN:

$$Rate_{UAV} = floor(1440 / Time_{Flight} + Time_{Charge}) \times \text{Payload} \quad (2)$$

$$Rate_{VN} = (speed \times area) / volume \quad (3)$$

## UTILITY ANALYSIS

### *I. Scores and Weights*

There are seven measures that are analyzed to determine the overall utility of each design alternative:

- Rate of removal - the rate at which the alternative can remove debris from the ocean (kg/day).
- Capacity - the amount of debris (kg) each alternative can carry before needing to be emptied.
- Lifecycle - the amount of time (years) each alternative can exist before needing to be replaced.
- Eco Friendly - how safe and non-disruptive each alternative is to the surrounding environment.
- Reliability - how likely each alternative is to last its entire expected lifecycle.
- Security - how likely each alternative is able to be used for anything other than its intended purpose.
- Technology readiness level (TRL) - where each alternative ranks on the TRL scale in terms of design development.

For the design alternatives, the measures are divided into three main categories: performance, risk, TRL. The performance category was determined to be three times as important as the risk category due to the need for the project to be completed as soon as possible. The risk was designated as one and a half times as important as the TRL. Using this method of weight calculation and the importance of performance, the performance category carries a weight of 0.643 on a scale of 0 to 1. The risk and TRL categories have weights of 0.214 and 0.143, respectively.

The same methodology was used in determining weights within the performance and risk categories. Under performance, this resulted in the weight for the rate of removal measure to be 0.357 and the capacity weight to be 0.286. Under risk, the lifecycle weight is 0.105, the eco friendliness has a weight of 0.052, the reliability weight is 0.034, and the security weight is 0.023. The TRL category has no sub-categories, so there is no need for further breakdown. The total utility for each alternative is based on the equation:

$$Total = \sum weight_i \times score_i \quad (4)$$

TABLE VIII

ATTRIBUTE WEIGHTS FOR EACH ALTERNATIVE

| Capacity | Eco Friendly | Life-cycle | Rate of Removal | Reliability | Security | TRL |
|---|---|---|---|---|---|---|
| 0.290 | 0.052 | 0.105 | 0.357 | 0.033 | 0.023 | 0.140 |

### *II. Utility Analysis*

Each value that is factored into the utility for the alternatives was calculated based on the range for that measure among all the alternatives. The value for the alternative was compared with the overall maximum and minimum values in order to convert them to a 1-10 scale using the equation:

$$Score = (x - min) / (max - min) \times 9 + 1 \quad (5)$$

TABLE IX

SCORE VALUE FOR EACH ALTERNATIVE

| | Capacity | Eco Friendly | Lifecycle | Rate of Removal | Reliability | Security | TRL | Total |
|---|---|---|---|---|---|---|---|---|
| B-ASV | 1 | 6 | 6 | 1 | 6 | 3 | 3 | 2.287 |
| B-UAV | 1 | 5 | 2 | 9 | 3 | 3 | 5 | 4.855 |
| VN | 7 | 1 | 1 | 6 | 6 | 3 | 10 | 6.004 |
| AV | 9 | 8 | 10 | 10 | 7 | 8 | 3 | 8.461 |
| AFI | 10 | 10 | 10 | 3 | 6 | 10 | 2 | 6.221 |
| AFI-S | 10 | 9 | 10 | 5 | 5 | 10 | 2 | 6.849 |
| AFI-M | 10 | 8 | 10 | 6 | 6 | 10 | 2 | 7.188 |

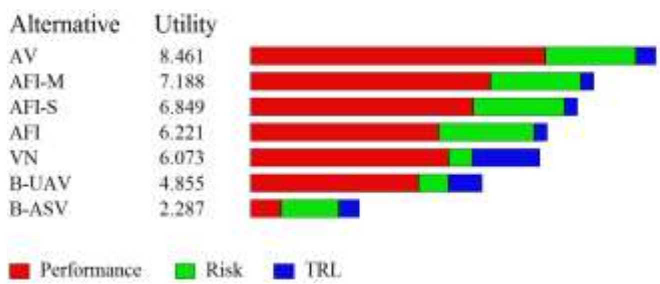


FIGURE 1

DYNAMIC UTILITY ANALYSIS

These values are multiplied by their weights and added up to obtain the overall utility for each alternative. Table VIII above shows the utility value for each alternative, and table IX below it shows the weight for each attribute. A cost versus utility analysis of these results show that the only alternatives with a utility value worth the cost are the AV, the AFI-M, and the AFI-S. Given that the AFI-M has a lower utility than the AV, it is also less expensive, keeping it an efficient option regarding cost. The AV has the highest utility value, but also comes with a higher cost than the AFI-M. Given the proximity of the these three alternatives in the cost versus utility analysis, it is impossible to select just one alternative that is signifigantly better than the others due to uncertainty associated with both utility and cost.

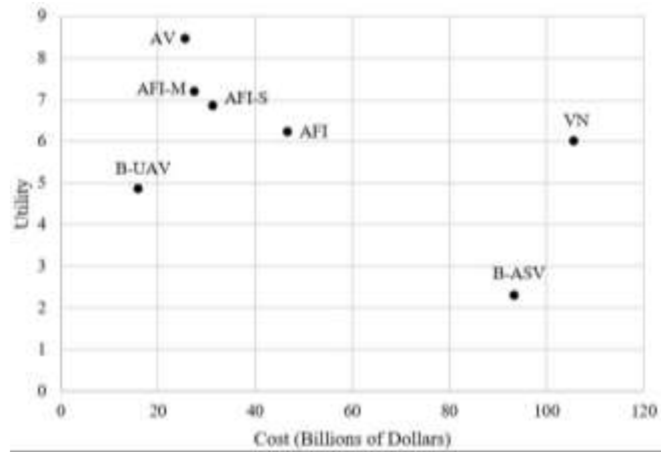


FIGURE 2
COST VERSUS UTILITY ANALYSIS

*III. Sensitivity Analysis*

Performing a sensitivity analysis on the utility results, as well as the weights, shows that the AV separates itself from the other alternatives mainly through the performance ratings. In order for the closest alternative, the AFI-M, to become the best option, it would need to have an overall better performance rating. That would include either improving the rate of removal or the capacity. Given the large weight placed on performance, that is the most likely measure to make an impact if one of alternatives were to have an improvement. The AFI-M is unlikely to surpass the AV by improving the risk category, as the two have similar high scores already, and the weight is not enough to make a significant difference. Similarly, due to the low weight for TRL, the other alternatives are highly unlikely to surpass the AV, even with a significant improvement in that category. All in all, the AV is the best alternative with the highest score, but that could change if there were to be significant improvement in the performance categories of the other alternatives.

## CONCLUSION AND RECOMMENDATIONS

Based on the results from the simulation and the multi-attribute utility analysis, the design alternative that is the best option for cleaning up marine debris is the AV. The capacity and rate of removal are the biggest factors in determining the best option due to the fact that the problem needs to be solved now. Although the AV has the best cost to utility ratio based on the calculation, the AFI-M and AFI-S are too close to the AV to make a clear decision. The AV, AFI-M, and AFI-S each are feasible options to be considered when looking for a solution to this problem. Further development of the AFI concept will alter the values it currently achieves. A recommendation to expand the efficiency of marine debris removal would be to combine the unique design alternatives in order get the best coverage, since the different alternatives have different methods of removal.

## REFERENCES

[1] "What is Marine Debris?," *NOAA's National Ocean Service*, 14-Nov-2008. [Online]. Available: http://oceanservice.noaa.gov/facts/marinedebris.html. [Accessed: 22-Mar-2017].
[2] "OR&R's Marine Debris Program," OR&R's Marine Debris Program. [Online]. Available: https://marinedebris.noaa.gov/. [Accessed: 22-Mar-2017].
[3] "Great Pacific Garbage Patch," *National Geographic Society*, 09-Oct-2012. [Online]. Available: http://www.nationalgeographic.org/encyclopedia/great-pacific-garbage-patch/. [Accessed: 22-Mar-2017].
[4] "Guide to Hull Claims." (2003): n. pag. Web. 28 Mar. 2017.
[5] "Understanding the Economic Benefits and Costs of Controlling Marine Debris in the APEC Region." APEC Marine Resources Conservation Working Group (2009): n. pag. Web. 28 Mar. 2017.
[6] D. Vella and L. Mahadevan, "The "Cheerios Effect"," *Harvard*, Feb. 2005.

## AUTHOR INFORMATION

**Thomas Chrissley,** Student, Department of Systems Engineering and Operations Research with Concentration in Aviation Systems, George Mason University.
**Morgan Yang,** Student, Department of Systems Engineering and Operations Research with Concentration in Engineering Systems, George Mason University.
**Connor Maloy,** Student, Department of Systems Engineering and Operations Research with Concentration in Operations Research, George Mason University.
**Anthony Mason,** Student, Department of Systems Engineering and Operations Research with Concentration in Financial Systems, George Mason University.