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Viability of a circular economy for space debris

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A B S T R A C T

The orbital debris population is rapidly growing, increasing the chance of a Kessler-style collision event. We report a novel method for the production of estimates for the total monetary value of all debris objects and total mass of all objects currently in orbit. The method was devised using debris object data from the European Space Agency's DISCOS dataset, classified via a decision tree. 'Reuse' and 'scrap material' scenarios were developed. A high-end estimate for reuse shows a net value of $1.2 trillion. Median and low-end net value estimates of $600 billion and $570 billion, respectively, are probably judicious. A scrap material scenario produced a high mass estimate of 19,124 tonnes, a median of 6,978 tonnes and a low estimate of 5,312 tonnes. Development of in-orbit services will be crucial to solve the orbital debris problem. A future circular economy for space may be financially viable, with potentially beneficial consequences for risk reduction; resource efficiency; additional high-value employment; and climate-change knowledge, science, monitoring and early warning data.

1. Introduction

Humans have been introducing items into outer space since 1957 when Sputnik 1, the first artificial satellite, was launched by the Soviet Union. Some fall back to Earth, and burn up in the atmosphere or land, mainly in the oceans (e.g. into the so-called "Spacecraft Cemetery" in the Pacific Ocean). Some are deliberately moved further away from Earth into a so-called "graveyard orbit" (also known as a "junk" or "disposal" orbit), ~200 miles farther away from Earth than the common operational orbits. However, many of these fast-moving objects, known colloquially as "space junk", remain in orbit around Earth. Orbital debris produced by human spacecraft activity was acknowledged as a problem in 1978. Since then, governments, and more recently high-profile private companies such as SpaceX, have continued to fund space exploration missions without any meaningful strategies to cease the growth of the orbital debris population. Space agencies have developed successful monitoring and modelling strategies for even the smallest of debris in the Low Earth Orbit (LEO) (the area of space below an altitude of 2,000 km above sea level), Middle Earth Orbit (MEO) (the area of space between 2,000 and 35,786 km above sea level) and Geostationary Earth Orbit (GEO) (a circular geosynchronous orbit at a constant altitude of 35,786 km above Earth's Equator). Ground-based radars have been able to catalogue the larger and therefore more dangerous debris objects (>10 cm). Whilst modelling and monitoring of orbital debris is important for situational awareness of active satellites and new rocket launches, it does not aid in tackling the physical presence of a growing debris population and the inherent waste of valuable resources, particularly high value metals, plastics and ceramics. In this context of decoupling human (economic) activity from the consumption of finite resources, the Ellen MacArthur Foundation (2020) introduces the principles and benefits of the circular economy, whilst Paladini et al (2021) discuss its relationship to the space sector.

This orbital debris population consists of active and inactive satellite payloads, intact rocket bodies and mission related objects (MRO) (e.g. rocket exhaust products, objects released in spacecraft deployment/operations, refuse from crewed missions), fragmentation debris and other objects. In-orbit servicing, such as life extension of inactive satellites as well as active debris removal (ADR), is in its relative infancy but is currently the main hope for delivering a practical solution. At present, ~60 % of the in-orbit service market is being developed by private start-ups with the hope of profiting from the services that they will be able to provide to players in the space economy (Catapult, 2021), whilst also working to clean it up for the benefit of everybody.

1.1. Context

Space debris is defined by the National Aeronautics and Space Administration (NASA) as the natural meteoroids and artificial orbital

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debris that can be found in Earth's orbit. Orbital debris is a subset of space debris concerning only the man-made objects that have been sent into space (Wild, 2010). Orbital debris is increasing at an unsustainable rate and presents an immediate threat to the thousands of active satellites upon which many of our 21st century systems rely (UNOOSA, 2019). Whilst tracking and cataloguing of orbital debris has been effective in protecting new spacecraft launches, the threat of a catastrophic event becomes ever greater without a reduction in the population of orbital debris (Murtaza et al., 2020). Recent studies have focused on orbital debris as an economic problem with international cooperation of space policies and the introduction of a cap-and-trade system as methods of introducing some accountability into the largely unregulated space commons (Adilov, Alexander and Cunningham, 2020). However, Maclay and McKnight (2021) argue that the success of any economic or policy mitigation strategies will be symbiotic with debris remediation efforts, such as active debris removal (ADR). Therefore, it is encouraging that technology such as Surrey Space Centre's RemoveDEBRIS or Astroscale's ELSA-d have had successful demonstrations as they will need to become operational as soon as possible to counteract the rate of new spacecraft launches (ESA, n.d.). Demand for these services will prompt a competitive in-orbit servicing market with the goal of achieving space sustainability and profitable business operations (La Rocca et al., 2020). There has been little attempt to estimate values for orbital debris objects. Estimations of this nature could affect attitudes towards investment in developing in-orbit service capabilities.

The first piece of orbital debris was the Vanguard 1 satellite, sent up in 1958 in response to the Soviet Sputnik 1. Whilst Sputnik 1 and its associated launch vehicle burned up upon re-entry a few months after it launched (Hall, 2014), Vanguard 1 is still in the MEO today, despite losing contact just six years after it was launched (Hall, 2014). It could be argued that allowing a satellite to remain in orbit beyond its usage lifespan, effectively dumping it there, set a precedent for all future space programs.

An issued raised by Donald Kessler in 1978 was the unintentional creation of a debris belt around the Earth, caused by human spacecraft activities. Now dubbed the 'Kessler Syndrome', he proposed that, much like the behaviour of asteroids in the solar system, debris from the break-up of spacecraft will begin to collide exponentially in Earth's orbit until it becomes an uncontrollable runaway system (Kessler and Cour-Palais, 1978). This situation would present colossal problems, reaching far beyond just a minor inconvenience to space exploration. The debris in the LEO in 1994 already presented a greater hazard to human spacecraft than natural meteoroids (Kessler, 1994), so this threat must be greater now. Studies estimate that orbital debris collisions would continue to occur for 200 years even if all launches were stopped from 2007 (Liou et al., 2007, Liou and Johnson, 2006). Spacecraft launches have increased since these articles meaning that their estimations would certainly have to be extended.

Orbital debris in 1975 was categorised as objects > 10 cm in diameter; however with the use of more advanced technologies, NASA has been able to analyse the orbital debris down to microns in diameter (Kessler, 1994). With the huge variations in debris size, different sensors are required for detecting and tracking debris. The US Space Surveillance Network (SSN) was set up for this reason, including the US Department of Defence that uses a global network of sensors to detect debris objects>10 cm in the LEO as well as larger debris objects in the GEO. NASA is tasked with detecting objects < 10 cm and uses the Haystack Ultrawideband Satellite Imaging Radar (HUSIR), HAX and Goldstone radars to achieve this in the LEO (Matney, 2016). Tracking these tiny objects in the GEO requires the use of optical equipment such as the Michigan Orbital Debris Survey Telescope (MODEST). Debris of this size (<10 cm) is currently near-impossible to catalogue so data on these debris population size and distribution are recorded for use in modelling only (Matney, 2016).

Modelling of orbital debris is an important way of understanding the current state of debris < 10 cm in the LEO and GEO, critical knowledge for future spacecraft launches. Currently, NASA's most high-tech model of orbital debris for both the LEO and GEO is the Orbital Debris Engineering Model (ORDEM). The model provides a tool for space sector designers, engineers and scientists to comprehend the long-term risk of collisions with orbital debris. The latest version (ORDEM 3.1) is able to model between the years 2016–2050 (Matney et al., 2019). This model was built using data from historical launches from 1957 to 2015, fragments from historical fragmentation events and known satellite material break-ups (Matney et al., 2019). ORDEM 3.1 provides information on debris flux, size, spatial density, impact speed and impact direction, useful information for spacecraft design and route planning (Liou, 2017). While modelling of debris this size is important due to there being an estimated > 300 million objects (ESA, 2021b), it will not be the focus of this study because none of the objects have been catalogued. For larger catalogued orbital debris objects, Fig. 1 shows a growing population and an increased growth rate in the most recent years (~2017 to present). Fig. 2 shows that there has been a dramatic rise in objects launched into space from 2017 to present.

This recent rise in objects in space is ascribed to the development of commercial small satellite constellations in the LEO, created with the goals of faster global communication services and higher bandwidth (Daehnick et al., 2020). Such constellations have been attempted before (e.g. Globalstar and OneWeb) but failed due to the high associated costs relative to the small market, however this has changed over the last decade with the increases in technological capabilities (Curzi et al., 2020). There is little argument about the benefit of the new technologies, however with the current state of debris in the LEO, there is concern for the increasing risk of collision and therefore further debris creation (Maclay and McKnight, 2021). SpaceX have had 42,000 satellites approved by the FCC to be launched as part of their Starlink satellite constellation (Henry, 2019), indicating that the market might be strong enough to support constellation proposals this time around. Muelhaupt et al. (2019) state that traffic management will become a significant issue, although their assessment does not consider the potential successes of any orbital debris solutions in this timeframe.

1.2. Solutions to orbital debris

There have been many proposed methods for the solving the issue of orbital debris. The Committee on the Peaceful Uses of Outer Space (COPUOS) presented a list of orbital debris mitigation guidelines that were accepted by the United Nations (UN) General Assembly in 2007; these guidelines should be considered during the mission planning, design, manufacture, and operational phases of spacecraft and launch vehicles (UN, 2017). The final two guidelines are particularly significant due to their focus on the reduction of debris by limiting the lifetime of defunct spacecraft (Lewis et al., 2012). Increased compliance with the mitigation guidelines is a key contributor to the success of ADR practices, with the goal of reducing the debris population (Adilov et al., 2020). For example, it has been concluded that a combination of following the Inter-Agency Space Debris Coordination Committee's (IADC) mitigation guidelines, specifically the existing maximum 25-year lifespan of defunct satellites, along with ADR of 4 objects (>10 cm) per year, would reduce the orbital debris population by 10 % (Lewis et al., 2012). However, at low levels of ADR (10 removals per year in the LEO), launches, solar effects, the mitigation guidelines, and explosion activity have a larger influence on how the debris population is predicted to evolve, than ADR (White and Lewis, 2014). This implies that an ADR must be undertaken swiftly if it is to have the desired effect. Unfortunately, it has been calculated that the cost-benefit ratio of ADR practices will increase as the orbital debris population heads towards an exponential growth rate. Therefore, ADR practices must be incorporated as soon as possible for them to be viable as well as have a meaningful effect (Liou and Johnson, 2009).

Boubellouta and Kusch-Brandt (2021) have reviewed and explored

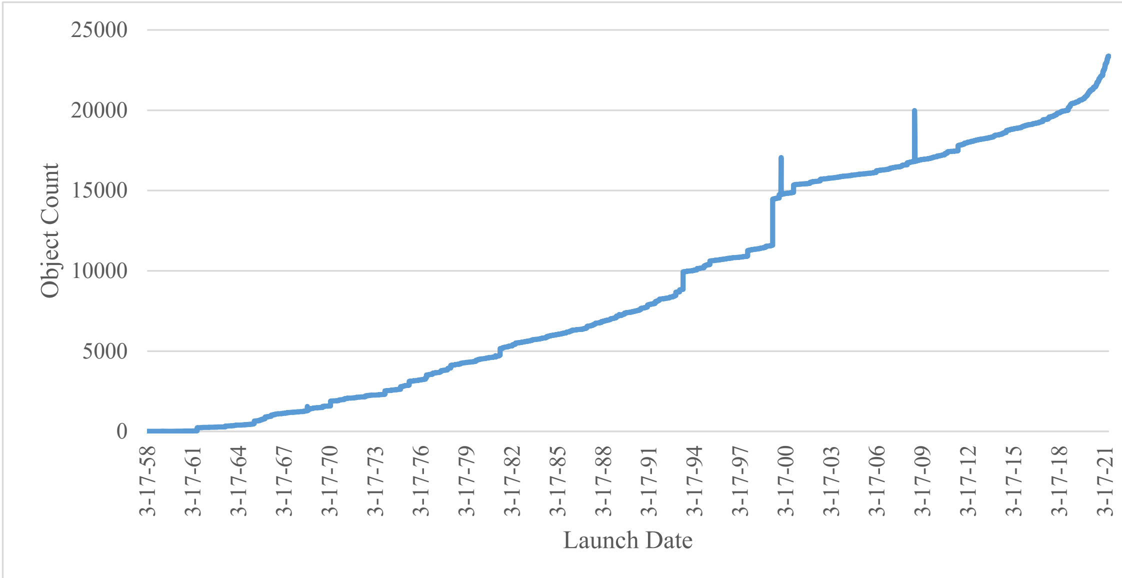

Fig. 1. Number of objects tracked in Earth's orbits from 1957 – 2021. (Source: Obtained via the Space Track website using data from the United States Space Command (USSPACECOM), United States Space Force (USSF) and satellite owners (2021)).

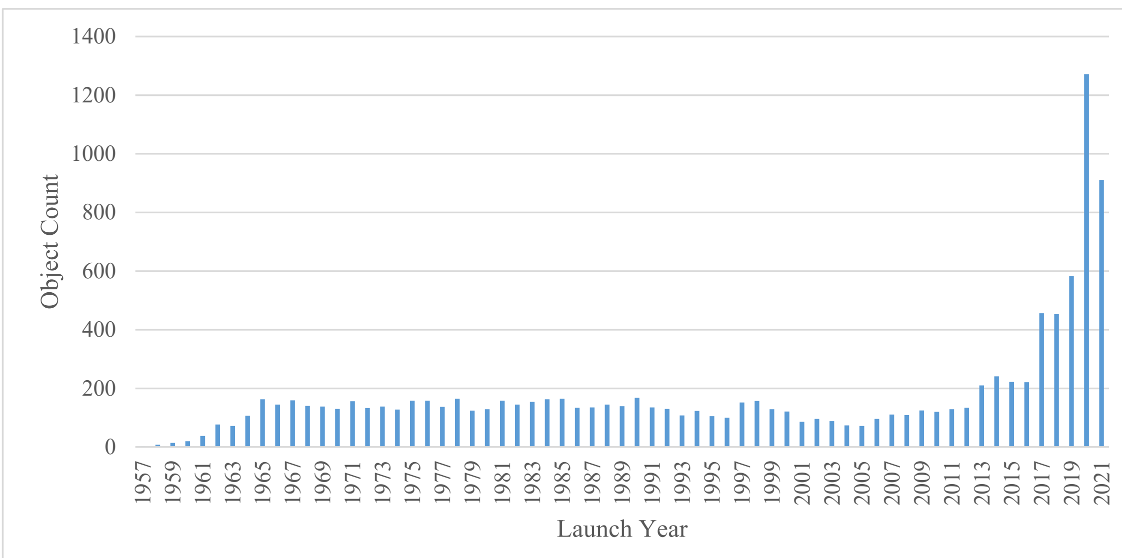

Fig. 2. Number of objects launched into space from 1957 to 2021 (Source: United Nations Office for Outer Space Affairs (UNOOSA)).

the relationship between economic growth and environmental degradation, concluding that the quantities of mismanaged e-waste decrease after crossing the Environmental Kuznets Curve turning point but crucially highlighting that this is not enough to resolve the challenge of sound e-waste management. In this context, there is currently no incentive for any single country to reduce their contribution to the orbital debris environment under international treaties, mainly because there is no precedent for directly attributing costs to a single actor (Taylor, 2011). For example, other than negative political responses, China received no punishment for their 2007 anti-satellite test that created over 3000 debris objects in the LEO (Zissis, 2007). This is a classic 'Tragedy of the Commons' scenario in which an effective solution has yet to be developed. Rose (1991) states that the most difficult to implement but most effective solution to this kind of problem is to treat the use of the commons resource as a tradeable commodity (PROP strategy in the article), in the form of taxation and tradeable allowances. This allows for the implementation of a cap on the total level of pollution in the environment and therefore control on the pollutant population size. This becomes a greater issue with the rise in private companies looking to capitalise on the 'New Space' era as there is no incentive for them to consider sustainability as they chase profit. A code of conduct for the private space industry has been suggested in order to bridge the gap between the current international treaties and guidelines, and the protection of the common resource of space (Chrysaki, 2020). Using such market-based solutions can incentivise the development and implementation of ADR through schemes such as tax credits for removal of debris objects as well as offsetting future debris creation against debris that space agencies/governments are responsible for removing (Taylor, 2011). To support this, calculations show that the implementation of an orbital use fee has the potential to quadruple the net present value of the satellite industry through a reduction in launch activity, therefore reducing collision risk (Rao et al., 2020). Despite strong arguments for economic-based solutions, they would require complex geopolitical cooperation such as negotiating terms for an international orbital debris convention (Migaud, 2020), something not yet been established.

Solutions often come from the development of specific technologies to tackle specific problems within the context of the broader common problem. Simulations of various ADR scenarios have indicated that development of one global entity to oversee orbital debris removal would be the most effective strategy for performing ADR (Klima et al., 2018). However, it is expected that a competitive market in ADR services will develop based on the growing demand for these services (Catapult, 2021), despite the potential externalities of an open market. Demand is driven by the benefits to the main three types of customer; Satellite operators require risk reduction to their active equipment, insurers also benefit from this reduced risk, and government responsibility to protect the orbital environment (Brettle et al., 2019). An open market would create beneficial solutions for the long-term goal of reducing the orbital debris population due to the technological innovation, improvement of policy and best practice, and a greater focus on the economic and safety factors that are all driven by competition and specialisation in an open market (Weeden, 2019). One example of the kind of market-incentivised need for ADR solutions is the anticipated demand for recycled aluminium alloys, potentially from reclaimed orbital debris, to satisfy the growing demand across the aerospace industry (El Hameed and Abdel-Aziz, 2021). To contribute to this market development, estimating a potential value for the orbital debris environment would provide a solid justification for these technologies to be developed.

ADR technologies are largely at the experimental phase, and many have yet to produce data that backs their proof of concept. Methods include the laser-based method, IBS-based method, tether-based method, sail-based method, collective method, satellite-based method, unconventional method, and dynamical systems-based method (Mark and Kamath, 2019). A lot of work will be required for these concepts to become functional solutions to the orbital debris problem. In-orbit/on-orbit servicing is another proposed solution that could help to tackle the thousands of inactive payloads that present the greatest potential for damage in a collision situation. Repairing, refuelling, upgrading, re-orbiting, and recycling are all examples of in-orbit servicing missions. Recycling of parts and materials from these older payloads onto newer payloads could be particularly useful as it would eliminate the cost of launching new materials into space as well as help to tackle the orbital debris problem in an economically viable way (Mejía-Kaiser, 2017). The European Space Agency (ESA) is currently accepting design proposals for on-orbit servicing craft that will aid the development of a market for these services to combat many of the externalities produced by the current spacecraft industry (ESA, 2021a). Under the right circumstances, on-orbit servicing of a satellite is the most financially viable option for the parent company, whilst also creating value for the servicing company (Liu, 2021).

Reuse of parts of spacecraft is starting to become another option to address the orbital debris problem. For example, Clark (2020) reported on and visually documented SpaceX's mission to recover its Falcon rocket booster after SpaceX's first crew launch and Ralph (2022) has highlighted how it has now been reused several times.

1.3. Attempts to quantify orbital debris

Previous studies have attempted to give values to orbital debris based on removal from orbit via ADR, therefore reducing the probability of collisions with active satellites. Vance and Mense (2013) derived a present value per object removed for small and large objects in the LEO. They estimated a removal value per small object to be $14,500 and $260,000 for a large object (e.g., a 2000 kg inactive satellite). While the methodology is relative to the practice of ADR, the valuation is based on the active satellite environment and not the value held within the inactive satellite and debris environment. In a similar study, Wang (2016) calculated the value of losses caused by orbital debris < 1 cm in each of the LEO, MEO and GEO environments. Using debris flux fitted with the Kessler model and combined with NASA's break-up model, Wang estimates that an orbital debris object (<1 cm) causes damage of $164.349 in the LEO, $231.923 in the MEO and $315.779 in the GEO. Again, this information would be useful to cost justifications in the ADR market, but it is relative to the active environment and not the inactive environment.

No attempt to accurately estimate the physical mass of orbital debris and provide estimates for the potential value of these objects based on their material composition has been undertaken previously. Estimates for these values could serve as financial incentives for in-orbit service providers in their attempts to develop the required technology. More importantly, the development of these technologies could signal a change from the historic linear to a new circular economy for space operations. This chimes with the UK government's new Plan for Space Sustainability that aims to improve the UK's sustainable use of space. With lower costs associated with return and reuse of million-dollar launch equipment, it is predicted that commercialisation of space will further usher in the 'New Space' era, full of profitable opportunities for start-ups as well as established companies (Denis et al., 2020). It has been speculated that significant value lies within 'Space Junk' (Anderson, 2019).

Thus, the aims of this study were to: i) develop and present a methodology that allows for the derivation of estimates for the monetary value and total mass of all catalogued objects in the ESA's Database and Information System Characterising Objects in Space (DISCOS) dataset ii) discuss the viability of a future circular economy for space.

2. Methods

2.1. Data sources

Robust and authoritative data were sourced from the ESA's DISCOS dataset that contains all the known objects in space that have been catalogued. It is suitable for this study since it contains all relevant data points, specifically: Name of Object; COSPAR ID – Committee on Space Research (COSPAR) International Designator; Object Class – classification of debris object; Mass (kg); re-entry Epoch (or lack of) – whether the object is known to have re-entered the atmosphere.

The DISCOS dataset was accessed using the DISCOSweb Application Programming Interface (API) via Python programming code provided by the ESA space debris helpline. The code contained a navigation through the API as well as a Comma Separated Value (CSV) reader that prompted a CSV file to be created containing all the information in the 'Objects' dataset. Once the CSV download had been completed, the data was imported into Microsoft Excel. The object data was sorted by their launch dates, which was extracted from their 'COSPAR ID'. Data that did not contain a 'COSPAR ID' would not have been assigned a launch date. These data were omitted to improve the accuracy of the final valuation. A second sorting activity took place using the 're-entry Epoch' date where an object was assigned a date if it was known to have re-entered Earth's atmosphere. It was assumed that the objects without a date remained in Earth's orbit as either active or inactive. The objects with assigned re-entry dates were omitted. A cleaned and completed dataset of orbital debris remained that was ready to be put through a decision tree classification that was developed for the study (see Graphical Abstract).

2.2. Defunct satellites

DISCOS contains a complete record of 7,787 'Payload' objects that are still orbiting the Earth. It is estimated that the number of defunct satellites outweighs that of active satellites (Muelhaupt et al., 2019). Some defunct satellites were sent up in the late 1950 s and some have only recently become defunct and joined the debris population. To be able to differentiate between active and defunct satellites, we assumed

Table 1
Rates of change in value between brand new terrestrial products and their resale values used to calculate an average % change per year in product value.

Product	Value New	Av. Resale Value	Years Since New	% Change Rate
iPhone 8 64 GB (2017)	£700	£180.4	4	−18.6 %/yr
Tesla 75D (2017)	£82,050	£59,233.70	4	−6.9 %/yr
Boeing 737–500 (1992)	$31,000,000	$3,500,000	29	−3.1 %/yr
Average % Change Rate:				**−9.5 %/yr**

that any payloads launched after 2001 are active and therefore any launched before this date can be considered defunct. This assumption is based on the average design life for a satellite being set at 15–20 years (NSR, 2018), so 20 years is a conservative estimate. Valuation of defunct payloads was undertaken with the goal of using as much available information as possible. A higher-end and lower-end estimate of the payload object class allowed for the assumptions and consequent uncertainties to be factored into the results. For the higher-end estimate, defunct payloads (launched before 2001) were separated by launch date based on their reuse potential. The date by which the defunct payloads were deemed as having reuse potential or not came from NASA's Space Launch System (SLS) launch vehicle project, built as part of the Artemis lunar missions. The SLS uses some of the actual hardware from NASA's Space Shuttle Program that ran from 1981 to 2011, as well as updated technology and manufacturing practices (Mohon, 2020). Defunct payloads launched from 1981 were assumed to have adequate technology and hardware for potential reuse in a manner similar to that of the SLS.

To determine an actual value from the DISCOS data, the mass of each payload was multiplied by an estimated per kilogram cost of production and materials (excluding workforce) derived from Newell (1980), who produced a table showing the cost per kilogram of various NASA projects. A mean cost per kilogram of $87,833.33 was calculated for 1970 and corrected for inflation to give a 2021 value of $618,009.25 per kilogram.

It is very challenging to estimate the economic value of reusing items (Ongondo et al, 2013), individually and collectively. The few published studies that have attempted this type of economic valuation have tended to firstly estimate the total quantity of items under study using available datasets (e.g. Ongondo et al 2013; Shittu et al, 2022) or established approaches such as material flow analysis (e.g. Mazzarano, 2020), followed by estimating the reuse value. Reuse value can be expressed as functional value + residual value; residual value being the value of materials obtainable from the product via recycling at end of life (Shittu et al, 2022). Reuse of technology occurs frequently with many mass-produced terrestrial products being resold at a depreciated value, so at a fixed time, functional value must take this into account. With no precedent of a reuse market for space-going payloads, an average value for terrestrial product value change rate was calculated and applied to each of the 'reusable' payloads. Table 1 shows the terrestrial products used to calculate an average annual value change rate of 9.523 %.

Using the theoretical approach outlined above, Equation 1 evolved that allows for a reuse value estimation of each object:

Table 2
Materials information used for the calculation of objects launched before 1981 in the reuse scenario, and for all objects in the scrap material scenario.

Material Class	Material (% Composition within Material Class)	Material Value ($/object kg)	% Composition Within Payload
Metallic materials	Aluminium (30 %)	0.791	**70**
	Steel (5 %)	0.023	
	Copper (10 %)	0.932	
	Aluminium Alloy (25 %)	3	
	Gold (5 %)	0.896	
	Silver (5 %)	0.001	
	Nickel (5 %)	0.946	
	Titanium Alloy (15 %)	6.75	
	Mean	**12.53**	
Polymerics, Composites, Ceramics	**Proxy Value**	**15**	**30**

In the high-end reuse scenario, the defunct payloads launched before 1981 were valued under the assumption that they had no functional reuse value and would therefore be valued based on their material composition for scrap. To account for the 25 payloads that fit the reuse criteria but did not have any mass data, the highest, median, and lowest mass values were used as inputs for these missing values. This lead to three sets of results within the high-end reuse scenario in an attempt to understand the possible spread of the data. The 'International Space Station', 'ISS Columbus Module' and the 'Hubble Telescope' objects were omitted to avoid massively obscuring the results as well as their internationally known presence in space, i.e. not being orbital debris.

The lower-end estimate scenario for the defunct payloads valued all payloads (launched 1959–2000) under the assumption that they had no reuse value and would be scrapped for their materials. Bhat et al. (2018) derived the four main categories of materials used in the aerospace industry, as found in NASA's Materials and Process Technical Information System (MAPTIS). These categories are metallics, polymerics, composites and ceramics. Using the 2004 European Cooperation for Space Standardization (ECSS) review of space product assurance, the most common metallic materials were identified and their value per kilogram (ECSS, 2004), as found on the London Metal Exchange (LME) and Infosys, was recorded. The metals used for this analysis are shown in Table 2 along with an assigned percentage of that metal, relative to the other metals that make up a generic satellite composition. The values used were assigned using data gained from studying satellite diagrams and blueprints as this information does not currently exist in any capacity.

The Materials and Processing Technical Information System (MAPTIS) holds a record of over 32,000 metals and non-metals that have been tested and used throughout NASA's history of space exploration (Reynolds, n.d.). It is near impossible to include every single material that makes up the orbital debris environment. The metallic materials chosen served as a proxy to the many other materials that are up there, mainly because their scrap metal value could all be found on the LME and InfoSys. As for the polymerics, composites and ceramics, the sheer number of compositional variations, along with the lack of information

$$ReuseValue(\$) = (2021AdjustedObjectValue(\$/kg)*ObjectMass(kg))*(AverageChangeRate(\%/year)(2022 - LaunchYear))$$

Equation 1: Used for calculating a 2021 adjusted reuse value for each payload.

on their percentage inclusion within a satellite, made it impossible to generate a proxy list. These limiting factors combined with the absence of a 'LME'-type marketplace for standardised valuation of the scrap

Table 3
Estimated valuations of the payload reuse and scrap metal scenarios.

(1981–2000) (1959–2000)	Reusable Metallics, Polymerics, Composites and Ceramics (1959–1980)	Potential Net Value	
Reuse scenario; Value ($)			
Highest	76.48 billion	7.789 million	47.74 billion
Median	65.99 billion	6.487 million	37.25 billion
Lowest	65.46 billion	6.463 million	36.72 billion
Scrap material scenario; Value ($)			
	Metallics (1959–2000)	**Polymerics, Composites, Ceramics (1959–2000)**	
Highest	26.41 million	13.55 million	
Median	24.71 million	12.68 million	
Lowest	21.18 million	10.86 million	

materials, meant a reasonable value of $15 /kg was assigned to these materials.

$$ScrapValue(\$) = \left(PayloadMass(kg)*MetallicValue(\frac{\$}{kg}\right)*CompositionPercentage$$

Equation 2: Used for calculating the Metallic scrap value of each payload.

Scrap material value ($/kg) was an average derived from the per kilogram values seen in Table 3 as 12.532 $/kg for Metallics. These proxy materials were assigned compositional percentages that were representative of their usage within payload construction. Similarly, the composition percentage in Equation 2 takes into account the greater percentage of metallic materials with which payloads are often constructed; this was assigned to be 0.7 (70 %) for the metallic material class. The remaining material classes of polymerics, composites and ceramics used an identical equation to Equation 2 with the only changes being a 15 $/kg material value, and a composition percentage of 0.3 (30 %).

2.3. Intact parts

The next objects for classification within the DISCOSweb dataset were the 'Payload Mission Related Objects', 'Rocket Mission Related Objects' and 'Rocket Body'. The mission related debris are defined by ESA to have been released intentionally after serving their purpose for a specific mission. Similarly, the rocket body class includes the various stages of launch vehicles used to deliver payloads into space. These definitions imply that the objects within this class are intact and have not undergone a break-up/fragmentation event. DISCOS has 3780 objects that fall within these object classes, after the data cleaning processes. Although payloads are often the focus of a spacecraft launch event, the rocket body and any related instruments often require the same level of development costs and, particularly with rocket bodies, will require more materials in the construction phase. Therefore, the same methodology used for payloads was applied to the 'Rocket Body', 'Payload Mission Related Object' and 'Rocket Mission Related Objects'. This produced reuse and scrap material scenarios with higher-end, median and lower-end estimates due to the incompleteness of the mass data.

2.4. Debris objects

The remaining object classes consist of debris objects created by the break-ups and explosions of payloads and rocket bodies. 'Payload Fragmentation Debris' and 'Rocket Fragmentation Debris' are defined as objects that were unintentionally released during a traceable fragmentation event. Similarly, the 'Payload Debris' and 'Rocket Debris' are defined as unintentionally released objects where genesis is unclear, but their properties can be traced to a payload or rocket body. A total of 11,465 of these objects within the dataset were used for analysis after the data cleaning process. DISCOS only has a record of name and launch year for all but 52 of these objects. This was deemed as not enough information to be able to include the fragmentation and debris objects in this study.

2.5. Unknowns

DISCOSweb has a significant number of unidentified objects that are being tracked but currently lack information that allows them to be classified. Therefore, these objects were omitted from the dataset as they would, similar to the fragmentation and debris objects, be impossible to derive a value for given such little information. They remain a significant threat to spacecraft as they are orbital debris; however, if they were of a significant size and/or mass, they would be classified and therefore be able to be incorporated into the calculations of this study. NASA has modelling software that simulates smaller objects of this nature; its goal is debris risk mitigation, which is necessary but not the aim of this study.

2.6. Cost calculations

The overall cost calculations were performed using the theoretical approach outlined in Section 2.2. For both the reuse and scrap material scenarios, related costs were calculated using Equation 3 in order to contextualise the object valuations. To do this, it was assumed that Astroscale's ELSA-d, a payload currently in orbit and demonstrating on-orbit servicing operations, was able to service 10 objects per launch. At ~ 175 kg, the cost of the ELSA-d payload was calculated using Equation 1. It was assumed that after its 10-object mission, ELSA-d would need to be serviced on the ground and would incur costs equivalent to a new ELSA-d payload. The cost of launch was calculated to be $1 million as part of the Space X Rideshare Program, again requiring one launch per 10 objects serviced.

$$ValueperObject(\$) = \frac{\left(ELSA - dMass(kg)*2021AdjustedObjectValue\left(\frac{\$}{kg}\right)\right) + RideshareCost(\$)}{ObjectsServicedperMission/Launch}$$

Equation 3: Used to calculate a cost per object and net value of the objects.

For the reuse scenario, on-orbit servicing assumes that the payload/rocket body/MRO would regain its function and therefore assumes its 2021 calculated value. The same principle was applied to the material values in the scrap material scenario.

The main classifier within the DISCOS dataset is the ‘Object Class’ column, therefore the dataset was split by these columns. ‘Payload Mission Related Objects’ and ‘Rocket Mission Related Objects’ were merged into a ‘Mission Related Objects’ class as their descriptors were similar and implied similar properties. Similarly, the ‘Payload Fragmentation Debris’, ‘Payload Debris’, ‘Rocket Fragmentation Debris’ and ‘Rocket Debris’ were merged into the ‘Fragmentations and Debris’ class.

3. Results

Note the results show estimated values for the higher, median, and lower-end valuations. The decision to substitute object mass values (instead of omitting these data points) was made so that the results would be more representative of the actual orbital debris environment, covering a range of all possibilities (by covering the highest and lowest potential mass values of the missing object mass data).

3.1. Payloads

Of the 2,634 payloads deemed inactive, 1,716 were classified as having reuse potential and the remaining 918 were considered to have outdated technology that would mean their value was held in their material scrap value. Results for the scenarios can be seen in Table 3. The highest estimated valuation of the ‘Payload’ object class, as obtained within ESA’s DISCOS dataset and using a reuse scenario methodology is $84.27 billion. For payload object class under a reuse scenario, the median estimate is $72.48 billion and the lowest estimate is $71.92 billion. The highest estimated valuation of the payload object class using a scrap material scenario methodology is $39.96 million, the median estimate is $37.39 million and the lowest estimate is $32.04 million.

Table 4
Estimated valuations of the rocket body reuse and scrap metal scenarios.

(1981–2000)	Reusable Metallics, Polymerics, Composites and Ceramics (1959–1980)	Potential Net Value (1958–2021)	
Rocket body reuse scenario: Value ($)			
Highest	735.4 billion	65.13 million	699.2 billion
Median	594.9 billion	12.59 million	563.9 billion
Lowest	576.9 billion	7.94 million	546.5 billion
Rocket body scrap material scenario: Value ($)			
	Metallics (1959–2000)	**Polymerics, Composites, Ceramics (1959–2000)**	
Highest	96.18 million	49.34 million	
Median	38.93 million	19.97 million	
Lowest	33.82 million	17.35 million	

3.2. Rocket bodies

There were 2,579 rocket bodies in the DISCOS dataset, 1,840 of them were deemed reusable and the remaining 739 were deemed for scrap material. Results for the scenarios are shown in Table 4. The highest estimated valuation for the ‘Rocket Body’ object class using the reuse scenario is $735.5 billion, with a median estimate of $594.9 billion and a lowest estimate of $577 billion. Using the scrap material scenario, the highest estimate for rocket bodies is $145.52 million, the median is $58.9 million and the lowest estimate is $51.17 million.

3.3. Mission related objects

Of the 1,456 mission related objects, 1,016 were classified as reusable and 440 were classified to be valued by their scrap material. Results for the scenarios are shown in Table 5. The ‘Mission Related Objects’ had a high valuation under a reuse scenario calculated at $446.7 billion, a median estimate at $11.51 billion and a low valuation of $6.078 billion. The highest estimated valuation of the mission related objects under a scrap material scenario is $158.9 million, with the median and low estimates of $1.375 million and $870,000, respectively.

Table 5
Estimated valuations of the mission related objects (MRO) valuation under the reuse and scrap metal scenarios.

(1981–2000)	Reusable Metallics, Polymerics, Composites and Ceramics (1959–1980)	Potential Net Value (1959–2021)	
MRO reuse scenario; Value ($)			
Highest	466.6 billion	47.69 million	430.8 billion
Median	11.52 billion	492,000	(4.373 billion)
Lowest	6.078 billion	369,900	(15.031 billion)
MRO scrap material scenario; Value ($)			
	Metallics (1959–2000)	**Polymerics, Composites, Ceramics (1959–2000)**	
Highest	105 million	53.89 million	
Median	908,500	466,000	
Lowest	575,200	295,000	

Table 6
Mass calculations and total final valuations for each scenario. NB: Mass calculations are for the high, median, and low scrap material scenarios. Total final valuations for the payload, rocket body and mission related objects in the orbital debris environment. Also shown is the total net value of the reuse scenario for each high, median, and low estimates.

Scrap Material Scenarios	Payload Mass (tonnes)	Rocket Body Mass (tonnes)	Mission Related Object Mass (tonnes)	Mass Total (tonnes)
Highest	2,910	10,427	5,787	19,124
Median	2,412	4,465	101.4	6978
Lowest	2,390	2,856	65.6	5312
Reuse Scenarios	**Reuse Scenario Value Total ($)**	**Total Potential Reuse Scenario Net Value ($)**	**Scrap Material Scenario Value Total ($)**	
Highest	1.258 trillion	1.177 trillion	344.4 million	
Median	672.5 billion	596.8 billion	97.67 million	
Lowest	648.4 billion	568.2 billion	84.01 million	

3.4. Total calculations

The higher-end valuation is drastically greater than the median estimate, whereas the median is relative close to the lower-end estimate. There is an even greater difference in the results of the reuse scenario versus the scrap material scenario. A simple addition determines a final valuation for the payloads, rocket bodies and mission related objects in the orbital debris environment, as seen in Table 6. Results of the mass calculations, also displayed in Table 6, show a high-end estimate of > 19,000 tonnes, a median of ~ 7,000 tonnes and a low estimate of ~ 5300 tonnes.

4. Discussion

4.1. Scenario estimates

When scenario estimates are made, a low-end estimate typically takes the lowest value, a conservative estimate the middle (median) value and a liberal estimate the highest value. Because of the inherent uncertainties in the calculations we have performed, the median reuse scenario results may considered as the best statistical indicators of central tendency for both the total value and total mass calculations of objects that make up the orbital debris population. A total object value of between ~$673 billion is consistent with space agency spending during this period. Specifically, over their 20-year reusable period, payloads averaged costs of ~$3.3 billion, rocket bodies and mission related objects averaged costs of ~$14.9 billion and ~$288 million respectively, over their 40-year reusable period. This comes to a total annual spend of ~$18.488 billion for the global space economy on these objects. Considering NASA's annual budget during this time averaged ~ $20 billion (The Planetary Society, 2021), the myriad of other sunk costs associated with funding a space agency and the launch costs for these objects, ~$18.488 billion per year across all global space agencies seems a judicious estimate.

Similarly, the median estimate for the total mass value of the objects in DISCOS is consistent with estimates from the ESA. Under a scrap material scenario, the median mass estimate was calculated as just under 7000 tonnes. In their frequently updated page, 'Space Debris by the Numbers', the ESA estimate that the total mass of all space objects in Earth orbit is > 9500 tonnes. This is encouraging for the result of the median estimate in this study for a number of reasons. Their definition of 'all space objects' implies that active satellites are included in their estimate which would explain the ~ 2500 tonnes difference (ESA, 2021b). However, even if active payloads were not included in their mass estimate, the discrepancy is explained by the omission of fragmentation debris and unknown objects by this study's method. These mass values, along with the hundreds of millions of uncatalogued debris < 10 cm, also explain the lower median estimate calculated in this study.

4.2. Limitations

Despite the comments in Section 4.1, the reuse scenario produces values that represent a somewhat idealistic situation. It assumes that all 'reusable' objects have retained their pre-launch value, arguably an unlikely outcome considering their years of exposure to extreme climate cycling. Furthermore, there is a strong possibility that the 1981–2000 technology of the payloads is outdated for the needs of modern society, rendering them surplus to requirements. Even rocket bodies, with the recent introductions of reusable boosters such as Space X Falcon 9, might be outdated technology at this point. The 1981 cut-off date for reuse versus scrap in the reuse scenario was based on NASA's SLS rocket reuse program. This program has been heavily criticised for delays and being over budget, as well as its capabilities are less of that than of Space X's more recently developed Starship. It must be noted that their design philosophies are completely different in that NASA chose to reuse parts and legacy manufacturing processes versus Space X's iterative manufacturing approach, lending itself to rapid development (Kordina, 2020). Therefore, Space X has shown just how outdated SLS is and this may somewhat discredit the 1981 reuse cut-off date chosen in this study.

Another limitation to consider comes from the assumption that all of the objects in the reuse scenario will be able to be serviced by a mission such as ELSA-d. SpaceLogistics had a successful in-orbit servicing mission of the GEO satellite Intelsat IS-901 in 2020 using their Mission Extension Vehicle (MEV) (Cox, 2020). However, this kind of technology is still in the demonstration phase for use in the LEO (Astroscale, 2021a), arguably the most susceptible orbit for a Kessler-style collision event. There is a pessimistic future where in-orbit servicing is not as capable as first hoped. Therefore, potential for reuse of certain objects is lost and they must be valued under the scrap material scenario, where their value would drop considerably. Furthermore, the current demonstration capability of ELSA-d is on a ~ 17 kg 'client' payload (Astroscale, 2021b). Whilst it can be assumed that this will be scaled up to accommodate for the much larger objects in the debris population, at present ELSA-d would only be able to service 243 of the 6,669 objects analysed in this study. Despite this being a very literal interpretation of the in-orbit service market, whilst the technology isn't yet fully operational, the assumption of in-orbit service success is supported by the prediction of expert market projections.

Possible explanations for the scrap material scenario's relatively low valuation estimates are based on the findings presented above. The ~ $-10 billion in net value loss of the scrap material scenario was largely due to the costing method for ELSA-d servicing missions. However, the difference in scenario outcomes is so great that it does indicate that a scrap material scenario should not be the target of profitable business endeavours. Instead, a value for removing scrap debris objects should be valued using a methodology similar to Vance and Mense (2013), where the value of object removal from orbit is attributed to the risk reduction towards the active satellite population. The findings for the scrap material scenario are very possibly due to the flaws of this methodology and could actually be more desirable than these simple calculations suggest.

4.3. Implications

Speakers at the 2013 Royal Aeronautical Society 'Space Traffic Control' conference agreed that in-orbit services such as satellite end-of-life, life extension and de-orbiting offer the most promising short-term solutions to the orbital debris problem (Slann, 2014), meaning they are in high demand. Other than the original satellite owners, in-orbit service providers are next best placed to recoup a large amount of the estimated net value through fees for their services. It is therefore encouraging to assess the total potential net values of the reuse scenario alongside Catapult's 2021 projections for the in-orbit service market. Their conservative estimate that the in-orbit servicing market will see revenues of ~$4.4 billion by 2030 is consistent with the median ~$600 billion potential net value for orbital debris calculated in this study. Hence, the median estimate net value could play an important role as an incentive for a private company to choose a higher risk-reward investment strategy, in the hope of capitalising on the potential gains of the developing in-orbit service market. By successfully developing a methodology that has estimated the monetary value and total mass of all catalogued objects in the ESA's DISCOS dataset, we have demonstrated for the first time that a future circular economy for space is potentially financially viable. The findings of our study can thus contribute to the acceleration of a practical solution in halting the growth of the orbital debris population that would be beneficial to society (in terms of risk reduction from Kessler-style collision events), resource efficiency (in terms of recovering materials from space), and to the space economy as a whole. Our data provides some support for the view of the UK space sector that a genuinely sustainable approach to space-related innovation will provide up to 15,100 additional, high value, "green" jobs to the UK economy, from just one sector, whilst simultaneously enabling "space-based technologies and space-derived information play a key role in climate knowledge, science, monitoring and early warning " (UK Space and WPI Strategy, 2020).

One potential knock-on effect of the rapid implementation of in-orbit servicing solutions would be the shifting of the space economy from linear to circular. A circular space economy would aim to maintain maximum utility of its products and materials (Brennan and Vecchi, 2020). Although Space X and other companies already have reusable rocket boosters in mission operation (Berger, 2021), even these designs only recover ~ 70 % of the rocket and upper stages (Sheetz, 2020). It makes sense to claim that the missing piece to the circular space economy puzzle is therefore in-orbit servicing, particularly ADR. If new disposable launches could be returned to Earth for reuse or recycling by an in-orbit service provider, then the loop of the circular economy has been closed. 'New Space', specifically the decentralisation of space operations around 2010, has enabled much of the innovation through public–private partnerships that we see today (Weinzierl, 2018), and the circular economy model just makes more sense in this situation where companies are competing for a slice of market share.

5. Conclusions and recommendations

The first method for robustly estimating the value and mass of orbital debris has been successfully delivered and the implications discussed. We conclude that a future circular economy for space may be financially viable, with potentially beneficial consequences for risk reduction; resource efficiency; additional high-value employment; and climate-change knowledge, science, monitoring and early warning data. The median to low-end net valuation estimates appear judicious at ~$600 billion and should be encouraging to actors in the growing field of in-orbit services. A total mass estimate of ~ 7000 tonnes is consistent with the ESA's estimate. Development of in-orbit services will be crucial to solve the orbital debris problem and to the viability of circular economy for space.

Future work should focus on reducing data uncertainties. This could be done by using exact compositional and per/kg values for metals, polymers, composites and ceramics, recognising that these data may be very challenging to obtain. Another improvement would be to develop a more up-to-date Equation 1 for calculation of a reuse value. A further improvement would be the inclusion of the 'Fragmentation', 'Debris' and 'Unknown' object classes; although, the DISCOS dataset does not hold much information about these objects, a methodology could be developed that would produce estimates.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

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