The Sociotechnical Implications of Space Debris: The Dilemma of Space Debris Production and Mitigation Legislation

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On my honor as a University Student, I have neither given nor received unauthorized aid on this assignment as defined by the Honor Guidelines for Thesis-Related Assignments

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Introduction: Space Debris and Research Motivations

Despite the rapid technological progress that has facilitated the evolution of early airplanes to interstellar spacecraft in just one century, the familiar issue of pollution has the potential to stunt the future of space missions if mismanaged. Though untarnished by human-made artifacts for the billions of years following the Universe's creation, the expanses of space neighboring Earth have accrued millions of fragments of waste since the late 1950s (Khatchadourian, 2020). Orbiting the Earth at speeds as high as 17,500 miles per hour, these fragments, collectively known as space debris, behave like high energy projectiles and are capable of obliterating much larger spacecraft upon collision (Garcia, 2021). In the event of a catastrophic collision, new clouds of space debris are generated, further increasing the risk of future collisions in a self-perpetuating phenomenon known as Kessler Syndrome (Kessler, 2010). If left unchecked, the eventual exceedingly high probability of catastrophic collisions would render low Earth orbit (LEO) condemned (Gregersen, 2021). The loss of functionality in LEO does not just affect scientists and groups associated with the aerospace industry; LEO is home to satellites used for satellite imagery, as well as large networks of telecommunication satellites (Types of Orbits, 2020). Given the monumental role that satellite-based communication fills today, the relatively sudden loss of telecommunication satellites in LEO would greatly hinder most Earth-based industries, as well as the activities of typical people. Through a sociotechnical analysis of space debris, including space debris' production and mitigation, methodologies for producing a more sustainable future in space are highlighted. The issue of space debris is evaluated through a wicked problem framework, whereby the normative, business-as-usual approach towards the management of space debris is contrasted with alternative approaches in order to illuminate more proactive and resilient behaviors in space. To thoroughly investigate the sociotechnical aspects surrounding space debris management, the following question requires exploration: what practices and policies must be adopted on a global scale to ensure a future of scientific development in space that is unobstructed by space debris.

Research Question and Methods

This sociotechnical analysis uses documentary research methods and policy analysis to explore the elements of space debris. Documentary research methods are used to analyze both encyclopedic articles, as found on governmental websites, as well as technical literature pertaining to the topic of space debris. The technical literature was found through scholarly databases, namely the University of Virginia's Virgo catalogue, and is mainly comprised of papers published in academic journals. Documentary research analysis of academic papers primarily informs all subsequent sections of this paper. Policy analysis is used specifically to evaluate international, national, and organizational policies and guidelines that pertain to space debris management. These sources were found through the University of Virginia's Virgo catalogue, as well as on the relevant entity's websites. Policy analysis particularly informs the Results and Discussion section. When conducting research through catalogues such as Virgo, keywords such as "space debris," "space debris mitigation," "space debris legislation," "space debris policy," and "space debris sustainability" were used. The information provided in the Results and Discussion section derived from this research is primarily organized thematically.

Background Information: An Overview of Space Debris and Likely Implications

Orbital debris, by definition, is any non-functional, human-made artifact that orbits the Earth (Garcia, 2021). This debris ranges drastically in size, with the list of objects including items as small as flecks of paint, as well as items as large as discarded rocket stages and derelict satellites (Gregersen, 2021). While functional satellites can be tracked with ease due to on-board GPS sensors, agencies such as the Space Surveillance Network, which is part of the Unites States Space Force, must use ground-based radar and telescope arrays to identify and track debris (Andrews, 2021). The wide range of space debris dimensions further complicates this issue; relatively large objects, or objects with a diameter greater than approximately four inches, can typically be directly tracked, while the number of smaller objects must be statistically determined (Garcia, 2021). Given that even small fragments of debris are capable of causing damage to spacecraft, the inability to track and maneuver around small fragments increases their inherent risk and requires the use of additional shielding, adding cost and weight to spacecraft (Schultz, 2013). Due to the great velocities associated with orbit, reaching up to 17,500 mph, even small objects have the potential to be destructive upon impact (Garcia, 2021). The significant energy characteristic to orbital debris makes collision avoidance a leading priority.

The history of orbital debris began with the dawn of the space age, with one of the first enduring orbital artifacts being that of Vanguard 1 (Hall, 2014). Though Vanguard 1's functional lifespan concluded in 1964, the object will remain in orbit for another 200 years (Hall, 2014). Since the first missions of the late 1950s, space has grown considerably more crowded, with 7,840 satellites in orbit, and of which only 5,000 are operational (Space Debris by the Numbers, 2022). Moreover, there are 30,040 debris fragments that are large enough to be catalogued and tracked, which make up a small minority of the estimated 330,000,000 total fragments in orbit that are greater than one millimeter (Space Debris by the Numbers, 2022). Space, and particularly LEO, is likely to become even more crowded with the advent of megaconstellations, which are systems of many thousands of functionally connected satellites, such as that of

SpaceX's Starlink (Andrews, 2021). The increasing congestion of LEO with respect to both satellite systems and debris can prove to be problematic due to a phenomenon known as Kessler Syndrome. Originally conceptualized in a 1978 paper, Kessler Syndrome reflects the self-perpetuating cascading effect of orbital collisions (Kessler, 2010). Given the high velocity and energy of orbiting objects, catastrophic collisions between artifacts can generate clouds of thousands of fragments (Gregersen, 2021). These fragments then encircle the Earth, increasing the risk of future cloud-generating collisions (Gregersen, 2021).

The exponential nature of space debris propagation has been validated through several high-profile collision events. As an example, just two events in the late 2000s, the purposeful 2007 destruction of the Chinese Fengyun-1C satellite and the 2009 collision between an Iridium satellite and a defunct Russian satellite, accounted for a 70% increase in the population of large orbital debris (Keeter, 2018). In order to prevent a future in which space missions are subjected to extreme risks due to the high probability of random orbital collisions, meaningful actions must be taken in the present. Creating effective and enforceable international legislation seems to be a natural solution to curtailing space debris, though in practice, the legality of space operations is difficult to parse (Quell, 2020). International legislation is further complicated by the introduction of private actors. Additional, seemingly promising methods of managing orbital debris include the removal of large, high-risk structures (Kessler, 2010).

STS Framework: Space Debris and Wicked Problem Framing

The multifaceted issue of space debris management is being considered through the wicked problem framework. As a concept, wicked problems first arose in the social policy field in a 1973 paper written by Horst Rittel and Melvin Webber. This paper explores the thought that societal problems were inherently different than that of scientific problems; whereas scientific problems were “tame,” meaning that the problem definition is clear and that it is possible to evaluate if the attempt to solve the problem was successful, social problems are “wicked” in they lack both of the tame characteristics (Rittel and Webber, 1973). The original nine characteristics of a wicked problem as described by Rittel and Webber’s paper include a lack of a definitive formulation, a lack of a “stopping rule,” meaning that external factors, such as time, do not terminate attempts at solving a wicked problem, a lack of objectively correct solutions, a lack of ultimate evaluation method for a solution, a cost associated with every attempt at a solution, a lack of enumerable potential solutions and ill-defined permissible operations, inherent uniqueness to the problem itself, interrelatedness to other problems, ambiguity in discrepancy explanations, and the inherent responsibility of the planner (Rittel and Webber, 1973). In essence, wicked problems differ from tame problems in that there is unforeseen complexity and ambiguity in most steps of the solution formulation methodology. Rather than a permanent solution, iterative attempts at improvements are often the result of attempting to “solve” a wicked problem.

Wicked problem frameworks have been applied to a number of contemporary and relevant problems, with the most prominent being social and environmental issues, including that of climate change, poverty, and crime. Though largely considered appealing and widely utilized, critiques have arisen largely due to the language of the original wicked problem framing formulation (Turnbull and Hoppe, 2019). One such critique involves the direct association by Rittel and Webber of social science and inherent wickedness, with a lack of nuance to particular social science problems (Turnbull and Hoppe, 2019). Additionally, a rather glaring issue with the wicked problems framework centers around the dichotomy between wicked and tame problems (Turnbull and Hoppe, 2019). Given that many wicked problems are considered to be unique, a gradient of wickedness and tameness would perhaps be less restrictive than rigid placement into one of two categories (Turnbull and Hoppe, 2019).

By the original definition as prescribed by Rittel and Webber, the issue of orbital debris can be considered to be sufficiently wicked. Orbital debris is inherently linked to space exploration itself, being that debris is oftentimes the byproduct of space operations. Orbital debris is self-perpetuating, indicating that inaction or failed attempts at mitigating orbital debris incurs an opportunity-cost in addition to wasted resources. Orbital debris can additionally not arrive at a natural, permanent solution and requires constant maintenance. The burden of resources and lack of technological capabilities prevents the removal of all nonfunctional artifacts in space, especially when considering natural meteoroids. With respect to critiques, orbital debris does not purely fit into the social science category that Rittel and Webber prescribe wicked problems to. Rather, orbital debris sits at the intersection between social and scientific issues. The wickedness of orbital debris additionally varies depending upon the aspect of orbital debris that is considered. While the complete removal of debris fragments is highly wicked, initiatives to regulate and mitigate orbital debris is noteworthily tamer. Though tamer than complete debris removal, the Results and Discussion section will discuss in further depth the wickedness particularly associated with the regulation of space debris.

Results and Discussion

Overview of Results

The issue of orbital debris is one to be continuously managed rather than one to be permanently solved, especially in the near future, as satellite megaconstellations become increasingly common and LEO becomes more congested. As elaborated on later in this section, the answer to the research question stated previously is largely political in nature and is shrouded in legal complexities. The specific behaviors that should be followed by responsible spacefaring nations have been previously outlined by entities such as the United Nations Office for Outer Space Affairs and the Inter-Agency Space Debris Coordination Committee. The list of responsible behaviors includes actions such as the discharging of destructive energy sources after the end of the mission's life and the retiring of higher altitude satellites into "graveyard orbits." While the adherence to these guidelines would aid in the mitigation of space debris, these guidelines are flawed in that they are not compulsory. In order to absolutely ensure a future in which space missions are not inhibited by debris, universal voluntary compliance to debris management guidelines or the creation of meaningful international legislation that is capable of enforcing such guidelines as law is necessary.

Five United Nations Treaties on Outer Space

Not unlike most other faucets of modern life, perhaps the most intuitive solution for the management of orbital debris revolves around official regulation. As the newest "final frontier," outer space is generally governed by a mixture of hard treaties and voluntary, soft guidelines (Martinez, 2019). The hard treaties, which are collectively referred to as the "five United Nations treaties on outer space," are antiquated, with adoption dates ranging from 1967 to 1984 (Space Law Treaties and Principles). The dates of the United Nations (UN) treaties additionally reflect the heights of the Cold War, and as such, tangentially echo tensions between the few spacefaring nations at the time (Gupta, 2019). More specifically, the Outer Space Treaty (OST), the first of the five treaties, primarily provides for equal access to space, a means of preventing warfare from expanding into space, the return of spacefaring items and personnel to their country of origin, and rudimentary outlines for state responsibility and liability (Gupta, 2019). This original treaty was then expanded into the subsequent Rescue Agreement, which revolves around the prompt assistance to and return of astronauts, the Liability Convention, which revolves around responsibility for damages caused by space objects, the Registration Convention, which concerns the registration of launches objects, and the Moon Agreement, which concerns the behaviors of entities on the Moon and other celestial bodies (Gupta, 2019 & Space Law Treaties and Principles, n.d.).

Given the historical context and age of the UN's five space treaties, where space exploration was in its relatively early stages, there is a disconnect between the modern state of outer space and the hard legislation that governs it. Though the issue of orbital debris has been recognized since the 1970s, the five outer space treaties do not outline protocol for managing orbital debris, and the UN Committee on the Peaceful Uses of Outer Space (UNCOPUOS) did not first officially consider the topic of orbital debris until 1994 (Gupta, 2019). From the early discussion of space debris came an immediate issue, especially in the legal academic field, where the definition of space debris became widely contested (Gupta, 2019). The particulars of this debate grew from the OST's ambiguous reference to a "space object," of which the spacefaring nation of origin is liable for (Gupta, 2019). At face value, the debate of the very definition of "space debris" reflects the "wicked" nature of space debris through a wicked problem framework, given that the lack of a clear problem definition is one of the primary characteristics of a wicked problem. Beyond this relatively surface level observation, the issue surrounding the definition of "space debris" reflects space debris' wickedness through its lack of "correct" solution, as different interpretations of the definition have different associated drawbacks. As an example, interpreting the Liability Convention, which seeks the compensation for damages caused by space objects, in the context of debris mitigation and including space debris under the umbrella of space objects, raises the inherent risk and cost of space exploration. Raising the cost of an already expensive venture "would disproportionately affect the access of the poorer developing nations to outer space in violation of the express unanimous declarations of the UN member states," (Gupta, 2019). Through the repurposing of the original five hard treaties on outer space, which were not designed with the complexities of space debris liability in mind, it is possible that an international environment that is hostile to budding spacefaring nations could be created.

Though the five UN treaties on outer space are technically legally binding pieces of international legislation, they are not without issue regarding meaningful enforceability. Given that the five space treaties are under the UN, judgement lies within the International Court of Justice (ICJ) (Kisiel, 2021). The ICJ, however, is enforced by the UN Security Council, which has spacefaring permanent members such as the United States, United Kingdom, France, China, and Russia (Kisiel, 2021). Given that these nations additionally have veto power, any judgement passed by the ICJ with respect to the five space treaties against any major spacefaring superpower is essentially nullified (Kisiel, 2021).

With respect to a wicked problem framework, the weakness of the five UN treaties on outer space and the inability to adequately enforce international space law reflect the traditional characteristics of wicked problems. Perhaps the most prominent of these characteristics are a lack of an objective solution towards binding space debris legislation and the interrelatedness between space debris management and other factors. Additionally, these characteristics directly connect in the context of space debris. Though archaic and rudimentary, the five UN treaties on outer space were, by design, intended to incorporate some level of ambiguity in order to allow for political compromise. This flexibility in enforcement of space law is associated with the second major wicked characteristic: interrelatedness to other issues. As previously mentioned, space law was never initially designed to manage space debris; hard space law is heavily influenced by the geopolitics of Earth. While rigid space law relating to space debris facilitates space debris management, rigid space law would potentially violate the original spirit of space law itself and further complicate political matters on Earth.

Soft Guidelines and Possible Solutions

To fill the gaps left by the original five treaties on outer space, a number of voluntary soft guidelines have been formulated, becoming increasingly prominent as non-governmental commercial actors have entered into the orbital scene (Martinez, 2019). Though voluntary, these soft laws still exert some force through the power of normativity and fulfil a variety of niches that are unaddressed by the hard law treaties (Gupta, 2019). Soft laws, such as those produced by the Inter-Agency Space Debris Coordination Committee (IADC) and UNCOPUOS in particular, assign definitions to space debris and provide for measures intended for mitigating debris creation (Gupta, 2019). Though voluntary guidelines hold some validity in the international community, recent and widely condemned debris-generating anti-satellite weapon tests, such as those exercised by India in 2019 and Russia in 2021, help push the notion that guidelines with meaningful enforceability are needed (Martinez, 2019 & Raju, 2021).

Similar to the five UN treaties on outer space, soft guidelines are associated with wicked characteristics. In addition to the characteristics attributed to hard treaties, soft guidelines are particularly affected by diverse stakeholder viewpoints. It can be assumed that most spacefaring nations, to some degree, understand the consequences of unchecked space debris and would prefer to not have their ambitions in space hampered by debris. This is reinforced by the fact that many countries have adopted voluntary guidelines of their own. However, each individual country is governed by a unique agenda, with varying long- and short-term priorities. As an example, anti-satellite tests are known to generate an irresponsible amount of space debris and are largely condemned by the international community. For spacefaring actors such as the United States, China, India, and Russia, who have all exercised anti-satellite weaponry at some point, issues of national security and military strength likely take strong precedence over space debris mitigation. The need for universal cooperation to mitigate space debris is undermined by the inherent unique agenda associated with each country.

The current state of international legislation and guidelines is arguably in a borderline nonfunctional state and requires great amounts of overhaul. In summary, the UN’s five space treaties were developed during the early stages of space exploration in the midst of the Cold War. The five space treaties were not intended to reflect on the complex web of liability that is associated with space debris, and the treaties are additionally difficult to enforce through the ICJ. The past several decades has seen the development of soft guidelines, which have seen increasing adherence, though they lack any meaningful enforceability as well. One proposed solution to the current legal inadequacy of space debris management is for the eventual jump to customary international law from national laws (Martinez, 2019). Were a critical mass of countries to develop national laws based on guidelines such as the UN’s Long-Term Sustainability (LTS) guidelines, which is a set of guidelines concerning space debris that was passed in 2019, this widespread national norm could outline a wider consensus and help inform decisions made by the ICJ (Martinez, 2019).

In addition to the widespread adoption of guidelines such as LTS, policy must be developed with respect to debris removal. Historically, debris removal was limited by technological limitations and thus was a null point (Kisiel, 2021). This barrier is rapidly being breached as technological innovations, such as those seen in the ESA's ClearSpace-1 project, are developed (Kisiel, 2021). Legislation, however, lags behind this technological progress. With aforementioned legal issues such as what separates space objects from space debris and who maintains sovereignty over space debris, questions such as the legality of removing space debris and who is responsible for paying for such removal remain contested (Kisiel, 2021). Because of this, rapid progress in clarifying space debris liability must be made in order to maintain clear pathways for the space missions of the future.

Limitations

This research paper is limited in that it primarily relies on the secondary parsing of international legislation, such as the UN's five space treaties and other guidelines, rather than a direct analysis of primary documents. This research additionally relies on a rather simplified approach to international space law and was not conducted by a student of law or political science. Economics additionally plays a large role in the development of international space programs, international space treaties and guidelines, policy adherence, and the development of space debris management technologies. The economics of space debris management, however, extends beyond the scope of this research.

Future Work

Future work on this topic can be done within a large number of fields, as the issue of space debris is highly multidisciplinary. As an example, large amounts of research can be done with respect to economics associated with space debris. In particular, economic research can be conducted to forecast the financial impact of space-debris related collisions associated with various international political conditions and rates of adherence to voluntary protocols. This research could likely then be continued to determine thresholds by which various international actors would be financially obligated to conform to customary debris management guidelines. Economic research can also be conducted to project the pace of debris-removal innovation with respect to the growing private sector of the aerospace industry, taking into consideration disruptive conditions such as the growth of megaconstellations. Additionally, thorough political science research can be conducted on the political landscape of spacefaring nations and their influence on space law.

Conclusion

The list of behaviors and practices required to manage space debris are largely outlined in preexisting voluntary guidelines as formulated by entities such as the Nations Office for Outer Space Affairs and the Inter-Agency Space Debris Coordination Committee. In order to make these guidelines meaningful, however, progress must be made on an international scale in creating de facto customary law that is universally followed. This adherence can either be entirely voluntary or impelled with the ability to meaningfully enforce and levy consequences towards bad actors. Additionally, work must be done to clarify the circular issue of vague liability in order to fairly address and remediate damages associated with space debris. With the projected rapid increase in the number of spacecraft in LEO within the coming decades, it is paramount that the proper frameworks are quickly set in place to address space debris. Failure to adequately manage orbital debris will likely greatly increase the risk of random orbital collisions and, in the worst case, completely prevent the use of the invaluable near-Earth space.

Works Cited

Andrews, R. (2021). Space Jam. *New Scientist.* https://doi.org/10.1016/S0262-4079(21)01939-4

Garcia, M. (2021, May 27). Space Debris and Human Spacecraft. *NASA.* https://www.nasa.gov/mission_pages/station/news/orbital_debris.html

Gregersen, E. (2021, July 30). Space Debris. *Encyclopedia Britannica*. https://www.britannica.com/technology/space-debris

Gupta, Arpit. (2019). Regulating Space Debris as Separate from Space Objects. *University of Pennsylvania Journal of International Law*. https://heinonline.org/HOL/Page?handle=hein.journals/upjiel41&div=8&g_sent=1&casa_token=&collection=journals

Hall, Loretta. (2014, November 6). The History of Space Debris. *Space Traffic Management Conference*. https://commons.erau.edu/cgi/viewcontent.cgi?article=1000&context=stm

Keeter, Bill. (2018, December 5). Space Debris. *NASA.* https://www.nasa.gov/centers/hq/library/find/bibliographies/space_debris.

Kessler, D. J., Johnson, N. L., Liou, J. C., & Matney, M. (2010). The Kessler Syndrome: Implications to Future Space Operations. *Advances in the Astronautical Sciences*, 137(8), 2010. https://www.threecountrytrustedbroker.com/media/kesseler_syndrome.pdf

Khatchadourian, R. (2020). The Elusive Peril of Space Junk. *The New Yorker*. https://www.newyorker.com/magazine/2020/09/28/the-elusive-peril-of-space-junk

Kisiel, Edwin. (2021). Law As an Instrument to Solve the Orbital Debris Problem. *Environmental Law*. *https://web.p.ebscohost.com/ehost/pdfviewer/pdfviewer?vid=0&sid=43c0c273-1648-458a-a30e-2b67dc6a0065%40redis*

Martinez, Larry F. (2019). Outer Space Sustainability: Legal Dilemmas on the "Final Frontier". *Global-e: A Global Studies Journal*

Quell, M. (2020). Lack of Space Law Complicates Growing Debris Problem. Courthouse News Service.

https://www.courthousenews.com/lack-of-space-law-complicates-growing-debris-problem/

Rajapaksa, Chandana R. & Wijerathna, Jagath K. (2017). Adaptation to Space Debris Mitigation Guidelines and Space Law. *Astropolitics.*

Raju, Nivedita. (2021, December 7). Russia's Anti-Satellite Test Should Lead to a Multilateral Ban. *Stockholm International Peace Research Institute*. https://www.sipri.org/commentary/essay/2021/russias-anti-satellite-test-should-lead-multilateral-ban

Rittel, H., and Webber, M. (1973). Dilemmas in a General Theory of Planning. *Policy Sciences*.

https://www.sympoetic.net/Managing_Complexity/complexity_files/1973%20Rittel%20and%20Webber%20Wicked%20Problems.pdf

Schultz, Colin. (2013, June 28). How Do You Shield Astronauts and Satellites from Deadly Micrometeorites? *Smithsonian Magazine.*

https://www.smithsonianmag.com/smart-news/how-do-you-shield-astronauts-and-satellites-from-deadly-micrometeorites-3911799/

Space Debris by the Numbers. (2022, January 5). *ESA.* https://www.esa.int/Safety_Security/Space_Debris/Space_debris_by_the_numbers

Space Law Treaties and Principles. (n.d.). *United Nations Office for Outer Space Affairs.* *https://www.unoosa.org/oosa/en/ourwork/spacelaw/treaties.html*

Turnbull, N., and Hoppe, R. (2019). Problematizing 'Wickedness': a Critique of the Wicked Problems Concept, from Philosophy to Practice. *Policy and Society* https://doi.org/10.1080/14494035.2018.1488796

Types of Orbits. (2020, March 30). ESA. https://www.esa.int/Enabling_Support/Space_Transportation/Types_of_orbits#LEO

Zhang, Yijun. (2021). An Analysis of the Regulations on Environmental Damage to Outer Space Caused by Space Debris. *Journal of Frontiers of Society, Science and Technology.* *https://www.clausiuspress.com/assets/default/article/2021/04/23/article_1619172383.pdf*