A life-centred design approach to innovation: *Space Vulture*, a conceptual circular system to create value from space debris.

Fatimah El-Rashid[(1)(2)*], Thomas Gossner[(1)(2)*], Tobias Kappeler[(1)(2)*], Mariona Ruiz-Peris[(1)(2)*]

(1) Imperial College London, Exhibition Rd, South Kensington, London SW7 2BX, United Kingdom, Email: {f.el-rashid19, t.gossner19, t.kappeler19, mariona.ruiz-peris19}@imperial.ac.uk
(2) Royal College of Art, Kensington Gore, South Kensington, London SW7 2EU, United Kingdom, Email: {fatimah.el-rashid, thomas.gossner, tobias.kappeler, mariona.ruizperis}@network.rca.ac.uk
**These authors contributed equally to this work.*

ABSTRACT

Space debris threatens modern society and future generations. It is a symptom of severe unsustainability, and an alarming sign that there is an urgent need for change. Solutions-based linear-thinking has resulted in current innovations predominantly being either technological or managerial. Space debris, however, is a systemic problem that requires global action, and here we consider it as not only an engineering problem, but rather an incentives problem with social and cultural implications. As design engineers, a process for design-thinking is proposed, which takes a values-based life-centred approach to debris removal. Set in 2070, the outcome is *Space Vulture*, a conceptual closed-loop system designed to capture orbital waste, process it into raw materials, to be used in space to manufacture objects that increase subjective well-being. We emphasise, herein, the opportunity of combining intuitive and rational thinking at a systems level to deliver multi-scale innovations that tackle space debris.

Key words:
Innovation Design Engineering;
Life-Centred Design;
Systems Thinking;
Circular Economy;
Debris Removal;
Space Sustainability

1 INTRODUCTION

Space debris, including rocket bodies, defunct satellites and other technological waste is increasingly occupying space around Earth. As Damjanov [1] eloquently put it,

> *"These remnants of technologies, which once sustained the global production and exchange of data, information, and images, are an extraterrestrial equivalent of the electronic waste discarded on Earth."*

Space debris is one of the largest human-generated waste formations, and its accumulation is a symptom of the increasing, unsustainable modernisation of human societies.

Humans have been exploring space since 1957, when the first artificial satellite was launched to orbit Earth [2]. Since then, thousands of rockets and even more satellites have been launched into orbit; and in the next few years, 50,000 additional satellites are expected to be sent to space [3]. To date, there are roughly 5,000 satellites in *Low Earth Orbit* (LEO), about 3,000 of which are defunct (i.e., non-operational) [4]. In addition, there are approximately 34,000 fragments of debris larger than 10 cm in size, and millions of smaller fragments which are no less hazardous due to their high velocity [5]. If space debris is left unattended, the risk of debris collision and the potential cascading effects, a phenomenon dubbed the '*Kessler Syndrome*' after Donald Kessler in 1978, could potentially threaten the continuity of modern life on Earth and the future of space exploration [6]. Despite this, throughout history humanity has all too often been irresponsible with waste, and the 'out of sight, out of mind' mindset has continued to prevail.

Like ocean plastics, space debris is considered a *wicked problem* since space itself is a social good but there is currently no central governing authority, and those seeking to solve the problem are also causing the problem [7]. In other words, space debris is a huge, complex, systemic challenge with no definitive formulation. While space debris is scientifically apparent, it presents great technical, economic and social complexity; the latter, in particular, results in the challenge of maladaptive behaviour, which makes it difficult to find sustainable solutions.

In our view, space debris is a global concern and there is a global need to enhance space safety and support long-term space sustainability. Despite this, a lack of global incentive to act has limited global efforts, with all current solutions being developed within the space industry by actors like the *European Space Agency* (ESA). To date, proposed solutions have been primarily technological or managerial. Technological fixes, targeting the removal of debris from orbit, and managerial fixes, focused on de-orbiting satellites at end-of-life, both adopt primarily science-based linear modes of thinking [8].

However, given the urgency to act, solutions-based linear-thinking processes for innovation alone will not be sufficient in tackling the challenges posed by space debris because they fundamentally change neither incentives nor behaviours. As Rao [9] stated, "*this is an incentive problem more than an engineering problem. What is key is getting the incentives right*."

Unfortunately, space debris is relatively unknown to most people, and even within the space sector, many know of the problem but aren't working on it. Therefore, a design-engineering lens was taken to view the problem in order to determine how we might design innovation that will create incentive for people to clean up space debris. In this paper, a process for design-thinking is proposed in Section 2, which takes a *values-based*, *life-centred design* approach to deliver debris removal innovations. Section 3 presents *Space Vulture*, a conceptual system design that transforms space waste into valuable raw materials, which are then used to manufacture objects that are found to increase subjective well-being. Herein, progress and key challenges faced by current debris removal efforts are described to emphasise the many inherent complexities founded in the problem space. Reasons for adopting broader life-centric systems approaches to design-thinking is discussed in Section 4, where the limitations of human-centred design (HCD) for tackling systemic problems are discussed together with the implications of circular economy production systems for managing space debris and all other types of waste. Finally, Section 5 considers the future of society and the planet, and urges problem-solvers to widen their view of the world in order to deliver multi-scale innovations for tackling systemic wicked problems like space debris.

2 METHODOLOGY: INNOVATION DESIGN PROCESS

2.1 Double Diamond

A holistic approach commonly known as the *double diamond* provided the necessary overarching framework to deliver an innovative concept. The approach blends technical and design tools for problem solving and opportunity exploration, and was described by Dorst and Dijkhuis as *opposing paradigms of design activity* [10].

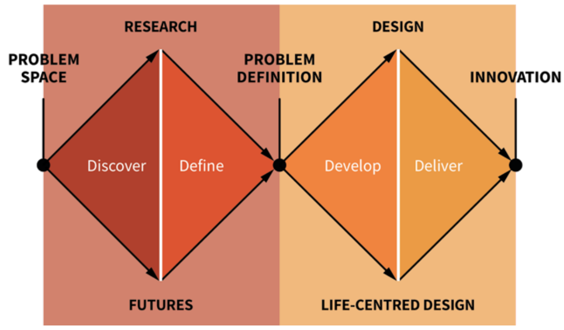

Figure 1. *The four-stage double diamond design model. Futures-thinking is applied to discover and define the problem; and a life-centred design (LCD) approach is applied to design innovation. The combination of methods requires both divergent (intuitive) and convergent (rational) modes of thinking. [11]*

The diamonds in Figure 1 represent the divergent and convergent processes of thinking employed at each of the key phases: *discover, define, develop* and *deliver*. Thinking either diverges and broadens (represented as the double peak), or converges and focuses (represented as the intersection), in order to reframe the problem and design innovation accordingly. Dynamically switching between divergent and convergent thinking and methodologies enables conceivement and delivery of creative yet rigorous innovation [12].

2.2 First Diamond: Defining the Problem

The purpose of the first diamond is to discover and define the problem. Divergent thinking was initially employed, where a futures approach was taken to identify the key trends and factors shaping the development of space sustainability, and to explore their implications for innovation in this area.

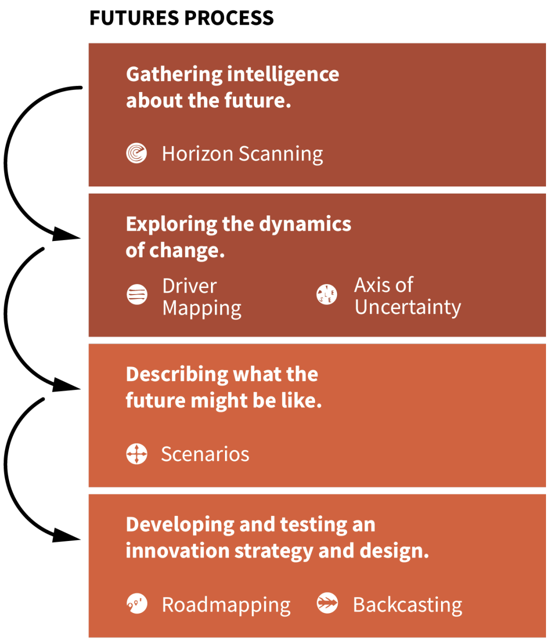

Figure 2. Futures process for developing and testing innovation design and strategy. An adaptation of UK GOC Futures Toolkit [13].

Fig. 2 provides an overview of the steps taken, and foresighting tools used, in the *futures process*, which is based on the UK Government Office for Science's *Futures Toolkit* [13]. Originally created for developing and testing policy and strategy, here it has been adapted for developing and testing innovation design. The core function of applying foresighting tools is to gather intelligence about the future, explore dynamics of change and scenario building, and to better define the problem by anticipating future opportunities and threats [14]. Given the uncertainties of the future of space sustainability, it is essential to apply foresight to understand potential future outcomes.

2.2.1 Horizon Scanning

The first step in the futures process was to gain an understanding of the future. This was done via *horizon scanning*, described by the Organisation for Economic Co-operation and Development (OECD) as, "*a technique for detecting early signs of potentially important developments through a systematic examination of potential threats and opportunities, with emphasis on new technology and its effects on the issue at hand.*" [15]. With divergent thinking employed it is not intended to predict future events, instead looking for early drivers of change [14]. Desktop research and workshop discussions were conducted to gather information about emerging trends and developments that could have an impact on the future of space sustainability.

2.2.2 Driver Mapping

Driver mapping facilitated horizon scanning, and was used to explore the dynamics of change. This process was conducted using the PESTEL conceptual framework to identify political, economic, societal, technological, environmental and legal drivers shaping space sustainability and the future of space debris. As shown in Fig. 3, drivers were mapped based on the potential impact they pose on space sustainability and the certainty of the outcome.

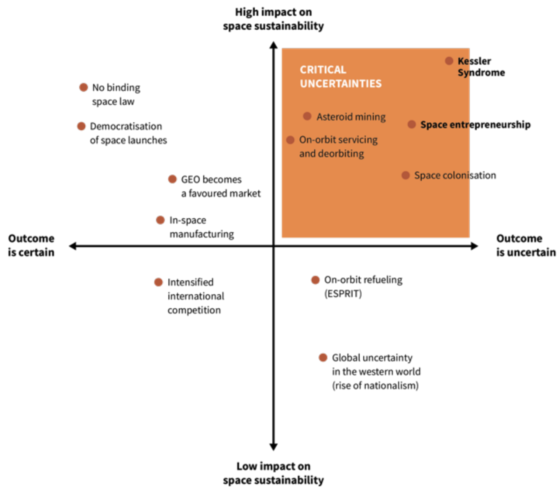

Figure 3. A map of drivers identified via PESTEL. Drivers of change found in the top right quadrant are known as 'critical uncertainties' for the future.

Drivers located in the top right quadrant are also known as *critical uncertainties* [16], that is, those which have the potential to highly impact the future of space sustainability and the problem of space debris, but there is significant uncertainty in the probable outcomes. In other words, drivers in this quadrant create the most critical and uncertain futures. Herein, *space entrepreneurship* and *Kessler Syndrome* are recognised as two of the most critical uncertainties that determine the future.

2.2.3 Axes of Uncertainty

Axes of uncertainty were used to characterise the nature of the selected critical uncertainties: *space entrepreneurship* and *Kessler Syndrome* to produce a scenario matrix, with the two most extreme situations plotted on either end of the axis for each of the critical uncertainties. This is shown in Fig. 4.

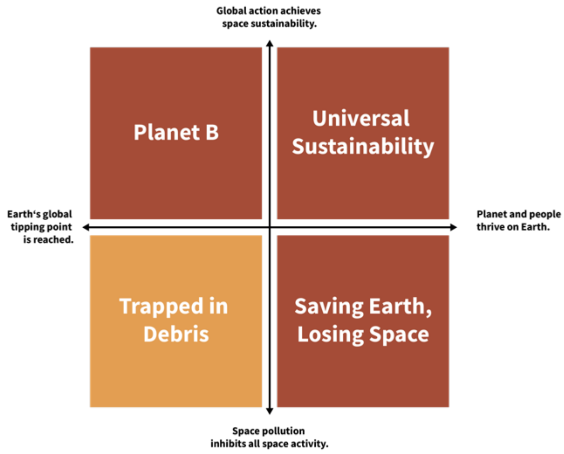

Figure 4. Scenario matrix based on axes of uncertainty of two critical uncertainties: 'Space entrepreneurship' and 'Kessler Syndrome'. Bottom left quadrant, "Trapped in Debris" was chosen as the hypothetical future scenario in 2070.

The top left quadrant was chosen as the hypothetical scenario for framing the space debris problem. Extensively informed by scientific research and forecasted trends, this scenario considers continuity of life on Earth to be increasingly threatened by global challenges like climate change, resource depletion and space debris [17]. For space debris, in particular, debris collisions have become more frequent, and now there's global concern and a growing movement to take collective action [18].

2.2.4 Scenario Building

Scenario building is a crucial step in the futures process because it is an opportunity to freely create alternative futures and explore the different drivers of change that might support or constrain achieving these futures. It is a tool used to help anticipate how the future might differ from today in order to define the problem. The purpose was to create a hypothetical future scenario based on the top left quadrant of the scenario matrix, enabling the design of innovation that works towards achieving that future. Three future scenarios set in the years 2030, 2050 and 2070 were developed.

2.2.4.1 2070: Hypothetical Future Scenario

As shown in Fig 5., this paper frames the problem of space debris and the future of space sustainability in the year 2070:

Humans have advanced considerably in the last 50 years. Space entrepreneurship has boomed, and along with it, came the addition of at least 50,0000 known satellites. As a result, space debris has rapidly accumulated over the last 50 years, and the frequency of debris collisions has grown exponentially making the Kessler Syndrome a highly likely phenomenon. Given human societies' reliance on space activities and exploration, and increased awareness of the major risks of space debris on human civilisation, global action is needed more than ever. However, with space actors mainly adopting debris avoidance technologies, there is little incentive even within the space sector to clean up space.

Figure 5. *A collage that illustrates the hypothetical 2070 future scenario.*

2.2.5 Backcasting

Backcasting is the last step in the futures process for discovering and defining the problem. The purpose of backcasting is to determine a problem view set in the future, and then work backwards. It offers space for a design vision and the impact which we would like to see happen. The process of backcasting fundamentally asks what actions must be taken in order to attain the desired future. It became evident that to achieve the desired future in 2070, global awareness about space debris would need to increase so that more people take action.

2.3 Second Diamond: Designing the Solution

For the second half of the double diamond process, the goal was to design innovation that could potentially create incentive for people to collectively tackle space debris. This was done by adopting *design-thinking*, a process popularised by *IDEO*, a design and innovation consultancy, which takes a *human-centred design* (HCD) approach to innovation that draws from the designer's toolkit to integrate technical feasibility, business viability and human desirability [19]. Key phases of the HCD approach are highlighted in Fig. 6.

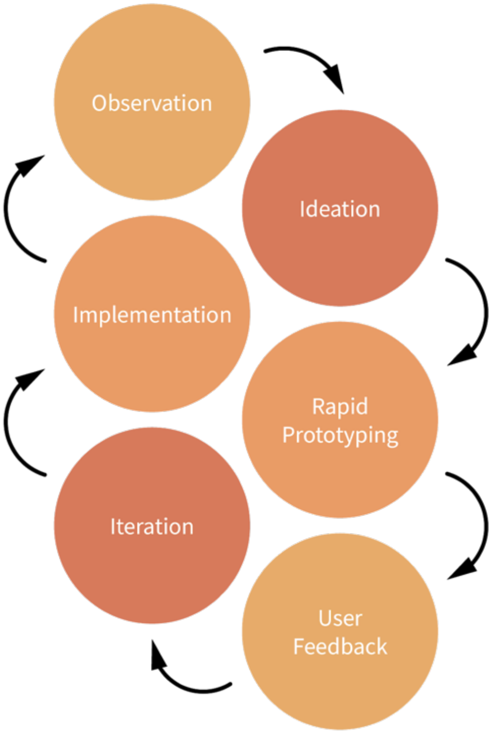

Figure 6. The design thinking process model.

HCD enforces broad thinking and, importantly, thinking about who the design is for. It can, however, be considered too human-centric when tackling systemic problems. If we put the human at the center, we often end up doing so *"at the expense of everything else"* [20], as it was simply stated by Johanna Fabrin. Certainly, the only way forward that ensures a good future for humanity is one that ensures the planet's wellbeing [20]. Thus, we need an approach that understands the complex system of interdependencies that inherently exist between society and the planet [20].

Being humane is characterised by compassion and empathy for not only humans but all living beings and the natural environment. To be sustainable is to be humane. This requires recognition that the wellbeing of humans, ecosystems and the common planet are all deeply interconnected. With this in mind, the HCD approach has been expanded to consider all living beings, to which we refer here as *life-centred design* (LCD), as illustrated in Fig 7.

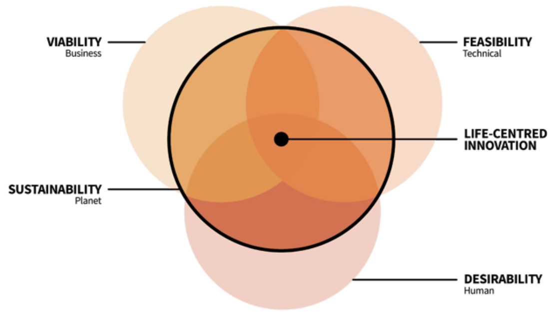

Figure 7. *A values-based life centred design approach goes beyond traditional HCD by considering the impact of design on the wider society and planet.*

2.3.1 Observation

The first phase of the LCD approach is to define the problem through observation. As previously outlined, because the problem of space debris is founded in uncertainty, especially for the future, the problem was defined in the desired future described in *Section 2.2.4.1*. However, since a well-framed problem is key to increasing the likelihood that the designed innovation will be more desirable, viable and feasible, the design-technique of asking 5 why questions was used to probe deeper. Here, it was recognised that there are two key challenges to achieving the desired future: current debris mitigation technologies like harpoon and net capturing systems, which incinerate debris at the end of the process [8], will not be sustainable in the desired future; and that there is a lack of global awareness about the problem of space debris.

2.3.2 Ideation

In the next phase of the LCD-approach, divergent thinking was employed for *ideation*. The purpose was to identify innovation that could potentially increase global incentive to tackle space debris. Tools involved in ideation included: brainstorming and mind maps; and prompting 'what if' questions to identify innovations at multiple scales. The outcome was a suite of conceptual ideas ranging from social approaches to increase awareness about the problem of space debris, to technological solutions to make debris mitigation circular.

2.3.3 Rapid Prototyping

'Rapid prototyping' is an important phase of the design-thinking process because prototypes are draft designs made tangible for evaluation with different stakeholders. It's worth noting that it is a challenge to prototype ideas that are set in a timeframe of 50 years from now. In order to help people understand the conceptual ideas, the format of advertisements was chosen as they are designed to stimulate peoples' thoughts and reactions. Fig. 8 shows the exploration of an early idea of making space debris a desirable product for the wider population.

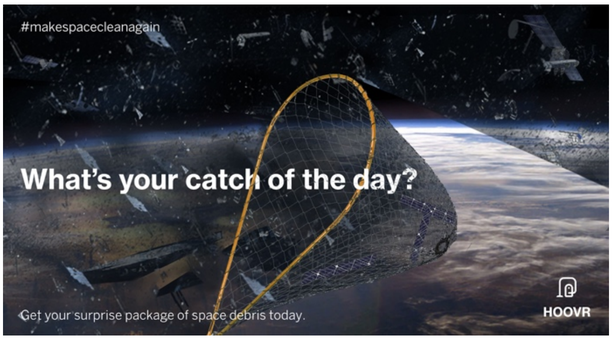

Figure 8. *Advertisement developed during the rapid prototyping stage visualising an early idea of space debris removal.*

2.3.4 Feedback

This was the most critical phase of the design process. Feedback was gathered from potential stakeholders ranging from regular people through to experts in the professional and academic fields of aerospace engineering, policy, sustainable consumption and manufacturing, material engineering, innovation and product design. The outcome was two key insights:

1. Like efforts to tackle climate change, raising awareness alone does not incentivise a call for global action. What drives action is if value can be found in tackling space debris for everyone. It's not a one-size-fits all innovation; rather a combination of innovations both upstream and downstream.

2. A key factor is missing when designing the closed-loop system, and that is human desirability. Similar to plastic clean up, there needs to be a reason for recycling space debris that goes beyond doing good for the planet and the people.

2.3.5 Iteration

Based on the feedback, the process was iterated, with the goal of obtaining a deeper understanding of the idea of a closed-loop debris removal system that creates human desire. Applying previously conducted techniques again, such as the *five whys,* allowed for a deeper understanding into what would compel humans to interact with recycled space debris. An insightful comparison was with that of ocean plastic, where material previously considered to be waste evolved to a sought after resource finding its way into the most diverse industries as demand by the wider population increased. Building personas and identifying the needs and desires of the potential end-users through storyboards, guided the ideation and design of the final elements of our system: objects of human desire that could be produced using our closed-loop conceptual framework.

2.3.6 Delivery

The final delivery focused on the validation and communication of the proposed concept. Various renderings, illustrations and sketches were created with the aim of communicating the outcome in a compelling, detailed and easily accessible way.

Finally, the concept was validated by the same group of experts and previous shortcomings were deemed solved. In collaboration with relevant stakeholders as well as the various space actors further iterations of this process would allow for continuous development and optimisation of the *Space Vulture* system.

3 PROPOSED INNOVATION: SPACE VULTURE

The outcome of adopting divergent-convergent modes of thinking in a double diamond process resulted in the *Space Vulture*, a conceptual design of a closed-loop system that captures space debris, recycling it into raw materials, which are then repurposed into humanly desired objects that deem of value for human psychological needs. As shown in Fig. 9, this section describes the phases of *Space Vulture*'s closed-loop active debris removal (ADR) mission, which consists of five phases: (1) launch and cruise, (2) capture, (3) onboard pulverisation, (4) material transport & maintenance, and (5) space recycling and manufacturing. It's worth emphasising that *Space Vulture* is a conceptual idea, which may not be technically feasible today, but is based on current and historic trends in scientific research, through which the feasibility of current technologies is projected 50 years into the future.

Metallic debris accounts for a large portion of artificial debris, with 44% of debris hitting the ISS composed of aluminium and 12% of steel [21]. Given rapid resource depletion on Earth, metallic space debris is an increasing, heretofore untapped source of valuable material in LEO [22] that could potentially be recycled and repurposed. Because of this, *Space Vulture* does not burn the captured debris in the Earth's atmosphere, instead feeding it into the inside of the chaser spacecraft where pulverisation technology grinds debris into fine powder.

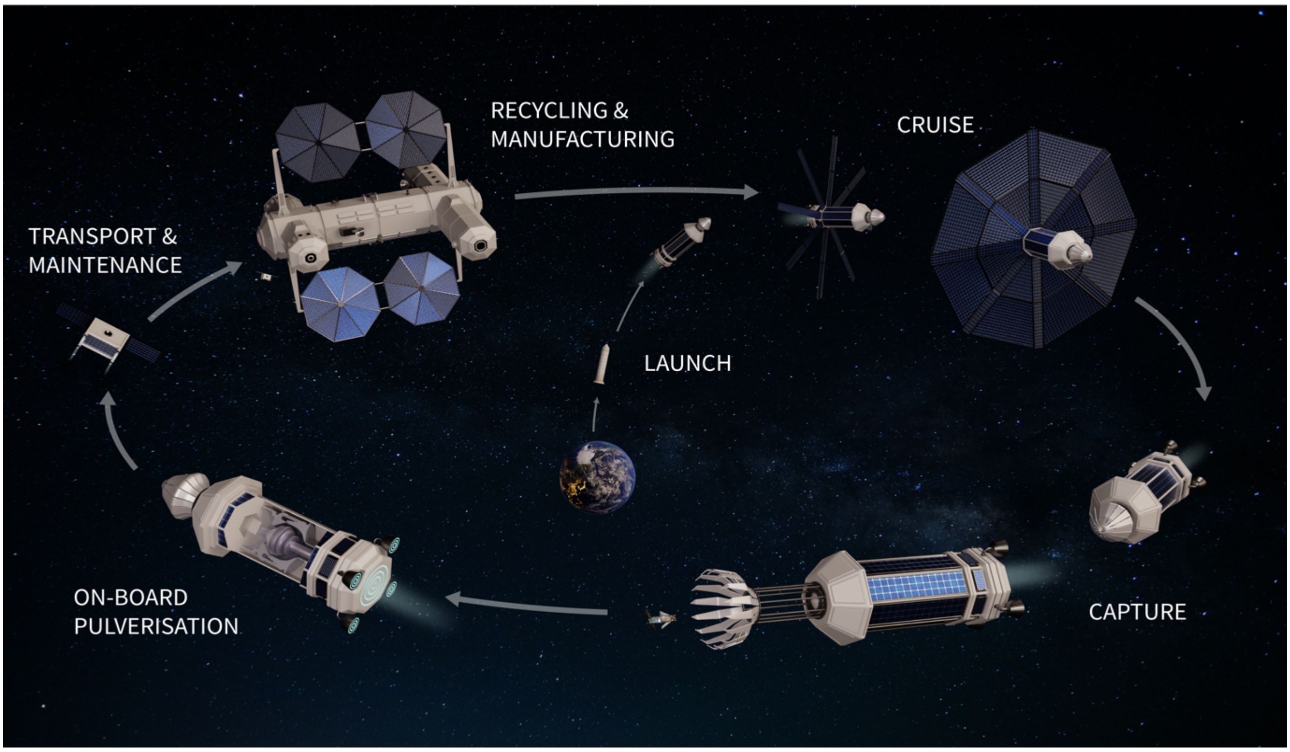

Figure 9. Overview of each mission phase of the Space Vulture system.

3.1 Phase 1: Launch and Cruise

The *Space Vulture* system comprises several chaser spacecraft scattered throughout LEO. The overhead cost of space launches is expected to dramatically decrease in the next fifty years for several reasons. Firstly, widespread adoption of *vehicle reuse* [23], first performed by SpaceX as a method to deploy *secondary payloads* aboard rockets that are already planned for launch [24]. This technique, which can be considered a ride share, is proposed for *Space Vulture* spacecraft, which will be launched into orbit as secondary payloads.

Current research suggests that similar strategies, with sustainability inherent at the core, in conjunction with increased space entrepreneurship, where more private companies might emerge in the sector, is likely to continue reducing the cost of space launches in the future [25]. In addition, the current trend towards adopting sustainability in the design process supports the system concept of *Space Vulture* as it is very likely that sustainability principles like reusability will be expanded to accommodate reuse of space debris.

Space Vulture's chaser spacecraft detaches from the launch vehicle upon entry in LEO and begins the long-term mission. A propulsion system is required for the spacecraft to continuously cruise, chase debris and manoeuvre captured debris into the main body of the spacecraft. Most importantly, *Space Vulture* spacecraft require a propulsion system that ensures long-term travel, either with a self-sustaining propulsion system or one that efficiently uses fuel thus requires little maintenance.

As shown in Fig. 10, a *solar electric propulsion* (SEP) system [26] was proposed. SEP is a non-chemical and has proved to be successful for various types of missions including near-Earth asteroid exploration [27] [28] and discovery-class missions [28]. The spacecraft has a foldable solar array that is used to power the SEP system [30]. High specific impulse characterises SEP, with fuel efficiency roughly ten times greater than those of chemical propulsion systems [31]. However, SEP systems operate at low power levels, which will be a challenge when the spacecraft chases and captures debris. Notwithstanding, there is ongoing research focused on increasing power levels of SEP [32].

While SEP is considered fuel efficient, it still requires a propellant in order to function, which suggests that on-orbit refueling systems need to be in place by 2070. Therein, propulsions systems that do not require a propellant were explored, namely *solar sails* and *nuclear fusion propulsion* (NFP).

Solar sails are typically used for deep space exploration because they are self-sustaining systems, which only require radiation pressure and momentum transfer to operate [26]. However, solar sails are deemed inadequate for *Space Vulture* due to challenges with acceleration and the mere size of the solar sails poses a large risk for debris collision [33].

NFP, on the other hand, has the potential to revolutionise space exploration by using nuclear to power vehicles. Unlike SEP, NFP is expected to generate high thrust with a high specific impulse [26, 34]. NFP is ideally the best option for *Space Vulture*, however, nuclear fusion is still in its infancy with a technology-readiness level (TRL) of 2 [35]. Given, however, current discourse regarding nuclear energy in conjunction with the uncertainties found in the problem of space debris, it is unclear whether NFP would exist in 2070. As such, SEP was chosen as the preferred propulsion system for *Space Vulture* chaser spacecraft. While it will have to rely on refuelling, on-orbit refuelling services are expected to exist in 2070 (see Section 3.5).

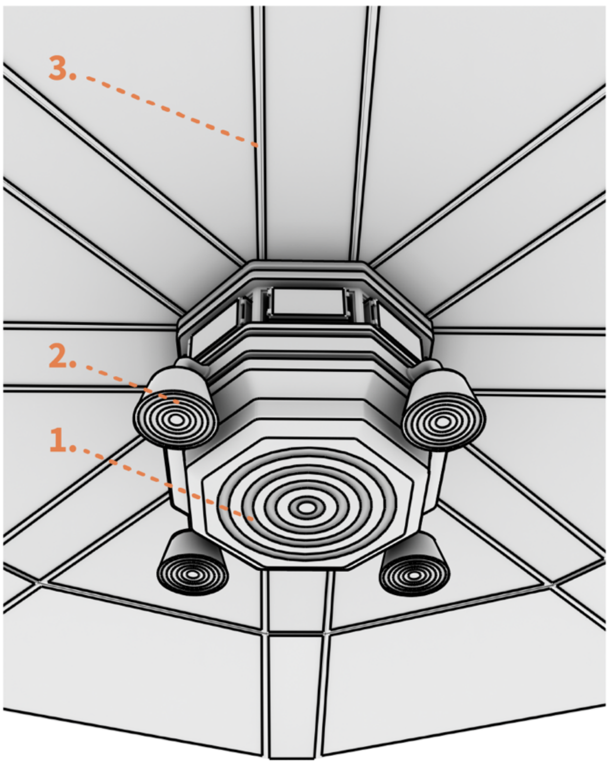

Figure 10. The Space Vulture chaser spacecraft is propelled by (1) a high-power solar electric propulsion system (2) that ensures controlled de-orbiting to capture debris. (3) An origami solar array is deployed to produce the electricity needed for solar electric propulsion.

3.2 Phase 2: Capture

Space Vulture's chaser spacecraft begins the long-term mission once placed LEO. Active debris removal (ADR) is performed, which is considered an effective remediation technique to permanently remove space debris from LEO [36]. There are three key steps for capturing debris: target, chase then capture.

According to ESA's Annual Space Environment Report 2020, there are currently 8782.5 tons of artificial objects in Earth's orbits [37]. Of the total, 2000 tons stem from 1,300 massive rocket bodies and defunct satellites [38]—equivalent to over 2,000,000 kg of mass [39]. These are among the most hazardous pieces of space debris as a potential collision is capable of generating more lethal fragments that can impact operational man-made objects [40]. From a materials perspective, recycling larger debris generates more raw materials to be used for manufacturing.

Current debris mitigation innovation has primarily focused on the physical removal of debris from LEO [8], and include nets [41], harpoons [42] [43], tethers [44] and laser [45]. Inspired by the *ClearSpace-1* satellite [46], *Space Vulture*'s capture mechanism, illustrated in Fig. 11, is a multi-arm robotics-based system that acts as a claw to capture debris larger than 10cm in diameter.

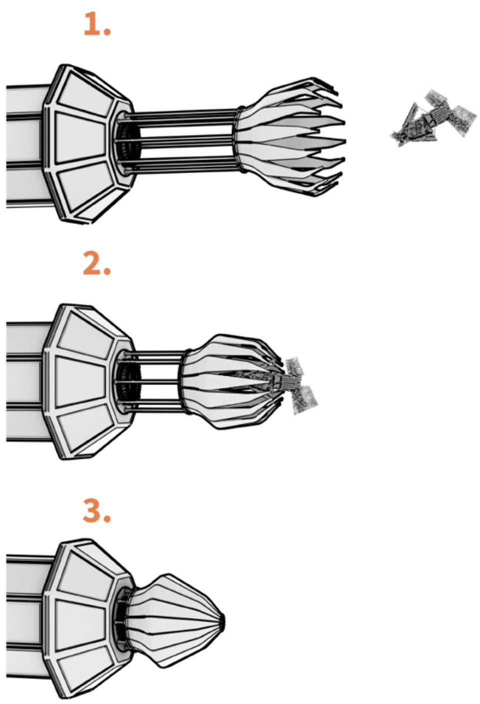

Figure 11. The multi-arm robotics-based system is designed to (1) target, (2) chase, and (3) capture debris.

Machine learning (ML) algorithms are increasingly used for object characterisation of *space resident objects* (SRO), which includes space debris [47]. Successful application of ML technologies in other areas of space exploration suggest it has the potential to be applied to debris tracking, with significant scope for intelligent, autonomous systems. More recently, the first data driven approach to classify space objects using real observational light curve data was developed [48]. Current methods are based on data capture on Earth (e.g. via telescope) but these advancements, if eventually combined with sensor technologies (e.g. laser ranging, infrared imagery) [48] pave the way for on-board real-time image detection systems, similar to ESA's *ClearSpace-1* on-board computer [49]. *ClearSpace-1* mission, planned for 2025, aims to implement a dedicated rendezvous payload computer system to address major ADR challenges, namely target tracking, proximity manoeuvre and capture.

After detection, the system has to achieve the right capture position by performing a set of orbital manoeuvres, a process that can also benefit from ML-based optimisation. Optical debris tracking techniques have been used for object positioning with improved accuracy with respect to other methods [50]. There are current approaches that suggest laser-induced thrust for this purpose as a good candidate in space debris removal operations [51].

However, when it comes to performing the manoeuvres, SEP poses a major challenge for acceleration and deceleration. Currently, a propulsion system that can accelerate the chaser spacecraft at varying speeds does not exist, but there is a need. Thus, in the future, it is likely that technical advancements in SEP and nuclear fusion propulsion will render it possible for the chaser spacecraft to effectively chase and capture targeted debris.

Today, ADR technologies that involve orbital robotics are considered relatively well-understood, since the technologies already exist; however, capture of large, non-cooperative objects is a highly challenging task, especially with a robotic mechanism [52]. Contactless ADR technologies are also currently under development, including laser systems [45]. These mechanisms might be better suited as they're not limited by debris size. Given today's pressing need for more advanced systems that can cope with uncooperative, tumbling objects, it is likely that these systems will be developed in the next 50 years. Therefore, the proposed capture mechanism of the *Space Vulture* system can be considered technically feasible in 2070 on the condition that future propellant systems provide adequate thrust.

3.3 Phase 3: Onboard Debris Pulverisation

As shown in Fig. 12, *Space Vulture* has been integrated with an onboard pulverisation mechanism that breaks down and subsequently crushes captured debris into fine particles ranging from 3µm - 45µm [53], which is the typical size required for additive manufacturing processes.

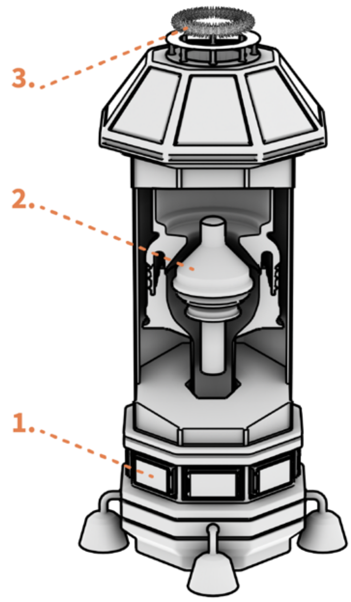

Figure 12. Pulverisation of collected space debris through (3) a rotating cutter head drill and (2) a cone crusher. The pulverised material is stored in (1) service vehicles connected to the chaser spacecraft.

Based on recent developments in asteroid mining technologies, captured debris is broken down into smaller pieces by a set of rotating cutter head drills, which was inspired by terrestrial hard rock processing [54]. *Space Vulture*'s robotic claw steers the small pieces of debris into the main body of the chaser spacecraft, in which the debris is pulverised into raw material composites of fine particles suitable for additive manufacturing.

The cone crusher is considered the most suitable for the *Space Vulture* system because the mechanism is capable of producing particles of various sizes due to its ability to adjust cone eccentricity [55]. As the final step, the raw material composite is collected and stored in *service vehicles* (see Section 3.4) fitted in the *Space Vulture*, ready to be transported to the *space recycling facilities* (SRF).

Pulverisation processes on Earth, like cryogenic grinding for example, operate at temperatures below freezing because it reduces tool wear significantly and causes the brittleness of materials to increase [55]. As such, all types of material including those with elastic and fibrous properties can be pulverised [57]. Given the freezing temperatures of LEO reaching levels around -120°C [58], pulverisation may be possible in space.

However, there are many challenges associated with pulverisation in space, especially on-board a spacecraft. The lack of gravity increases the risk of high-energy particles being generated during the pulverisation process. As such, safety measures must be in place to ensure the safe storage and collection of raw composite materials and to prevent any fine particles from escaping the spacecraft. Explosive batteries and propellant tanks may also pose a challenge, in addition to the potential corrosion caused by them. Therefore, systems must be in place that disarm debris before pulverisation takes place.

3.4 Phase 4: Transportation and Maintenance

The next phase of the *Space Vulture* system transports the raw material composites to the SRF. Inspired by CubeSats [59], *service vehicles* (Fig. 13) are used to interchangeably transport the raw material composites from the spacecraft to the SRF, and to transport fuel from on-orbit refuelling stations back to the chaser spacecraft. The advantages of service vehicles is the optimisation of space, weight and time for the spacecraft, in addition to making sure the spacecraft receives regular maintenance. However, there are several challenges that need to be addressed, which include determining the right ratio between *Space Vulture* spacecraft and refuelling stations; and making sure the service vehicles safely dock onto the chaser spacecraft without generating more debris and increasing collision risk.

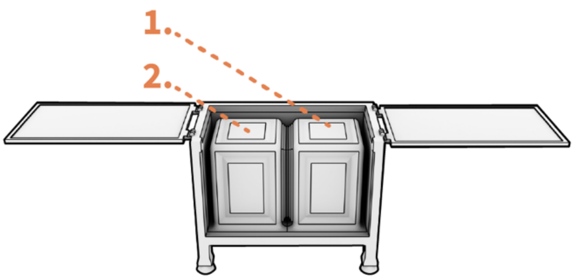

Figure 13. The service vehicles are designed to (1,2) store and transport either raw material composite or fuel.

Assemblage, maintenance and manufacturing of space infrastructure has currently been shifting away from on-Earth to on-orbit [60]. It is argued that such a shift could potentially reduce the costs of launch and transportation [61]. There are several private actors in this space including *Orbit Fab* attempting to create gas stations in space [62], *Astroscale* currently developing novel logistics systems for on-orbit manufacturing [63], and *Maxar* developing on-orbit assembly robotics [64].

On-orbit services, like those mentioned, are expected to provide significant economic value [61] [65] and have the potential to become commercially viable 15 years from now [61]. While current satellites were designed without maintenance in mind, the last few years have seen increased adoption of sustainability principles, like reusability, for the design and development of space technologies [60].

In the 2070 hypothetical future scenario, recycling facilities are expected to exist in space. Current advancements in on-orbit assembly suggest that there is potential for large infrastructure, like facilities, to be constructed directly in space [61], which suggests that the potential existence of *space recycling facilities* (SRF) is plausible.

3.5 Phase 5: Material Recycling and Manufacturing

The SRF of the *Space Vulture* system includes a material separation, analysis and an additive manufacturing facility as highlighted in Fig. 14. Additive manufacturing (AM) in space has been widely explored [66] [67] and several processes have already been tested in orbit [68]. In 2018, for example, the *International Space Station* (ISS) successfully attempted *liquid phase sintering* (LPS) [69], a sintering process for pulverised material composites to fabricate durable, net-shaped composites of any shape. Currently, LPS is a widely adopted AM process used across industries ranging from construction to automotive [70].

Given the rapid adoption of AM on Earth and the successful attempts in space, it is highly plausible that AM operations will be conducted in space in 2070. As such, the final phase of the *Space Vulture* system is the separation of the raw material composites into material types at the SRF. The separation process can be achieved using techniques like *electrostatic* (ES) or *magnetic* (MS), both of which are currently being explored for lunar and asteroid mining [71]. Successful experimentation [72] in recent years have proven ES to be a potentially viable technique for in-space material separation, especially *tribocharging* [73], which is considered to have the highest technology-readiness level (TRL) for separation in space.

Space Vulture's raw material composites may pose a challenge for separation because it's likely to be made up of many different material types. A terrestrial chemical analysis method called *Laser Raman Spectroscopy* (LRS) has been widely explored for space material analysis [74], and can be used in this instance to determine the exact material types found in the raw material composites. This analysis is also useful for manufacturing processes to be adapted accordingly.

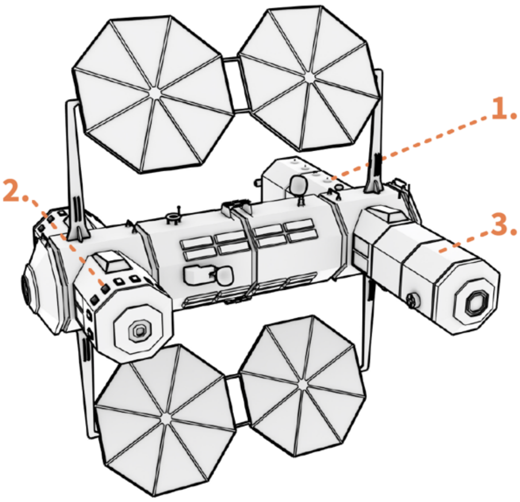

Figure 14. The Space Recycling Facility consists of a module to (2) separate the collected raw material composite, (1) conduct material analysis and (3) manufacture products on demand.

3.6 Creating Value Out of Waste

Finally, the retrieved and separated material composites are used in the SRF to produce a wide variety of products in space. A participatory co-design workshop was conducted, which involved the participation of 6 individuals ranging in age and profession. The purpose of the workshop was to identify humanly desirable objects that could potentially be manufactured from recycled space debris in 2070.

As illustrated in Fig. 16, three conceptual objects emerged from the workshop, each providing a service that could potentially increase life satisfaction and subjective well-being on a finite planet. These were envisioned to exist in a 2070 world of scarcity, where neither society nor the planet thrive.

According to Maslow [75], humans are "*perpetually wanting animals*". This prompted further exploration into what is needed, when basic needs are met, to increase life satisfaction and subjective well-being on a finite planet. As history has shown, people rarely consider what is enough or what is too much, but instead they have simply wanted more. This pursuit for short-term gains can be considered irresponsible if done without any concern for long-term consequences [76].

Human societies would have ideally transformed from consumerism to sustainability in 2070. For this to happen, a shift in values from materialism to *post-materialism*, where the latter describes a shift towards self-expression and quality of life [77], would ultimately require changes in thinking and behaviour [75]. According to Inglehart [78], a shift towards post-materialism is already happening today in Western societies, and is likely to improve subjective well-being. Also described by Maslow, it is a shift to social inclusion and needs of love, esteem and achievements [79]. This is illustrated in *Maslow's Hierarchy of Needs*, as shown in Fig. 15. Notwithstanding, in 2070, it is crucial that they are necessary for human survival on a finite planet.

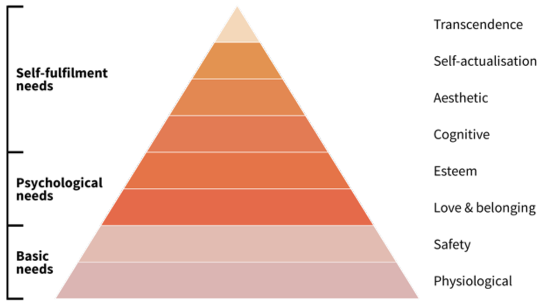

Figure 15. Maslow's Hierarchy of Needs [75], adapted from Balint & Pangaro [80] highlights the focus on psychological and self-fulfilment needs, with the exception of transcendence.

Interestingly, the history of humanity is, "*often marked, commemorated and announced by objects*" [81] as it is human nature to extend ourselves through objects [82]. This suggests that even in light of a shift towards post-materialism, it is likely that production of objects will continue in the indefinite future.

Figure 16. Proposed conceptual objects manufactured from recycled space debris that increase subjective well-being: the antenna, trenchcoat and a pair of holographic 3D glasses.

This became evident in the objects envisioned by participants of the co-design workshop. The *antenna* was proposed as a desirable object that increases social inclusion and meets the need of love and belonging. The rapid advancements in telecommunication is an indicator of the need for humans to communicate and connect, and this need is likely to prevail in the future. The *trenchcoat*, and more broadly fashion, was considered desirable for individuals as it is a medium for self-expression, and meets the need for aesthetics and self-actualisation. Since the beginning of human civilisation, fashion has empowered people to truly express themselves. Lastly, the pair of *holographic 3D glasses* was proposed as humanly desirable for meeting the need for esteem and cognition; and it does this by enabling easy access to all forms of knowledge ranging from education to entertainment.

4 DISCUSSION

In this paper, design thinking at a systems level was employed because the problem of space debris is considered *wicked*, as previously described, a term used to "*encompass highly complex issues, like climate change, which cannot be overcome through traditional solutions because the cause-and-effect relationships are often uncertain*" [83]. The multifaceted nature of space debris has led to many different problem views being considered viable, which has meant no definitive formulation of the problem space. This suggests that solutions are not necessarily true-or-false, but rather, good-or-bad [84]. As such, it requires a combination of both intuitive (i.e. divergent) and rational (i.e. convergent) thinking to establish a mindset that does not focus on finding the *correct problem view* or the *optimal solution* [84], but rather focuses on embracing needs that may arise from the problem. Accordingly, design thinking typically results in innovation that society either embraces or rejects. If embraced, it can catalyse large-scale social change.

The process begins by first framing the problem: "*Craft clarity [!]. Produce a coherent vision out of messy problems. Frame it in a way to inspire others and to fuel ideation.*" The problem of space debris is typically viewed in the near future. In this paper, however, it was framed in a hypothetical future scenario set in 2070. Foresight was attempted to frame the problem because it allowed us to be deterministic rather than opportunistic in our approach. In other words, it presented an opportunity to problem solve for a future we would like to see happen. Despite the prevalent notion that design is about creating new objects and artefacts; design is in fact an attempt to change current situations into preferred ones [85].

Space Vulture is a conceptual system, in which we have suggested piecewise design solutions for interconnected technical challenges to debris removal that were identified through research. However, it has not been presented as a feasible innovation, but instead, to highlight that the many inherent complexities require more holistic, integrated, non-linear strategies to deliver innovation. Thus, *Space Vulture* is an attempt to connect the dots using a process of design-thinking to associate seemingly disparate aspects of debris removal, to deliver creative yet rigorous innovation.

Over the last decade, the widely adopted human-centred design (HCD) approach to design thinking has come under fire for being too human-centric [86]. HCD has played a large role in creating modern society, but that has included forming a destructive and exploitative behaviour in humans towards Earth and its finite resources. Many argue that because the process of HCD is architected to focus solely on humans, by definition, it actively ignores many facets of a problem [87]. Thus, it is not architected to solve systemic problems that increasingly threaten modern society. Living in the Anthropocene, an era in which the future of civilisation is determined by human activities [75], there is increased recognition that the relationship between humans and the planet has to fundamentally change. In other words, it can no longer be a linear relationship, but rather it has to be recognised as a complex system of interdependencies [86]. For this reason, the process of design thinking set out in this paper takes a values-based life-centred design (LCD) approach, which goes beyond HCD by factoring in the wider impacts of design on society and the planet. LCD takes cognisance of the fact that humans can be considered a medium to integrate sustainability and the HCD process [85]. In doing so, we recognised that debris removal is not merely extraterrestrial housekeeping [88]; but instead, a challenge that requires fundamental changes to the way in which human relations with man-made objects, and the waste they generate, are currently perceived and dealt with. Herein, space debris was not considered merely waste, but instead perceived as valuable finite material that could potentially be reused to meet human needs without further degrading the natural environment. Accordingly, the *Space Vulture* system design demonstrates a move towards a circular economy production system in order to meet the needs of current and future generations.

As demonstrated in efforts to tackle ocean plastics, designing circular waste systems have proven to be effective at creating multi-scale incentive for a global audience to collectively take action. Ocean plastics have been recycled and reused in manufacturing to produce goods ranging from household items to clothing and accessories [89]. As is currently the case for debris removal, technological and managerial innovation originally dominated the ocean plastics space, which resulted in solutions-based approaches to plastic waste prevention and monitoring [90]. In recent years, however, values-based approaches to plastic waste transformation and collection spurred global action, most likely because such innovations operate at multiple scales and across multiple industries. Today, there are over 30 start-ups and small-medium enterprises (SMEs) that capture and recycle plastic waste, which is then used in manufacturing of goods [89]. The example of oceans plastic suggests a circular space waste system in 2070 is not farfetched. The example highlights the potential for society to change provided there are incentives.

5 CONCLUSION

Herein, this paper demonstrates a values-based life-centred design-thinking process for understanding and identifying multi-scale innovations to tackle wicked problems like space debris. It integrates a combination of divergent and convergent thinking tools, but rather than focusing solely on human needs, it is implemented at a systems level in order to embrace human needs without exploiting Earth. Modern society is plagued with wicked problems ranging from climate change to fighting for human rights. These problems demand critical analysis of the current reality, and reflection on the roots of the problem including consumerism and human-nature interdependencies. As is the underlying notion of this paper, the perception of the problem frames possible solutions. If, as is the case today, current thinking, systems and tools are considered satisfactory to tackle space debris, a blind eye is turned on the human dimension, namely behaviour, and the wickedness of the problems emerging from the disconnect between humans and the planet. In other words, the critical aspects of humanity, and the threat to life on Earth because of human activities, are largely ignored. In reality, however, humans play an important role in the process by which innovation happens. In future, therein, life-centred design-thinking at a systems level remains a flexible process that can evolve with the wicked problem, providing new angles to view the problem. The outcome will be multi-scale innovations that are technically feasible, economically viable, humanly desirable and inherently sustainable.

6 ACKNOWLEDGEMENTS

The authors would like to thank especially Dr. Tibor Balint and Dr. Chandramohan George for their continuous support and providing their expertise and technical guidance in the development. The authors would also thank the module leads of the XY module, Dr Marco Aurisicchio, Dr. Chandramohan George and Dr. Maria Jose Apud Bell as well as all tutors and guest speakers of the faculty of the Dyson School of Design Engineering at the Imperial College London and the School of Design at the Royal College of Art involved in the XY module.

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