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Optimizing the Space Debris Removal Process: An In-Depth Analysis of Current Debris Removal Technologies

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ABSTRACT

As humanity progresses towards mainstream space transportation and eventually space colonization, the accumulation of space debris orbiting around Earth has become critical, jeopardizing safety, operational economics, and ultimately overall success. The scope of this project is to analyze data from existing technologies - some still “concepts” and some in early commercialization stage - to pinpoint the most efficient technology in removing debris. Efficiency is a function of both the removal volume (effectiveness) and operational costs associated with the debris removal technology. Primary and secondary research was conducted to identify the most prominent technologies, collect data associated with their operation, define the main cost categories, assume relative cost relationships across the various technologies (in reference to the cost categories) and quantify their ability to remove various debris types and volumes. Eventually each technology was described via a “Total Cost” (a mathematical formula summarizing the various cost types) and a “Total Efficiency” (calculated as Removal Capacity over Total Cost). Given the large number of independent variables (for which only a min/max value range and a normal distribution could be assumed) a simulation code was programmed in Python to generate a population of outputs (for Total Cost and Efficiency) based on millions of random input values (for the independent variables). Out of a list of seven technologies (OrbitGuardians, Astroscale, Clearspace, Aurora, D-Orbit, Airbus RemoveDEBRIS Net and Airbus RemoveDEBRIS Harpoon), Astroscale is best technology in terms of efficiency because of its extreme reusability and its unique mechanism of driving debris out of orbit.

1. Introduction

Space debris is a growing problem that threatens our planet and future space explorations. The need for effective methods of removing space debris has never been greater. Humanity is looking into space exploration for the purpose of finding resources, for potential future colonization, and by all means because of its inherently curious nature. As investments and expeditions continue, the accumulation of space debris in orbit and in outer space must be met with solutions actively geared towards debris reduction. Removing such debris requires the application of advanced technologies; however, such technologies need to be effective in debris removal while also being cost-efficient so that they can be practical, scalable, and economically viable. Also, control measures such as not leaving rocket bodies and other payloads in space “will significantly increase the cost of debris control measures; but if we do not do them, we will increase the cost of future space activities even more.”[1] This research will focus on building economic models and running advanced simulations to identify the technologies with the highest efficiency; the ones providing maximum effectiveness (debris removal capacity = removal volume per time) for the least amount of cost (*efficiency = removal capacity/total cost*). The work could help our society in the near future - especially as space exploration efforts intensify - in reducing safety risk concerns due to orbital debris and ensuring smoother overall operations. This

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[1] Kessler, D. J. (2009). *The Kessler Syndrome*. Kessym. Retrieved September 14, 2022

is equally important for the long term as humanity is thinking of building space factories to assemble spaceships, produce new types of materials (that can only be made in microgravity), and more.

1.1 Proliferating Chaos

To undergo the journey of cleaning space, one must first begin with understanding the origin of space debris. Over the last few decades, many events have contributed to the creation of space debris such as the collision of two satellites, Iridium 33 and Cosmos 2251, which is thought to have produced thousands of fragments that pose dangers to other orbiting satellites.[2] Then, in January 1986, a flight rule was established after the Challenger incident which provided a procedure for collision avoidance of trackable space objects.[3] Space objects, commonly known as space debris, are not merely man-made satellites (or their fragments following collisions); in fact, debris can also originate from naturally-created meteoroids. These meteoroids were hypothesized to exist in Earth's orbit around the time of the space race, the first expeditions to space. Loretta Hall, a member of the NSS space ambassadors subcommittee, suggested that Fred Whipple, an astronomer during that era, "warned that a spaceship traveling toward the moon would have a one in twenty-five chance of being destroyed by a meteoroid."[4] However, they could not provide evidence because they assumed that space debris was moving too fast to be photographed. These assumptions were proven wrong when Russia's Sputnik 1 was launched into space and provided a clear image from scientific telescopes. While Whipple's theory was undermined it was not necessarily wrong. As stated earlier, natural debris does exist in space, however, the bigger threat is man-made debris. According to the National Aeronautics and Space Administration, commonly referred to as NASA, and their Jet Propulsion Laboratory, there exist more than half a million man-made pieces of debris that range from paint chip sized to objects larger than 4 inches.[5] These pieces of debris move at speeds close to 20 times the speed of sound and can easily puncture holes in satellites or space stations. In a study of damage from space debris by Gerhard Drolshagen, the Chair of the Space Missions Planning Advisory Group from the European Space Agency, "small craters can lead to erosion and to the change of optical, thermal, or electrical properties of surfaces. Craters can also be the precursors for more extended damage."[6] Drolshagen's study provided valuable information about the short and long-term damage that can come from space debris. An example of debris causing damage and changing thermal or electrical properties is when debris hits the solar panels on a satellite/space station. The debris' impact changes the effectiveness of gathering energy because of cracks/holes the debris might have made and leads to further costs of replacing or fixing the panels. Because of this information, it increases the urgency of collecting and/or removing debris because of costs that will only increase exponentially. Even astronauts themselves have expressed their opinions on space debris, including Garrett Reisman, who stated that debris is extremely dangerous and must be removed whilst on a podcast.[7] This is also more important when including future and current supply chain operations in space. These supply chain operations are as important to sustain as future space exploration/colonization. Without supply chain operations, going out into space for resources would prove to be useless. Nevertheless,

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[2] Kessler, D. J. (2009). *The Kessler Syndrome*. Kessym. Retrieved September 14, 2022

[3] Klinkrad, H. (2012). *Space Debris: Models and Risk Analysis*. Springer.

[4] Hall, Loretta. "The History of Space Debris - Embry–Riddle Aeronautical University." *Embry-Riddle Aeronautical University Scholarly Commons*, 2014

[5] NASA. (2012). *Waste in space*. NASA. Retrieved September 14, 2022

[6] Drolshagen, G. (2007, September 15). *Impact effects from small size meteoroids and space debris*. Advances in Space Research. Retrieved September 25, 2022

[7] Reisman, G. (2020, February 7). *Astronaut Garrett Reisman on space junk and micrometeorites*. YouTube. Retrieved September 14, 2022

our current utilization of supply chain operations in space is still superficial, as we have yet to begin any large operations in space. An example of our superficial use of supply chain operations would be the International Space Station, which utilizes a global supply chain that complies with their codes of conduct.[8]

It is important to understand that debris stuck in space will not stay still and wait for satellites to collide with them. A common occurrence in space is when debris (usually man-made) collides with other satellites at high speeds and creates what's known as a fragmentation event where particles and shards of both debris and satellite get launched further into space at speeds 20 times that of sound. This theory is known as the Kessler Syndrome. Originally proposed by Donald J. Kessler, an American astrophysicist, "the 'Kessler Syndrome' was meant to describe the phenomenon that random collisions between objects large enough to catalogue would produce a hazard to spacecraft from small debris that is greater than the natural meteoroid environment."[9] Should humanity proceed with space exploration without removing existing space debris, the repetition of fragmentation events will conclude in a sheet of debris in orbit covering the Earth. This phenomenon was modeled in a paper by Alessandro Rossi in which he uses formulas to predict the growth of the space debris environment in the coming decades.[10] The removal of debris is vital for the continuation of humanity's conquest in space, and thankfully many companies have begun projects and experiments to remove debris from space with different approaches. However, with the different approaches used to remove debris, it is necessary to evaluate which technology is the best in terms of efficiency and effectiveness.

1.2 Gap: No Studies on Efficiency

As explained previously, the gap of this paper is finding the most effective and cost-efficient technology currently available and being constructed. Because of the variations in technologies and the lack of data, it is difficult for new companies and organizations to decide which to trust and use in the removal of space debris. Therefore, by conducting research which covers this gap, I will be able to help produce a more scalable solution to space debris removal. This lack of knowledge is acknowledged in a paper by Mark Priyant, an acknowledged researcher in the space industry, in which he and others studied different technologies but concluded with the statement that "all the ADR systems are at a conceptual/experimentation phase and require more study to be established into commercially viable platforms."[11] However, in the case that this analysis of different technologies concludes to have more assumed data than previously hypothesized, it will only help progress the finalization of a superior technology and not come to a certain conclusion. Nevertheless, some progress is better than no progress since this subject is widely understudied, and as Joel Wooten stated in his paper, "remediating the current space waste and avoiding future additions will require study."[12] And as stated by Dr. Darren McKnight, removing space debris will only get more difficult and expensive through time because of effects such as the Kessler syndrome so removing space debris in the near future is pivotal.[13] Through existing data analysis and economic models, I plan to answer the question: What is the most efficient technology to remove space debris that can damage future supply chain operations in space?

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[8] *ISS Supply chain policy - ISS world*. ISS World. (2017). Retrieved December 19, 2022,

[9] Kessler, D. J. (2009). *The Kessler Syndrome*. Kessym. Retrieved September 14, 2022

[10] Rossi, A., Anselmo, L., Cordelli, A., Farinella, P., & Pardini, C. (1999, February 15). *Modelling the evolution of the space debris population*. Planetary and Space Science. Retrieved September 25, 2022

[11] Priyant, M. C., & Surekha, K. (2019, January 29). *Review of active space debris removal methods*. Space Policy. Retrieved April 17, 2023

[12] Wooten, J. O., & Tang, C. S. (2018). *Operations in space: Exploring a new industry*. Operations in Space: Exploring A New Industry. Retrieved September 14, 2022

[13] McKnight, D. (2010). *Pay me now or pay me more later: Start the development of active ...* AMOS Conference. Retrieved April 18, 2023

1.3 Seven Competing Technologies

There are not many companies (or technologies) that currently exist in the space debris removal industry. It is useless to research scientific papers because those technologies referenced inside the papers are mostly concepts with no usable data. Therefore, in order to find suitable technologies/solutions, the researcher will have to use marketable technologies such as those produced by companies. This allows the researcher to potentially find publicly available data, or at least a higher chance to find the data when compared to research 'concepts. As discussed in an article published by the European Space Agency, there three main types of technologies: "Pulling Technologies", "Pushing Technologies", being the main two types as well as "Contactless Technologies".[14] There also exists another type of technology which is just titled as 'other technologies. Under these classifications are the current hypothesized concepts in which a few have been realized into the space debris removal market. Of course, technologies that have usable data for this project do not only operate separately; for example, "ministers [from ESA's Ministerial Council] agreed to place a service contract with a commercial provider for the safe removal of an inactive ESA-owned object from low-earth orbit."[15] An example of a company that has cooperated with the International Space Station is Nanoracks, in which they deployed a RemoveDEBRIS satellite into Earth's orbit and ran experiments using it.[16]

A common question that arises when studying this topic is "why should these companies remove space debris, and how do they make money?" In a study published by the Pew Research Center, it was stated that "one recent business study [estimated] that the global market for monitoring and removing debris will generate $2.9 billion in revenue by 2022."[17] This estimation shows that the market for removing debris is quite large and companies can find success in solving this problem. Of course, funding is not a problem because big-name organizations such as the European Space Agency (ESA) or National Aeronautics and Space Administration (NASA) provide funds to small companies to develop technologies. To answer the question of why they remove debris is not difficult to answer. The threat of space debris blocking humanity on Earth is a big enough reason for these companies to act and begin allocating funds to begin removing the debris.

After looking through all available technologies, the researcher decided upon seven main satellites/technologies: Orbit Guardians, Astroscale, Clearspace, Aurora, D-Orbit, Airbus RemoveDEBRIS Net, and Airbus RemoveDEBRIS Harpoon.

2. Method

In order to successfully gather accurate conclusions of the data from technologies used in this paper, I have used various existing databases created by the technologies' creators. The best and most accurate method used for this paper, through careful consideration, is Secondary Data Analysis because it "provides a viable option for researchers who may have limited time and resources", which was the case in this research project.[18] Some examples of the limitations present in my experiment are the costs of original technologies and the time needed for launching to space and gathering data. "While Secondary Data Analysis is a flexible approach and can be utilized in several ways, it is

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[14] Wormnes, K, et al. "ESA Technologies for Space Debris Remediation." *European Space Agency*,

[15] *Esa Commissions World's first space debris removal*. ESA. (2019, December 9). Retrieved September 25, 2022,

[16] *Removedebris in orbit - largest satellite deployed from ISS to date*. Nanoracks. (2020, April 15). Retrieved September 14, 2022,

[17] Strauss, M. (2020, August 25). *As debris piles up, Americans are skeptical enough will be done to limit space junk*. Pew Research Center. Retrieved September 25, 2022,

[18] Johnston, M. P. (2014). *Secondary Data Analysis: A Method of which the Time Has Come | Qualitative and Quantitative Methods in Libraries.*

also an empirical exercise with procedural and evaluative steps", just like True Experimental.[19] Though True Experimental might be more efficient in finding data by personal use of the technologies, it was impossible in this case because of the massive costs included in performing experiments in space.

2.1 How SDA Aligns

The method of Secondary Data Analysis lines up with the research question because it successfully counters the limitations and allows the researcher to complete the project without problems. While looking for possible methods to solve this research question, Secondary Data Analysis was the only plausible one because it allows for researchers to study a topic without problems such as lack of funds or any physical dangers.

2.2 Example Paper: Value Analysis for Orbital Debris Removal

In a similar paper by Leonard Vance, a Senior Engineering Fellow at Raytheon Missile Systems, he acknowledges "members of the NASA Orbital Debris Office, including Nicholas Johnson and J.C. Liou, for their encouragement, resource help and feedback"[20], demonstrating his use of exterior resources for data in his experiment. Furthermore, in his beginning paragraphs, he states how the authors "chose a set of publically available databases permitting proof of concept for the overall techniques while providing a first cut at substantive results."[21] By using this paper as a base, the researcher was able to progress the study and finalize the choice for an effective method.

2.3 Variables and Technologies

For this research experiment, a control group was not used (since this method does not require any); however, a base technology was used to build assumptions off of. Orbit Guardians served as a placeholder to compare other technologies to and make assumptions. For example, by comparing the sizes of Orbit Guardians and another technology, the researcher was able to scale the costs relating to size for that certain technology.

In this analysis/experiment, I use a mixture of technologies that are not concepts and are included in markets or are in experimental phases. This is because concept technologies do not have any data that is usable for evaluation, whereas marketable technologies have usually been tested. Thus, companies such as Clearspace or Aurora and their products will become the independent variables used for analysis. The data dependent on the technologies, the dependent variables, will consist of variables such as the cost of launch, the cost for debris removal (either one or many), the amount of debris removed, along with manufacturing costs, reset and disposal costs, maneuvering costs, and disposal costs. The controls used in the analysis consist of the distance from the Earth, the quantity of debris to be removed, and the time period for debris to be removed along with other variables. The analysis will cover as many technologies as possible for a larger range of techniques to remove debris and the process will repeat for as many technologies as there are. Furthermore, more analysis could be done by changing controls to differ by how far the technology can be from space, or how many times the technology can be used to remove debris before maintenance (this will be explained further in the procedure).

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[19] Johnston, M. P. (2014). *Secondary Data Analysis: A Method of which the Time Has Come | Qualitative and Quantitative Methods in Libraries*.

[20] Vance, L. (2013). *Value Analysis for Orbital Debris Removal* (A. Mense, Ed.).

[21] Vance, L. (2013). *Value Analysis for Orbital Debris Removal* (A. Mense, Ed.)

Before beginning to elaborate on the procedure of the experiment, it is necessary to expand on what databases will be used in the paper. It is unfortunate that many databases for companies are private and not available to the public, therefore there may be technologies that have been tested in space that aren't used in the analysis because of the inaccessible data. Possible databases that will be used in this paper are strictly from companies that have them public and that are out of the conceptualization/brainstorming phase.

3. Procedure

To begin researching the effectiveness and efficiency of debris removal technologies, the researcher will first find credible sources related to the technologies' parent companies. This is done first to ensure that the data generated is credible and usable for future research. After collecting relevant information about technologies, the researcher will then sort the information into a Microsoft Excel spreadsheet under different columns. In this spreadsheet, the rows represent the information relevant to one technology, changing technologies as it goes down. Then the researcher will gather research on the effectiveness of each technology (such as their debris removal capacity and the speed of debris removal) and then break down the costs of the overall debris removal operations as shown below in **Table 1.**

Table 1 – Minimized version of researcher's Excel spreadsheet filled in with available data and variables to substitute values in while simulating. Full excel in the appendix.

Technologies	Relative weight	1 - Cost for Manufacturing	2 - Cost for Launch	3 - Fixed Operating Costs	4 - Cost for Maneuvering	5- Cost of disposal and reset	Volume (removal capacity)	Total Cost
Orbit Guardians - Active Debris Removal (Absorbs + ejects)	W	M	X	F	Y	Z	5V	M + X + F + Y + Z
Astroscale - Active Debris Removal (End of Life/Life Extension/Physical Debris Removal)	2W	2M	2X	2.5F	3Y	10Z	20V	2M + 2X +2.5F + 3Y + 10Z
Clearspace - (Spider-form debris grasping)	2W	2M	2X	0.5F	1.5Y	2M + 2X + 1.5Y	V	2M + 2X +0.5F +1.5Y + 2M + 2X + 1.5Y = 4M + 4X + 0.5F + 3Y
Aurora - (deorbiting device) - End of life solution	0.01W	0.02M	0.01X	0.5F	0.05Y	0.02M + 0.01X + 0.05Y	V	0.02M + 0.01X + 0.5F + 0.05Y + 0.02M + 0.01X + 0.05Y = 0.04M +0.02X +0.5F +0.1Y
D-Orbit - End of Life solution	0.01W	0.02M	0.01X	0.5F	0.01Y	0.02M + 0.01X + 0.01Y	V	0.02M + 0.01X + 0.5F + 0.01Y + 0.02M + 0.01X + 0.01Y = 0.04M +0.02X +0.5F +0.02Y
Airbus RemoveDEBRIS Net - Net of satellite with different technologies	W	1.5M	X	F	0.5Y	3Z	10V	1.5M + X + F + 0.5Y + 3Z
Airbus RemoveDEBRIS Harpoon - Harpoon	W	1.5M	X	F	Y	0.5Z	5V	1.5M + X + F + Y + 0.5Z

Because of the lack of data that comes with studying space, the researcher fills the missing areas of data by using similar information from other areas. Again, the researcher does not mean plucking numbers out of thin air, but instead looking at already existing data that is similar to what is missing. For example, the researcher analyzes photos of the different technologies to compare how one's weight (Variable W) is different to another's. By doing this, the researcher can scale the variable that correlates to weight (launch cost and manufacturing cost) depending on how many times bigger one technology is. This is crucial since it is bound to happen because of the massive lack of data.

Afterwards, the researcher writes a python code that uses ranges for certain variables found by looking at other industries, as previously mentioned, as well as the total cost equations in the table and outputs a set of graphs for ten different simulations that express total cost for each technology which are then overlapped. Simultaneously, the code will output a graph of the efficiencies of all technologies, which is found by using the total removal volume of a satellite as the numerator and the total cost equation as the denominator. Then, the researcher will gather the results of the first run (simulation #1) and store them in a different Excel file for further analysis. Subsequently, the researcher will run another simulation with the same values as the first; however, with manufacturing costs and launch costs in gamma distribution to simulate the assumed decreasing costs over time because of different innovations in technology. This pattern will continue for ten total simulations, with alterations after every second simulation.

After running the simulations and the graphs are outputted, the researcher will gather them into an excel. This step is done to ensure no mistakes by incorrectly assigning a graph the wrong simulation number. Upon doing this, the researcher can then look at the graphs and find the most efficient technology by seeing which normal distribution has the highest average. The next step would be to analyze the commonalities between the winning satellites of the simulations to find any implications.

Overall, by proving the superiority of one (or more) technology over the others in the field, hopefully, companies and organizations can utilize the information and begin large-scale operations to remove space debris.

4. Findings

In this section, the procedure explained in the previous section was conducted and the results are shown here.

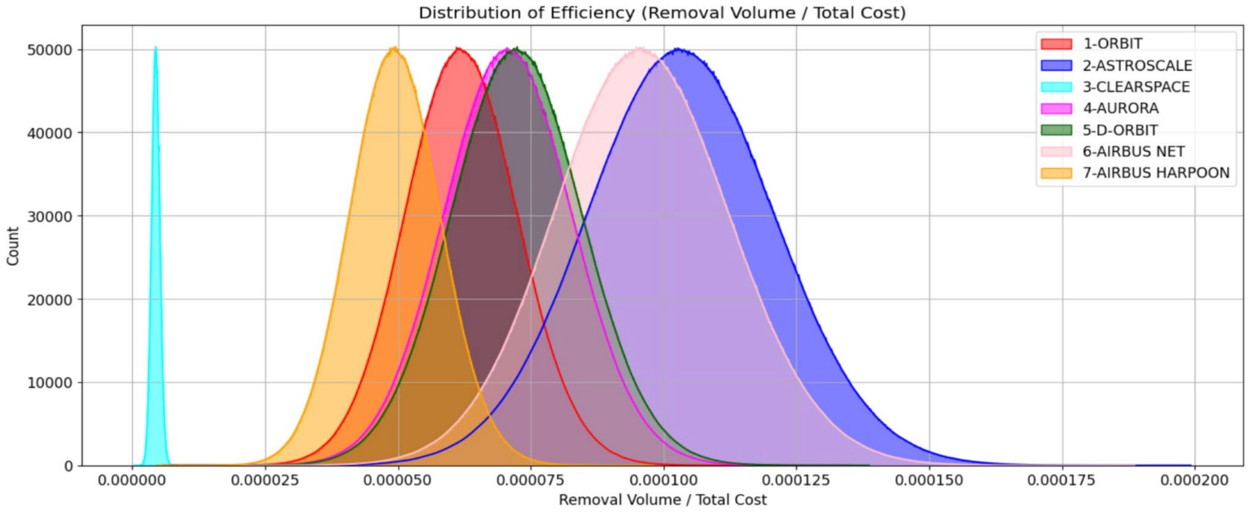

Figure 1. The overlapping graphs of all technologies showing Efficiency (Removal Volume/ Total Cost). Simulation #1.

As shown in **Figure 1**, when all variables and ranges stay the same for all technologies, Astroscale is the most efficient by a small margin. The y-axis in all graphs represents the number of times the efficiency was a certain number on the x-axis during the 10 million random samples. The trend shown in the graph showing the distribution of efficiency for simulation #1 is that the more **reusable** an object is, the higher the efficiency. This is true for both Astroscale and the Airbus Net technologies because they can capture/remove multiple debris in one deployment. Another trend visible is the efficiency shown by technologies that either attach or remove one debris per deployment such as Clearspace, Aurora and D-Orbit. Aurora and D-Orbit both attach to satellites before launch and propel them towards the atmosphere to burn up. Because Astroscale was dominant among the other technologies, the researcher changed the values for Astroscale to see what values directly affected the efficiency.

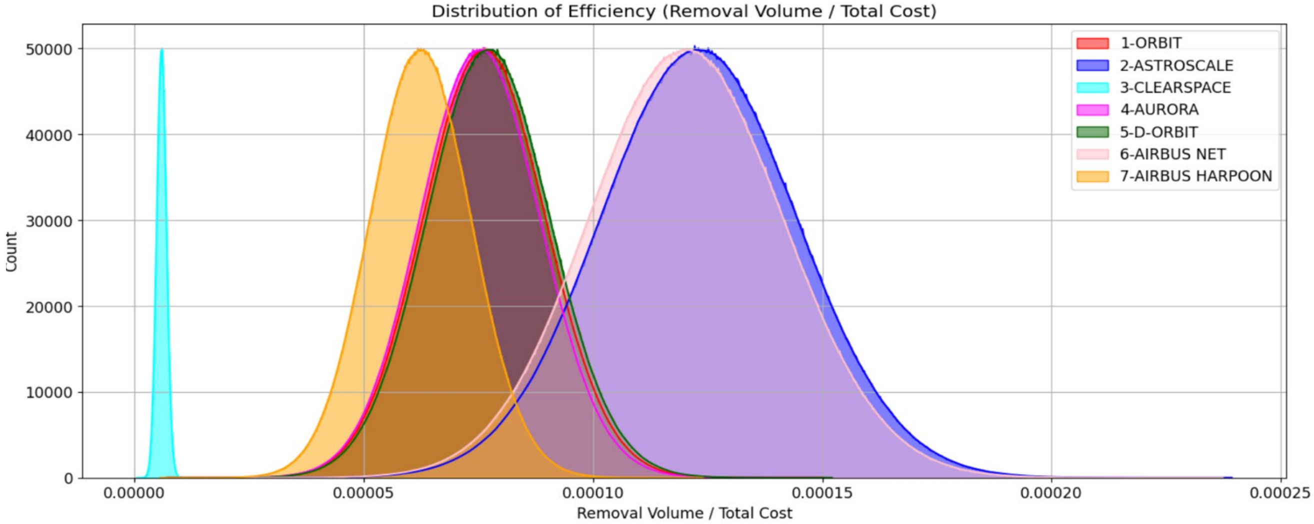

Figure 2. The overlappeoverlappingf all technologies showing Efficiency (Removal Volume/ Total Cost) after gamma distribution for manufacturing and launch costs. Simulation #2.

As discussed in the procedure, the researcher changed the values for manufacturing cost and launch costs because of the assumed innovations of technologies in the future. The remaining values stay the same. Because of this change, each normal distribution for all technologies was shifted to the right since the total cost decreased. This change showed that Airbus Net would be a close competitor should the prices be lowered in the future because of innovations.

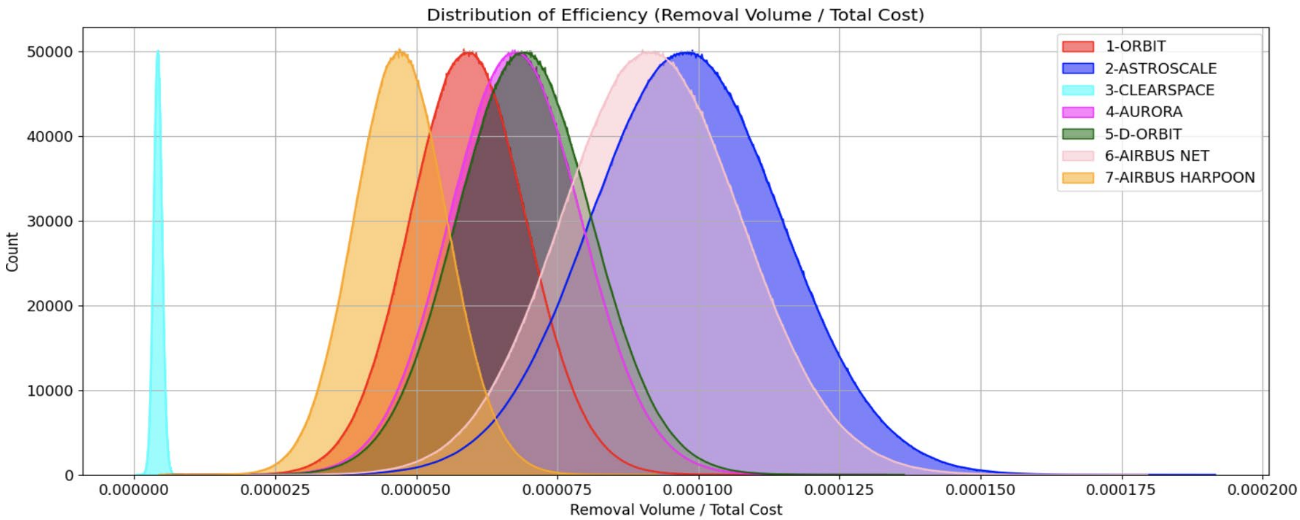

Figure 3. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with normal distribution and 10% higher costs for Reset & Disposal (Variable Z) for Astroscale. Simulation #3.

In simulation #3, the researcher altered Astroscale's cost for Reset & Disposal to be 10% more. This change in range did not change the efficiency of Astroscale by a significant amount thus staying the leading technology.

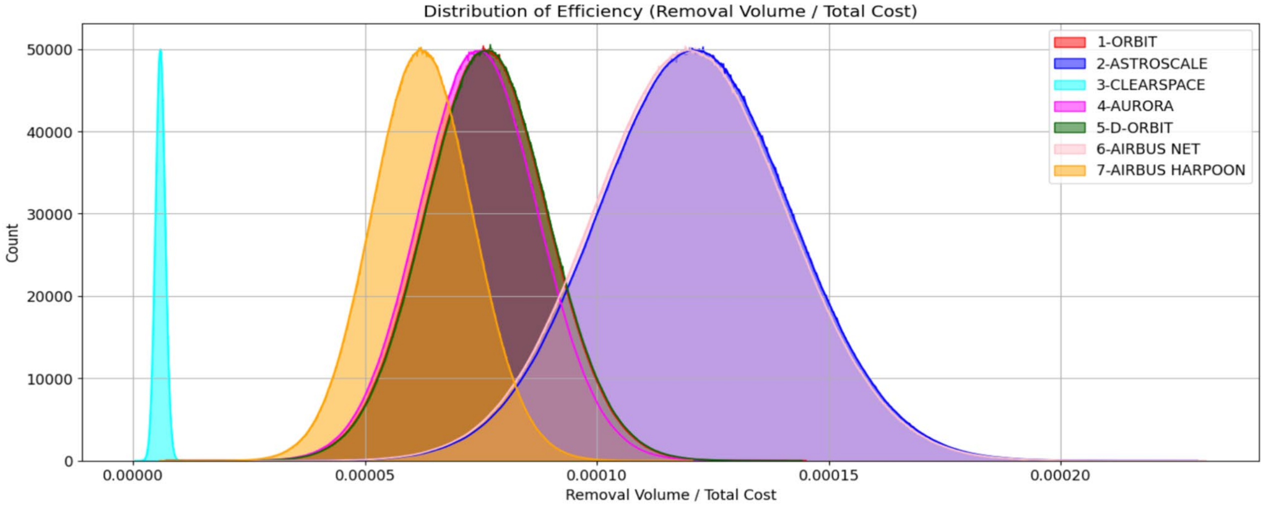

Figure 4 The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with gamma distribution for manufacture and launch costs and 10% higher costs for Reset & Disposal (Variable Z) for Astroscale. Simulation #4.

In simulation #4, the costs for manufacturing and launch were altered, for all technologies, to be skewed left to simulate the improval of technology. As well as this change, the costs for Reset and Disposal were increased for Astroscale. This change in range made a significant difference in the efficiency of each technology, however Astroscale was the most efficient in this scenario as well. By doing simulation #3 and #4, the researcher was able to see that the variable with the biggest influence is not Reset & Disposal. However, when combined with the change in other costs, the other technologies shorten the lead on Astroscale.

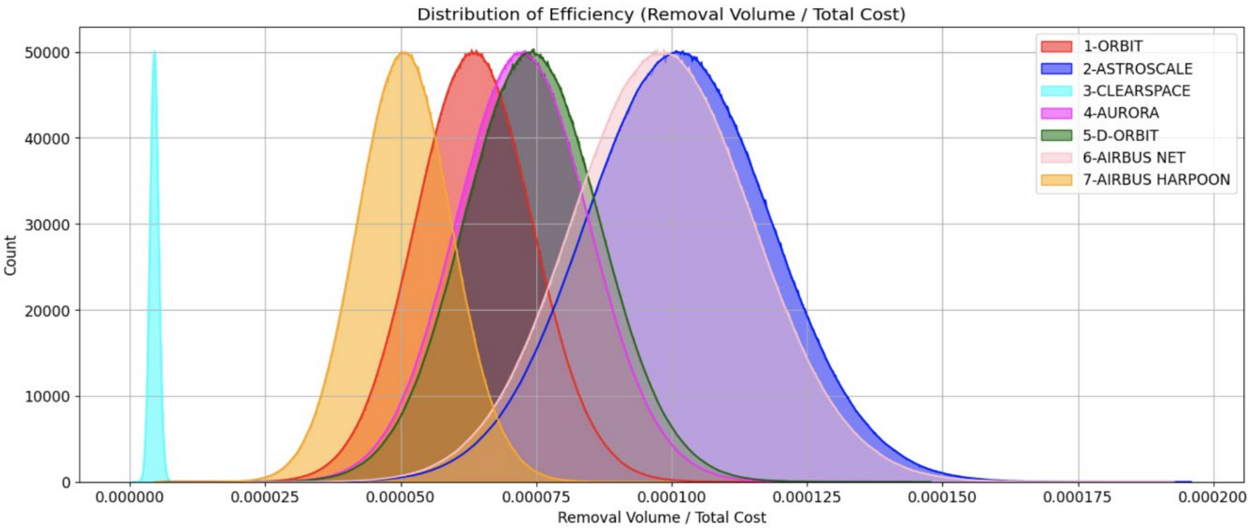

Figure 5. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with normal distribution and 10% higher cost for manufacturing (Variable M) for Astroscale. Simulation #5.

In simulation #5, the researcher increased the manufacturing cost for Astroscale by 10%. By itself, this change in range caused a significant decrease in the efficiency of Astroscale, almost being passed by the Airbus Net.

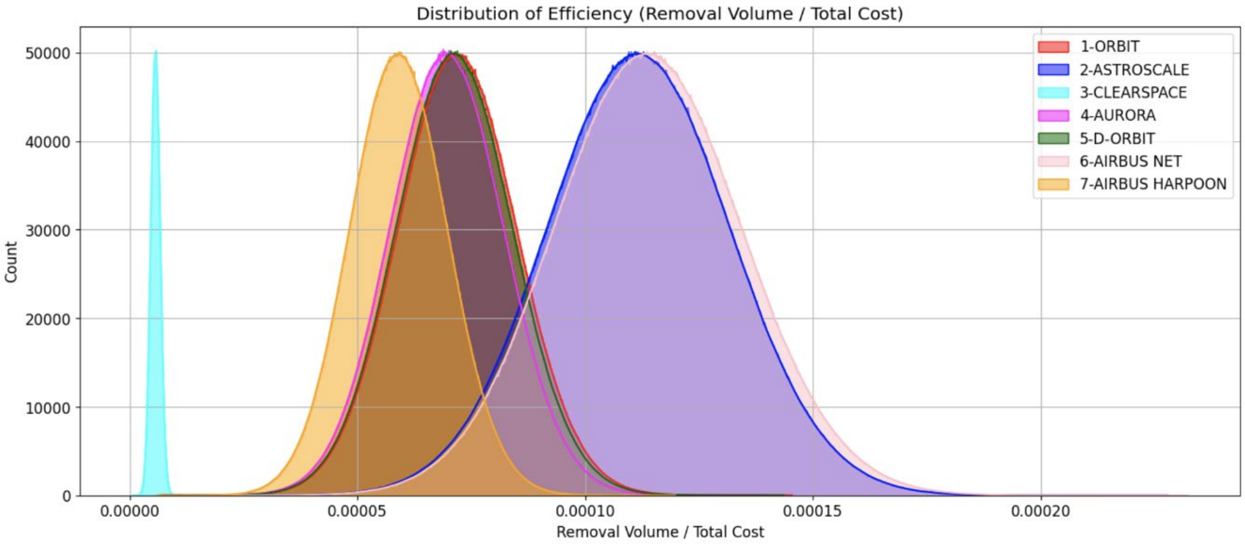

Figure 6. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with gamma distribution for manufacture and launch costs and 10% higher cost for manufacturing (Variable M) for Astroscale. Simulation #6.

In simulation #6, the researcher increased the manufacturing cost for Astroscale by 10% along with including gamma distribution of manufacture and launch costs for all technologies. This change resulted with the Airbus Net being the most efficient technology, along with Orbit Guardians passing D-Orbit and Aurora. By running simulation #5 and #6, the researcher was able to see that manufacturing has potential to be the most influential variable on a technology's efficiency.

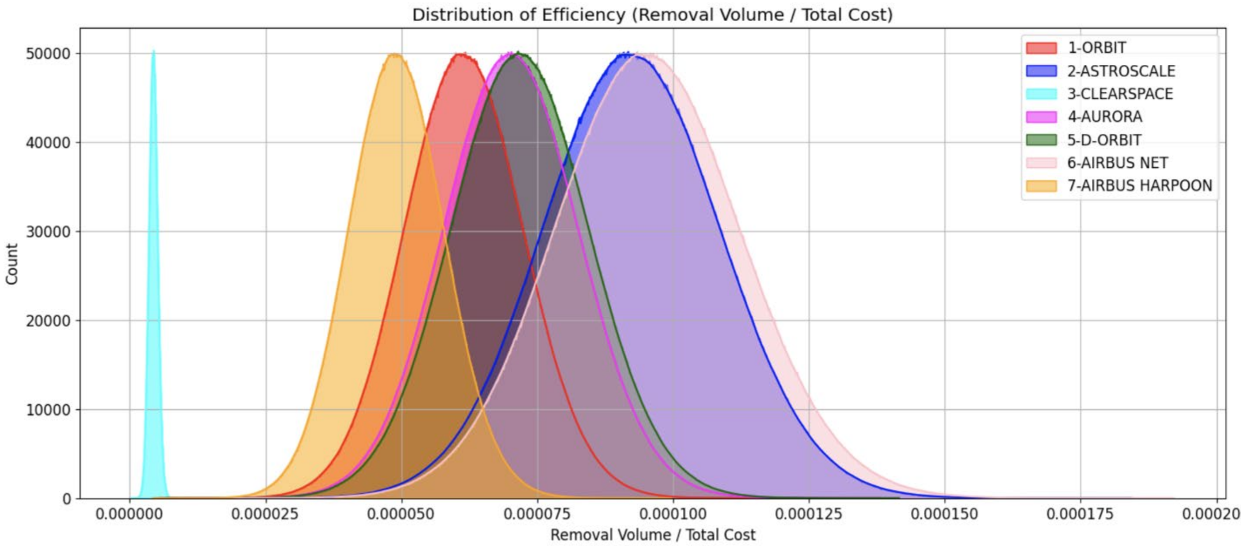

Figure 7. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with normal distribution and 10% less removal capacity (Variable V) for Astroscale. Simulation #7.

In Simulation #7, the researcher decreased the removal volume of Astroscale by 10% which caused the efficiency to significantly decrease, leading to Airbus Net having a higher efficiency.

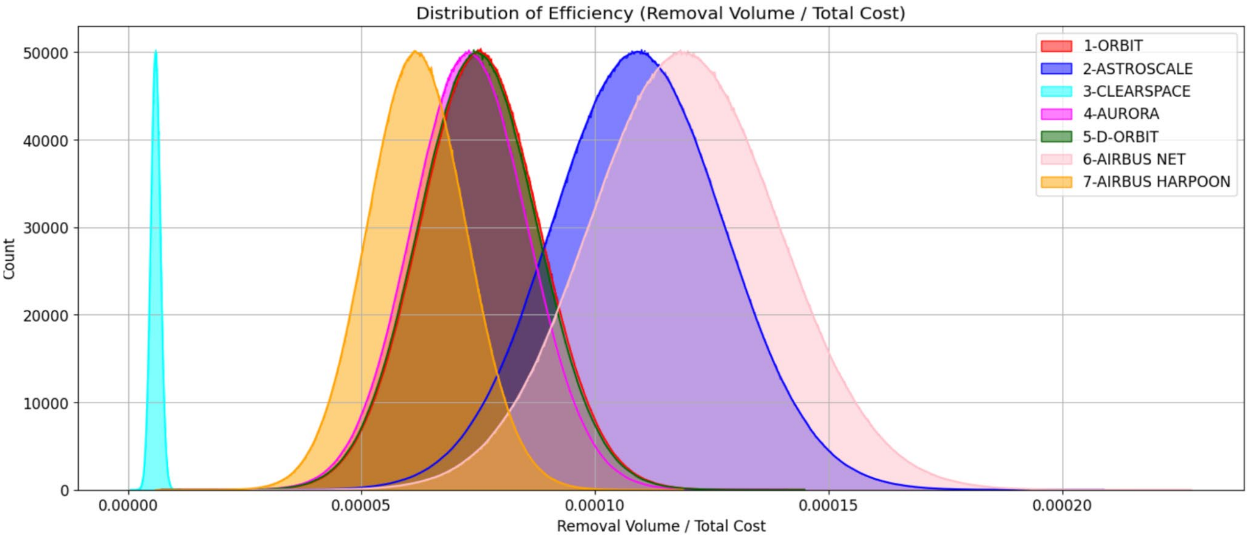

Figure 8. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with gamma distribution for manufacture and launch costs and 10% less removal capacity (Variable V) for Astroscale. Simulation #8.

In Simulation #8, the researcher decreased the removal volume of Astroscale by 10% along with including gamma distribution for manufacturing and launch costs. This alteration drastically decreased the efficiency for Astroscale, putting it behind Airbus Net by a large margin. By running simulation #7 and #8, the researcher was able to see that altering removal volume caused the greatest change in a technology's efficiency. This is likely due to the big part volume in the efficiency equation (Removal Volume / Total Cost).

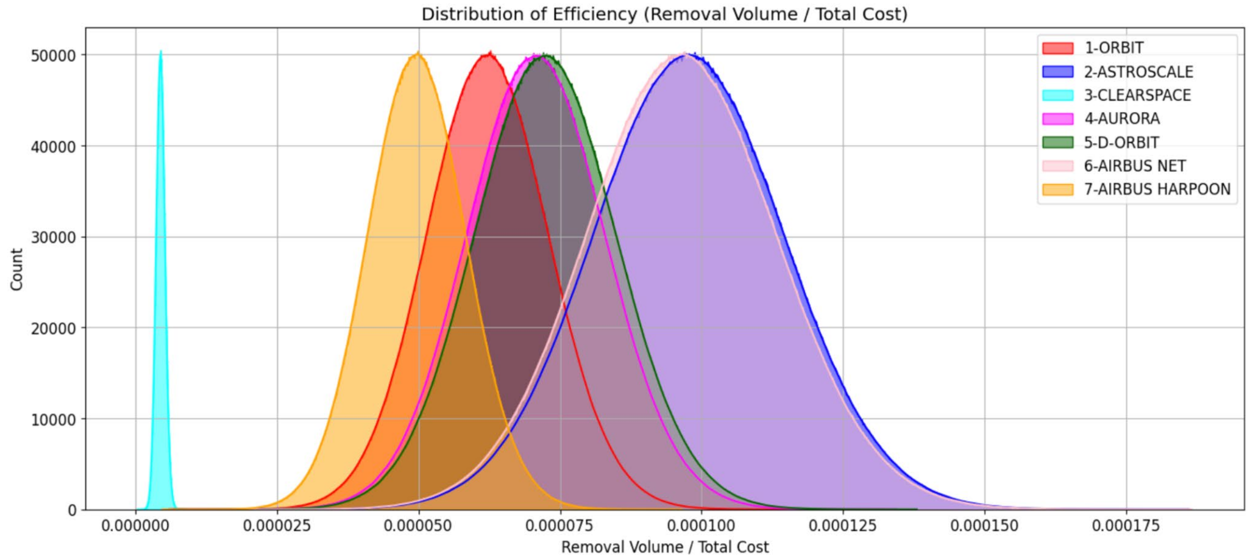

Figure 9. The overlapped graphs of all technologies show Efficiency (Removal Volume/ Total Cost) with normal distribution and 10% less removal capacity (Variable V) and 10% less manufacturing cost (Variable M) for Astroscale. Simulation #9.

In Simulation #9, the researcher decreased the removal capacity for Astroscale and decreased the manufacturing cost to see if the two variables would cancel out the effects on efficiency. The efficiency for Astroscale decreased, proving that the two variables did not cancel out. However, Astroscale still had a greater efficiency with Airbus Net being the runner up.

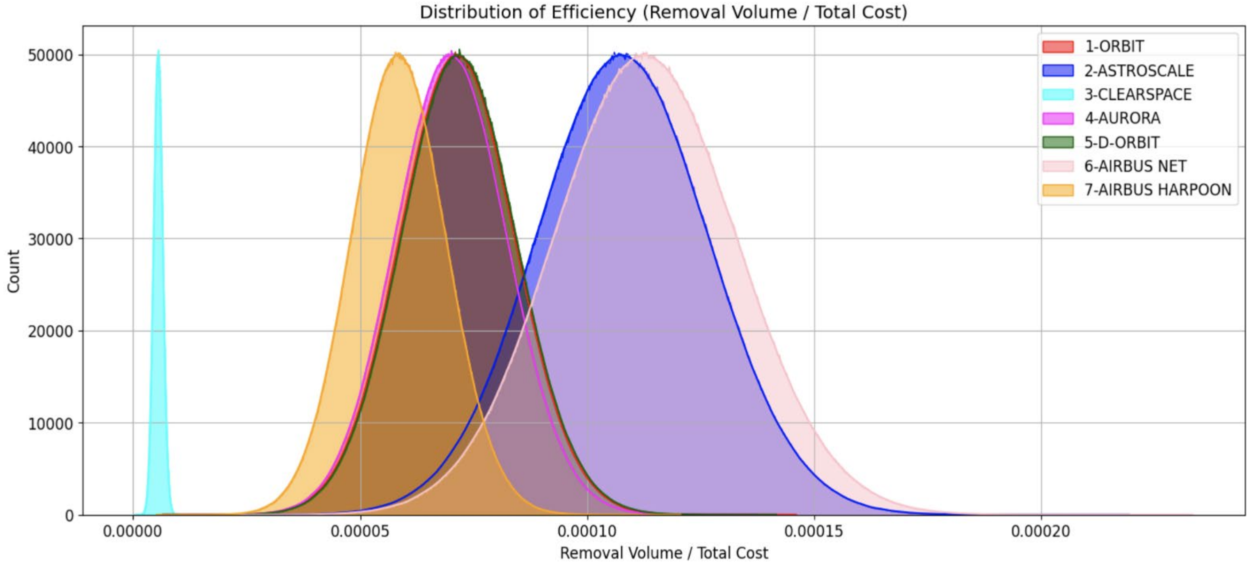

Figure 10. The overlapped graphs of all technologies showing Efficiency (Removal Volume/ Total Cost) with gamma distribution for manufacture and launch costs, 10% less removal capacity (Variable V) and 10% less manufacturing cost (Variable M) for Astroscale. Simulation #10.

In Simulation #10, the researcher decreased the removal volume for Astroscale by 10%, decreased the manufacture cost for Astroscale by 10%, and used gamma distribution for manufacturing and launch costs for every technology. This change in ranges caused a decrease in efficiency for Astroscale, with Airbus Net passing it in efficiency. By running simulation #9 and #10, the researcher was able to see that the removal volume variable's influence was large enough to not be affected when other costs are also decreased.

In 60% of the simulations, run across different distribution scenarios (normal and gamma) for the independent input variables and 10,000,000 random samples, technology #2 (Astroscale – ADR) demonstrates the highest efficiency (Removal Volume Capacity/Total Cost). This outcome is not influenced by the fact that Astroscale is the 2nd highest in cost technology; this is attributed to the reusability of the Astroscale technology across various space debris objects.

In 40% of the simulations, technology #6 (Airbus Net) demonstrates the highest efficiency. However, there is a key differentiator. Whereas Astroscale is best suited for large objects (including large satellites and big size debris), Airbus Net is best suited for Small/Medium debris that get captured through its net-based technology. Because of this difference in the types of debris that can be captured, comparing the technologies becomes difficult. However, this is a key factor because there has yet to be a technology that can remove all types of debris, so studying these different technologies can be a deciding factor for which technology should be changed to be able to remove all types.

In 100% of the cases, based on all different types of distribution and based on the same number (ten million) of random samples technologies #1 (Orbit), #3 (Clearspace), #4 (Aurora), #5 (D-Orbit) and #7 (Airbus Harpoon) were outperformed by Astroscale and Airbus Net. The primary reason is their high-cost structure, combined to either single-use operations or comparatively low removal capacity.

5. Analysis

After conducting the experiments and reviewing the data gathered, the researcher was able to come up with solutions to the problem of the most efficient technology to remove space debris. Overall, the most efficient technology to remove space debris is Astroscale's debris removal satellite. This technology performed outstandingly in all 10 simulations and demonstrated why: reusability. By saving the satellite body before burning up in the atmosphere, Astroscale continues the process of removing debris until the fuel, or any unexpected circumstance, incapacitates the satellite (which is removed with the last remaining fuel). This method of reusability was also proved by the Airbus RemoveDEBRIS net. This net is assumed to be used multiple times to capture and store debris inside the satellite body allowing for a longer lifespan and larger removal capacity.

By conducting this study, the researcher hopes to spread awareness of space debris and urge companies to use the reusability shown by Astroscale to further the removal of debris and save money to be able to mass produce these technologies in the future. This issue of reusability was highlighted in a paper published in Aerospace Research Central, which states that "resources that might be available for recycling are lost and debris is launched in space creating a hazard to navigation."[22] Reusability is a fundamental trait that can be applied to many areas of space, as highlighted in that paper. Should debris stay in our atmosphere, they will replicate until they cover the Earth with a blanket of man-made materials making it so no man or woman can leave the Earth. Not only that, "Sustainable space

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[22] Evans, W. (2006). Logistics and Supply Chain Management - A Space Operations Enabler. *SpaceOps 2006 Conference*.

exploration [. . .] is impossible without appropriate SCM beyond Earth."[23] However, with these findings companies can find the common themes in successful debris removal satellites and begin the next stage of removing debris.

Like many studies, limitations played a big part of the research process. As a high school student, gathering data from private libraries and private corporations was difficult, so the researcher used similar databases and assumptions to gather accurate information. Additionally, the researcher was unable to go out into space to gather more credible information, and instead used information from companies that have conducted such experiments. Another limitation is presented inside a paper written by Hanspeter Schaub, an affiliate of the University of Colorado, where he brings into question different variables that are too difficult to incorporate into a study like this. Such costs can consist of "Direct costs", "Indirect costs", "Political costs, and "Environmental costs".[24] Had these limitations not existed, the researcher would be able to provide wider results with greater accuracy.

5.1 General Observations

The accuracy of assumptions for the independent variables (launch, manufacturing, fixed operational costs etc.) as well as for the relative cost/volume performance across technologies has the largest influence on the simulation results but does not influence the overall trends and observations.

5.2 Relative Weight of Each Independent Variable

From all relative, across technologies, performance relationships (including both volume and cost performance variables) it was observed that the volume removal capacity relationship is the single largest influencer of results. For example, a 10% decrease in the volume removal capacity of Astroscale is sufficient to change its overall efficiency ranking.

5.3 Effect and Contribution of Different Costs in the Overall Structure

Manufacturing costs are the most significant contributor to the total cost structure. This has an amplifying effect for technologies focused on one-time (Single use) debris removal operations. An assumed gamma distribution for certain cost types skews the random population and reduces their influence in the simulated total cost number.

6. Implications

Based on economic simulations using 10,000,000 random samples, ten separate simulation scenarios and varying types of distribution densities for the independent variables (normal and gamma), technology #2 (Astroscale) and technology #6 (Airbus Net) demonstrate the highest efficiencies for long-term scalable operations. The engineering exercise has clearly demonstrated that the most effective (in removing significant debris volumes) technology may

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[23] Galluzzi, M., NASA Kennedy Space CenterSearch for more papers by this author, Zapata, E., Weck, O. de, Massachusetts Institute of TechnologySearch for more papers by this author, & Steele, M. (2012, June 18). *Foundations of Supply Chain Management for Space Application*. AIAA SPACE Forum. Retrieved September 25, 2022

[24] Schaub, H., Jasper, L. E. Z., Anderson, P. V., & McKnight, D. S. (2015, April 3). *Cost and risk assessment for spacecraft operation decisions caused by the space debris environment*. Acta Astronautica. Retrieved September 14, 2022

fail to commercialize if the associated costs are not contained within reasonable ranges that will enable scalable operations. The engineering exercise has also revealed that for any future technological development a key factor is the reusability of the technology for multiple debris. This is because the cost numbers for any space-related operation are prohibitively high to allow for single-use operations. It is the equivalent to the latest concepts of rocket science which leverage the re-usability of space rockets to reduce costs and enable commercialization.

7. Future Directions

It is difficult to draw a definite conclusion of the best technology to remove space debris from this study because of the constant and definite improvement of humanity and its creations. However, by utilizing the never-ending creativity of humanity, this research and these conclusions can help form a fitting solution for the removal of space debris. Additional research to accurately find solutions to the space debris problem will be formed after more companies experiment in space and begin missions. For now, research can be done to find the most efficient technology in different orbits along with more accurate results from specialized labs, should they actually experiment in space.

Should the researcher decide to further the research, an experiment using a personal device for removing debris would be able to gather more precise data. However, as explained in the analysis, limitations were present in this study. If a future study could replicate these results with greater access to resources and databases, the results would be more precise. However, should no study be done to create more precise results, this research still demonstrated the reason for efficiency --- reusability.

Further research to test that reusability is the trait that makes a technology efficient could be conducted, should any companies with large funds decide to conduct it. Research to study the positives of reusability have been conducted in other areas of the space industry such as reusable rockets, which save costs for the companies that use them. Overall, studies to further elaborate on this research should be conducted by organizations and people with the credentials to view the private resources that the researcher could not.

As humanity improves technology and has breakthroughs in different fields, technologies to remove space debris will continue to advance. Because of this, researchers in the future should repeat this experiment whenever new technologies emerge, or current technologies are improved. Altogether, the researcher hopes that the conclusion of this research will influence companies to alter their technologies to be reusable and viable as to secure the safety of future supply chain operations.

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