DESIGN FOR X: ENABLING THE REUSE OF SPACE HARDWARE?

Weiss, Bernd Michael;
Öhrwall Rönnbäck, Anna;
Laufer, René;
Clauss, Margot

Luleå University of Technology

ABSTRACT

With a growing number of objects in space, the pressure to be sustainable and more efficient with resources is increasing. Driven by technological advancements, the reuse of space hardware becomes feasible and viable as alternative to spacecraft end-of-life disposal. Reuse of space hardware promises benefits in areas like mitigating space debris risks, cost reductions, and environmental sustainability on Earth and in space. However, challenges related to the space environment, like micro gravity, unknown changes due to radiation, and the energy requirements to perform maneuvers in space must be addressed in order to enable spacecraft reusability. Nonetheless, reuse of space hardware is an important objective related to long-term space exploration with implications on the human expansion into space. This paper investigates the requirements for reusability of spacecraft and if circular economy strategies can support implementing reusability for spacecraft. Based on the finding of expert interviews, it argues for design as a key enabler. It introduces design for X, design for circularity, and design for reusability, and explores how reusability of space hardware implies the need to include the space environment in design decisions.

Keywords: Spacecraft Design, Design for X (DfX), Circular economy, Sustainability, Spacecraft Reusability

Contact:
Weiss, Bernd Michael
Luleå University of Technology
Sweden
bernd.weiss@ltu.se

Cite this article: Weiss, B. M., Öhrwall Rönnbäck, A., Laufer, R., Clauss, M. (2023) 'Design for X: Enabling the Reuse of Space Hardware?', in *Proceedings of the International Conference on Engineering Design (ICED23),* Bordeaux, France, 24-28 July 2023. DOI:10.1017/pds.2023.126

1 INTRODUCTION

The rapid growing number of objects in Earth orbits is leading to environmental concerns related the space and Earth (Lawrence 2022; Miraux, 2021). Most satellites that are currently launched into space are planned to be disintegrated and burned up in Earth atmosphere by the end of their life cycle where long-term effects on the environment are still largely unknown. In addition, non-operational and non-functional spacecraft can case collisions with catastrophic outcomes like the Kessler Syndrome, where collisions between objects can cascade and generating more and more debris (Kessler, 2010). Actors in government, research, and industry alike, now look to mitigate the involved risks. Implementing circular economy principles can be seen as one path for risk mitigation and sustainability in space. The circular economy is a sustainable economic model and the attempt to integrate economic activity and environmental wellbeing, aiming to keep resources in use for as long as possible (EU Parliament, 2022; MacArthur, 2013, 2021; Murray, 2015). It is based on three core principles, reuse, repair, and recycle, with the goal to minimise waste and pollution, and to maximize the use of resources. In contrast, in a linear economy, resources are extracted from the Earth, turned into products, and then sold to consumers. Once the products are used, they are thrown away, typically with only some parts reused or recycled. Spacecraft are generally produced and used in a linear way and built with a one-mission purpose to be disposed, either burned up in Earth's atmosphere or placed in a disposal orbit (also: graveyard orbit, a specific orbit away from common orbits, where decommissioned spacecraft can be placed without posing harm to another spacecraft). The circular economy and circular principles have the potential to address challenges faced by linear products on Earth, such as environmental pollution and impact, societal and economic impact, or resource depletion on Earth (MacArthur, 2021). It is reasonable to assume that extending the circular economy to space, establishing a circular space economy, and applying the concepts to spacecraft and space hardware can have similar effects in space and in the space industry, potentially helping to reduce the impacts on the space environment and with becoming overall more resource efficient. The mentioned effects related to Earth during the production and operation of space mission related activities on Earth would apply additionally. Historically, circular principles, the Circular Economy, and a circularity perspective are focused on Earth and do not take space environment related challenges like micro gravity, limitations in collecting and processing materials, energy needs etc. into consideration. While it is assumed that circular principles like upgrade, repair, remanufacturing, and reuse of components can mostly be applied across industries on Earth, questions on the applicability to the spacecraft and space hardware remain largely unanswered. Several authors suggest that design can be a major driver behind the circular economy (MacArthur (2013, 2021); Waste360 (2021); Münster a al. (2022); Fleischmann (2018); Bocken et al. (2016); Andrews (2015); Sassanelli (2020); Dokter 2021). Diaz (2020) points out that it's not necessarily the designers and the design process itself, that are a major driver for the circular economy, as the primary decision regarding a product are made before the design stage (Diaz 2020). The aim of the paper is therefore to advance knowledge on design as enabler for reusability of spacecraft and how circular economy strategies can support the reusability of spacecraft. Expert interviews to collect preliminary insight in experts' thoughts on the benefits of spacecraft reusability are complemented with literature search for circular economy strategies. The underlying assumptions are that design has an impact on reusability and that design can support extending the circular economy to outer space.

2 THEORETICAL FRAME OF REFERENCE

The concepts of a circular economy and Design for X/Circularity are well documented in literature (MacArthur, 2013, 2021; Kirchherr, 2017; EU Parliament, 2022, Sassanelli, 2020, Suppipat, 2022, Salvador at al., 2021). However, research related to circular economy in space is limited and a large amount of literature focuses on the possible use of space debris and the refuelling of satellites (Leonard, Williams, 2023). Hence, general context and theoretical knowledge on circularity seems necessary (Weiss et al. 2021). We provide an introduction into spacecraft categories and an overview on circular economy principles, discuss the idea of a circular space economy and reusability in a space context, and close with the concept of Design for X/Circularity.

https://doi.org/10.1017/pds.2023.126 Published online by Cambridge University Press

2.1 spacecraft categorization

Chandra (2008) explains a spacecraft as "[…] a vehicle or device designed for travel or operation outside the Earth's atmosphere, whereas a satellite is an object that orbits the Earth, the moon, or another celestial body." Spacecraft are categorized in flyby, orbiter, atmospheric, lander, rover, penetrator, observatory, and communications spacecraft (NASA, 2003). For this research, spacecraft is used equally to describe satellites in any Earth orbit, a space station, or rovers, satellites, or other space hardware like the Hubble space telescope or rovers on Mars.

2.2 Circular economy principles

The guiding principles of a circular economy have the intention to maximise resource use and to limit resource waste (MacArthur, 2021; Blomsma and Brennan, 2017). While resource efficiency and waste reduction are intended results for a circular economy, it is still about the economy (Webster, 2021, Hina 2021). Webster (2021) argues that a circular economy cannot deliver *"ready-made"* solutions that *"wrong-headed material recovery"* recycling advocates supports. The inherent issues stemming from a new perspective and system change needs to be investigated further, however, this paper limits its view on the economy-view and follows Websters call for more interdisciplinary work related to the circular economy (Webster, 2021). An indicator that is pointing to the broadness of the circular economy can be found in the research of Kirchherr (2017). Kirchherr (2017) found 114 definitions of a circular economy and used them to create the 9-R Framework (Figure 1). While the sub-strategies are more in detail, the core principles align with the 3 core circular economy principles, reduce, reuse, recycle, as presented in MacArthur (2021).

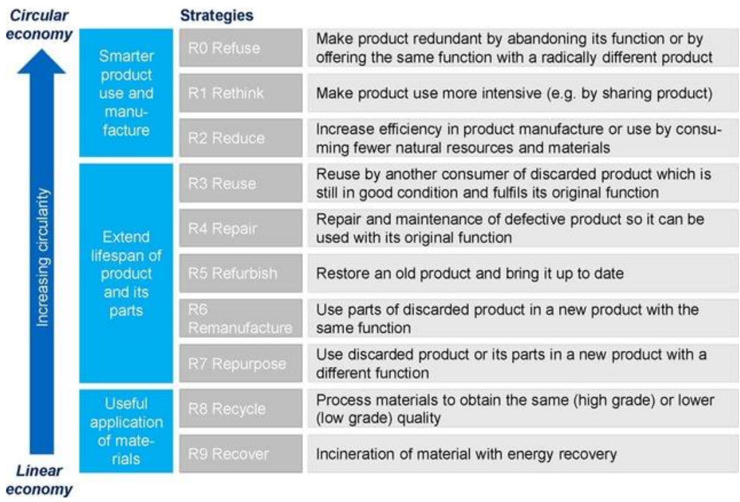

Figure 1. Kirchherr (2017).

One general reason to implement reusability and driver for the reuse of components or materials is economic benefits, which can be supported by continuous innovation of products and the production process. Babbitt at al. (2016) notes the need to continuously innovate and decuple economic growth from resource use as a clear difference between the circular and linear economy. In a circular economy, the whole life cycle perspective needs to be considered and with this, an end-of-life strategy. To be able to reuse them, spacecraft need to be designed to support their collection and the processing. This is especially for smaller spacecraft complicated and financially not feasible with current technologies. Due to rapid changing technologies, circular products can be optimized towards efficient use of materials and effective production processes. Implementing circular economy principles adhere the adaption of holistic innovation management, supporting constant change and optimization. In principle, the circular economy promises to help solving some of the most pressing issues in our time. However, Anastas (2020) points out that any problem statement needs to be designed and implemented wisely and "a half-designed circular economy would be, yet another example of good intentions gone awry." The mentioned problem statements help to find appropriate approaches for the implementation of circular material flows in products but can also be applied to innovation management.

https://doi.org/10.1017/pds.2023.126 Published online by Cambridge University Press

2.3 Circular space economy

The circular space economy can be understood as an extension of the circular economy concept but applied specifically to space exploration and development. The concept of a circular space economy gains traction as technology advancements and lower launch cost leading to increasing amount of objects in space. It aims to promote sustainable space exploration and development by minimizing waste and maximizing the use of resources in space. This involves strategies such as developing closed-loop systems, using in-situ resource utilization to extract and utilize resources from other celestial bodies, and designing spacecraft and habitats for disassembly and reuse. There are several reasons why the circular economy should be extended into space, like the need for an efficient use of resources, environmental protection, economic benefits, and human expansion and settlements. Overall, extending the circular economy to space, or creating a separate circular space economy, can help to promote sustainability, protect the environment in space and on Earth, and can support economic growth. It also promises to be an approach for a sustainable and resilient future in space and on Earth.

2.4 Reusability in a space context

Reusability of space hardware is still limited and mostly theoretical. This is due to missing technologies for capture and manipulation of spacecraft in orbit. Reusability, spacecraft reusability, and reuse of space hardware refers generally to the reuse of all robotic spacecraft as defined by Chandra (2008). The space industry is still considered an emerging industry and must develop fundamental technologies and procedures. Hence, reuse applies mostly to space transportation systems like rockets, modules for the space station, and capsules for cargo or human transportation, like the Lunar Lander example in de Freitas (2021) and the reusable rockets of SpaceX, Isar Aerospace, Rocket Factory etc. The progress and technological advancements of the last 5-10 years is increasing the hopes for new options to become feasible, like the refuelling of spacecraft. However, due to the high launch cost per kilogram, these options are considered only economical for large (mostly communication) satellites, typically in geo-orbits. The technology needed to be able to reuse of space hardware in lower orbits or even to reuse or remanufacture the components of spacecraft is still in its infancy and won't be broadly available in the coming years. The two concepts, first, spacecraft reusability, refers to any spacecraft to be designed to be reused. Second, reuse of space hardware, refers to reusing any component or the materials of spacecraft. For this research, both concepts are used together as both imply the applicability of the second circular economy principle, reuse, and the five strategies R3-R7 (Figure 1). The goal is to enable an automated extension or adjustment of spacecraft objectives or missions, as human service missions are limited with current available technology (Daxer 2021).

2.5 Design for X, design for circularity, circular design

Design for X (DfX) is a product design approach that is incorporating a range of disciplines with a focus on the entire product life cycle. Gatenby (1990) described the X, as "manufacturability, install ability, reliability, safety, serviceability, and other downstream considerations beyond performance and functionality." DfX is a holistic approach that considers a variety of the product aspects, from design, development, production, maintenance to its disposal (Sassanelli, 2020). DfX is an iterative process that involves continual improvement and refinement of the design to ensure that the product meets the needs of the customer. It is based on the premise, to include design from the start of the product development and to address the needs of all stakeholders, such as the customer, the manufacturer, the environment, the user, and the society. Design for Circularity (DfC) is a product development approach that seeks to minimize the use of resources and maximize the value of a product throughout its entire life cycle (Berwald 2021). This approach encourages designers to think beyond just the initial phases of a product's life and to consider the resources used to create, use, repair, repurpose, and ultimately recycle the product (Suppipat, 2022). DfC encourages the use of renewable materials, efficient manufacturing processes, intentional design for reuse and disassembly, and to design for repairability and upgradability (EEA 2017). In addition, research related to circular design and design for product life extension can be found in Moreno (2016). Moreno (2016) identifies key circular design strategies and mapped them out against circular business model archetypes. Knowing the relationships *"[...] between design strategies and multiple business models is imperative to make the transition from a linear economy of take-make-dispose to a circular one."* (Moreno, 2016).

https://doi.org/10.1017/pds.2023.126 Published online by Cambridge University Press

3 RESEARCH METHOD

This paper presents the results of interviews that were carried out with experts related to spacecraft design and space missions. The rational was to gather state-of-practice knowledge related to reusability of spacecraft. Specifically: categorization of reusable parts of spacecraft, the benefits, perceived barriers and how reusability can be achieved in future spacecraft. Therefore, a semi structured interview guide was developed, covering these areas. Six senior level experts were selected based on their background and expertise related to reuse of materials, in-situ resource utilization, space sustainability, and their general knowledge on the space industry. When possible, interviews were recorded and stored for later analysis. The appendix provides an overview on the participants, their background and main area as well as their take on the obstacles and benefits of reuse of space hardware. A table with the interview questions and information on the experts can be found in the appendix. Even though we refer to circular economy in this paper, it should be noted that we did not consider all strategies, concepts, or perspectives of a Circular Economy in the interview, like Life Cycle Analysis or an environmental perspective. The interviews made it clear that design and an economic perspective are the first dimensions to be addressed.

4 FINDINGS

Following chapter, we provide the key findings from the analysis of the interviews. Understanding, and reusing, materials or components depends on the background and discipline the interviewed expert operates in. So can components be seen as components, but also as a foundation for additive manufacturing feedstock. The question regarding benefits of reusing spacecraft, little discrepancy was found. All experts saw value and clear benefits not only related to resource efficiency but moreover in the implications for future space missions, like cost saving, innovation drivers, and time saving.

4.1 Components, materials, units, categorizing reusable spacecraft parts

Depending on the position and background of the interviewed expert, differences in understanding units, components, and materials were visible. The granularity in detail was higher for the expert 2 while expert 1 did not directly differentiate parts as challenges were seen in melting and sorting of materials. Having different terms and using top-level categories can help connecting possible options for reuse. For this paper, we found to use parts, a component with multiple sub-components, a components, and materials in components, that can be reused.

Table 1. Sup-categories of spacecraft; units, components, and materials

Sub-Category	Main Purpose	How to Reuse?
Unit	Multiple components together, in one functional unit.	Exchange with upgraded units (e.g., within a modular system); options to disassemble of components needed.
Components	Functional parts of a unit.	Exchange of full components, upgrade, remanufacture.
Materials	Materials in components.	Melting as new materials for additive manufacturing and to create new components or parts. Reuse (recover) rare-earth materials as a positive side effect.
Waste	None	Recycling.

4.2 Benefits for reuse of space hardware

Without measurable benefits, reusing space hardware will not work. We do not categorize the benefits for this research and refer to all areas jointly: economic, environmental. monetary, technical, and procedural alike. All experts saw a major benefit in cost reductions that are a result in less weight to be launched and therefore less fuel. Environmental aspects were mentioned, however, as research on the impact of rocket launches is limited, this research did not consider it. The implication, of course, is that all technologies to capture, process, and reuse (refurbish, repair, upgrade) of spacecraft is available. All participants agreed, that designing spacecraft with a view on reusability is critical and a first step to develop reusable spacecraft. Like other industries, this change can lead to cost reductions in the development phase and using the same components can lower the overall cost for development

https://doi.org/10.1017/pds.2023.126 Published online by Cambridge University Press

of spacecraft and can even support with the recovering of rare-earth elements (Babbit et al., 2021). Similar to other industries on Earth, the ability to upgrade products can lead to significant reductions in cost and optimized production (Zikopoulos, 2022). In their findings on the viability of a circular economy for space debris, Leonard and Williams (2023) presented a novel report model on the monetary value of space debris. They developed "reuse" and "scrap material" scenarios to estimate valuations of the payloads (Leonard, Williams, 2023). To conclude, there are benefits of reuse of space hardware however, with the technology to capture, process the components and materials in its infancy, the economics are limiting factor.

4.3 Single mission objective spacecraft

Historically, spacecrafts are being designed for a single mission objective or purpose. The findings were not conclusive. Components are specifically built and integrated into a spacecraft, either a single or even in constellation settings. The interviews did not go into detail regarding this question, findings show, however, more research related to repurposing spacecraft is needed.

4.4 Product assembly and disassembly

A common point is the obligatory need and ability to disassemble and (re-)assemble spacecraft. As Boothroyd (1992) argues, there are enormous benefits if implementing design for assembly and disassembly at early stages of design phases. Adding the option to disassemble a spacecraft is a basic requirement to for the reuse principle. Without the technology to perform a disassembling task, there is no need for spacecraft be designed for disassembly. With the repair and service missions to the Hubble Space Telescope, technically, the first human-based, in-space disassembly and assembly mission has been performed. The interview finding is a suggestion to consider not only the ability to assemble and disassemble a spacecraft, but also to design components, units accordingly.

4.5 The path to design for spacecraft reuse

The main finding of the interviews was the apparent need to design spacecraft to be reusable and to implement DfC strategies is suggested as first step towards spacecraft reusability. However, design concepts like DfX, DfC, Design for Assembly (DfA), etc. are fundamental design concepts that are enable circular material flows on Earth. They do not, however, take the implication due to the space environment into considerations.

Table 2. The path to design for spacecraft reuse, based on Boyaci (2016), Gatenby (1990), Sassanelli (2020), Suppipat (2022), verified through interviews.

	Design for Circularity	**Design for Reusability**	**Design for Spacecraft Reuse**
Aim	Minimize the use of resources, maximize the value of a product, sustainability, lower cost.	Maximum potential of product, lower cost, sustainability.	Maximum potential of the product with extended use of components, and minimum use of resources. Recovering of rare-earth materials, long term cost and system reliability.
Perspective	Multiple life cycles, resource focus.	Entire life cycle, product focus.	Circularity and multiple life cycles with possible changes of mission objectives.
Tools	Life cycle and used resources (materials) knowledge.	Material and component changes over time.	Detailed knowledge of materials used and understanding of their features at any given time, spacecraft blueprint with detailed components, including their sub-components, materials.
Special Consider-ations	Repairability, Assembly, Disassembly. Integrating components in different products to extend lifetime.	Obsolescence, Trade-off reuse vs. remanufacture. Diss/assembly of products and components. System vs function reliability.	Space environment, complicated logistics, energy needs, distances, systems vs component reliability, business models. Sustainability for space activities (Chanoine, 2015),

Table 2 provides the background on the novel concept that combines the general premise of DfX, like the DfC and the Design for Reusability (DfR) and adds another perspective for the space environment to it: Design for Spacecraft Reuse (DfSR). The novel concept is based on the interviews and supported by a literature search related to DfX. The goal is to encourage designers (and design-decision makers) to actively consider all requirements and design adjustments for reusability, that are implied by the space environment, e.g., lower gravity, radiation, space debris, temperatures, vibrations during launch, energy needs, and end of life scenarios. The authors suggest DfSR as required step towards in-space reusability of spacecraft. Depending on the spacecraft location and type, DfSR would suggest adding design elements for diss/assembly, repairability, re-manufacturability, upgradeability, or optimizing the life cycle of a component and spacecraft. Reusing spacecraft and maximizing the time-in-use of space hardware can ensure maximum potential of materials, in the best case and with adjusting or changing space mission objectives and spacecraft repurposing, over multiple life cycles. With an intentional focus on designing reusable spacecraft, energy and resources can be saved, as well as overall mission risks and total cost reduced.

5 DISCUSSION

The aim of the paper was to advance knowledge on how design impacts reusability of spacecraft and how circular economy strategies can support reusability of spacecraft. A main finding is that spacecraft are not yet designed to be reused. One reason seems that the technology to reuse spacecraft components and materials is not available. Some of the newer spacecraft have refuelling capabilities, but standards for docking, capture manoeuvres and ultimately to perform reuse operations are not commercially available. In addition, ownership and liability questions related to the capturing of spacecraft, especially considering risks during docking are widely unanswered. However, as our research is focussed on reuse of components and it is reasonable to assume that, if spacecraft are designed to be reusable and once the technology is available to process components in space, even the production of missing parts in space, can add significantly more value to the spacecraft value chain. The proposed novel concept of Design for Space Reuse can support the extension of the circular economy to space. With this increase of total value and possible profit of reusing spacecraft components and materials, trade-offs calculations related to refuelling old spacecraft vs. launching newer with upgrades, vs. individual performing upgrade missions in-orbit can be overworked. In addition, de Freitas Bart (2021) argued for the trade-off to not implement reusability based on the amount expected missions, with the option to implement hybrid reusability if more missions are added at a later stage. This trade-off might then be partially or totally obsolete. Koch (2021) presented a business case and compared the prices to transport 100 tonnes of aluminium into space vs. using space debris. The results are promising and show enormous cost saving potential. Our interview findings pointed out three significant challenges that must be overcome: First, spacecraft are typically built with a specific mission concept. Changing a mission objective after a first one is achieved, can have significant increased value on spacecraft total return on invest. One interviewed expert suggested switching between missions, like having a foldable seat row in a car to transport goods or to have more seats for passengers. Second, knowledge and technology for assembly and disassembly of spacecraft in space are limited. Spacecraft are typically built manually and by humans on Earth and are not intended to be disassembled otherwise. The Hubble space telescope can be a case for the possibility to upgraded and change parts, but the majority of spacecraft are not built to be reusable. One possible explanation is that the disposal of spacecraft is leading to early design decisions that make it impossible, or very hard, to add the option for reusability. Third, even if capturing a spacecraft and automated disassembling and reassembling are possible, the reuse-related knowledge about material degradation, which components that can be reused, exchanged, upgraded, etc is not available yet. Similarly, guidelines and standards regarding the re-certification of reused parts or materials is in early stages, however, NASA (2016) introduced methods to catalogue materials characterizations and approved parts for in-space manufacturing and utilization. Like this, a catalogue for used (and certified) components will be needed towards fully reusable spacecraft. The findings of this research presented DfX as an approach to implement reusability in spacecraft and suggests the novel DfSR to extend Earth-based design concepts with space environment related considerations.

6 CONCLUSION AND FUTURE RESEARCH

The findings suggest that spacecraft design changes are needed for the reusability of spacecraft in-space and introduced Design for Spacecraft Reuse (DfSR) as a novel approach to address challenges and requirements based on the space environment within the design of spacecraft. Consequently, future research analysing strategies to overcome barriers for circularity and approaches to extend the circular economy to space is needed. Knowing how other industries implement full or partial circular material flows and the circular economy principles can result in reduced time for knowledge transfer into the space industry. In addition, the impact of spacecraft reusability on the financial performance and environmental impact within a circular economy on Earth and in a circular space economy need to be investigated and verified. Finally, the Design for Spacecraft Reuse is a first step, but needs to be further developed and tested against other DfX concepts in the context of circular economy principles, in space and on Earth.

ACKNOWLEDGMENTS

This research is a part of the Creaternity Space Lab at Luleå University of Technology (LTU) and RIT2021+. The idea and concept for Design for Space Reuse is a result of interview conversations between Bernd M Weiss and E1 and E2. The authors want to acknowledge the participants of the interview for their support.

REFERENCES

Andrews, D. (2015). The circular economy, design thinking and education for sustainability. Local Economy, 30(3), 305–315. https://doi.org/10.1177/0269094215578226.

Anastas, P. T. (2020). Circularity. What's the Problem? ACS Sustainable Chemistry & Engineering 2020 8 (35), 13111-13111. https://doi.org/10.1021/acssuschemeng.0c05714.

Babbitt, C. W., Althaf, S., Cruz Rios, F., Bilec, M. M., and Graedel, T. E. (2021). The role of design in circular economy solutions for critical materials, One Earth, Volume 4, Issue 3, 2021, Pages 353-362, ISSN 2590-3322, https://doi.org/10.1016/j.oneear.2021.02.014.

Berwald, A, Dimitrova, G, Feenstra, T, Onnekink, J, Peters, H, Vyncke, G. and Ragaert, K. (2021). Design for Circularity Guidelines for the EEE Sector. Sustainability. 2021; 13(7):3923. https://doi.org/10.3390/su13073923

Bocken, N.M.P., de Pauw, I., Bakker, C. and van der Grinten, B. (2016). Product design and business model strategies for a circular economy. Industrial Product. Eng. 33, 308–320. https://doi.org/10.1080/21681015.2016.1172124.

Blomsma, F. and Brennan, G. (2017), The Emergence of Circular Economy: A New Framing Around Prolonging Resource Productivity. Journal of Industrial Ecology, 21: 603-614. https://doi.org/10.1111/jiec.12603.

Boothroyd, G. and Alting, L. (1992). Design for Assembly and Disassembly. CIRP Annals, 41, 625-636. https://doi.org/10.1016/S0007-8506%2807%2963249-1.

Boyaci, T., Verter, V. and Galbreth, M. (2016). Design for Reusability and Product Reuse Under Radical Innovation (March 18, 2016). ESMT Working Paper No. 16-02, Available at SSRN: https://ssrn.com/abstract=2752343 or http://dx.doi.org/10.2139/ssrn.2752343.

Chanoine 2015 Integrating sustainability in the design of space activities- development of eco-design tools for space projects.

Chandra, Q&A: General Astronomy and Space Science, 2008. Via https://chandra.harvard.edu/resources/faq/astrophysics/astrophysics-19.html.

Daxer A., Domagala R., Hämäläinen I., Schelin M. and Zhang J. (2019). Human services mission to GEO satellites - Red Team - Spacecraft Design, 2019. RED TEAM - SPACECRAFT DESIGN GROUP REPORT, via https://www.kth.se/polopoly_fs/1.1022420.1603372299!/SpacecraftDesign_RedTeam.pdf.

de Freitas Bart, R. and Hoffman, J. (2021). Reusability Analysis for Lunar Landers, 2021 IEEE Aerospace Conference (50100), 2021, pp. 1-10, https://dx.doi.org/10.1109/AERO50100.2021.9438228.

Diaz, A., Schöggl, J-P., Reyes, T. and Baumgartner, R. J. (2021). Sustainable product development in a circular economy: Implications for products, actors, decision-making support and lifecycle information management, Sustainable Production and Consumption, Volume 26, 2021, Pages 1031-1045, ISSN 2352-5509, https://doi.org/10.1016/j.spc.2020.12.044.

Dokter, G., Thuvander, L., and Rahe, U. (2021). How circular is current design practice? Investigating perspectives across industrial design and architecture in the transition towards a circular economy. Sustain. Prod. Consum. 26, 692–708. https://doi.org/ 10.1016/j.spc.2020.12.032.

EEA (2017), Circular by design Products in the circular economy, 2017 European Environment Agency. ISSN 1977-8449.

Ellen MacArthur Foundation (2013). Towards the circular economy. Economic and business rationale for an accelerated transition. https://www.ellenmacarthurfoundation.org/assets/downloads/publications/Ellen-MacArthur-Foundation-Towards-the-Circular-Economy-vol.1.pdf

Ellen MacArthur Foundation (2021). Circular economy introduction, Ellen MacArthur Foundation. Via https://ellenmacarthurfoundation.org/topics/circular-economy-introduction/overview.

EU Parliament (2022). Circular economy: definition, importance and benefits. [online] European Parliament. Via: https://www.europarl.europa.eu/news/en/headlines/economy/20151201STO05603/circular-economy-definition-importance-and-benefits.

Fleischmann, K. (2018). “Design Evolution and Innovation for Tropical Liveable Cities: Towards A Circular Economy”, eTropic: electronic journal of studies in the Tropics, 17(1). https://doi.org/10.25120/etropic.17.1.2018.3642.

Gatenby, D.A., and Foo, G. (1990). Design for X (DFX): Key to competitive, profitable products. AT&T Technical Journal, 69, 2-13.

Hina, M., Chauhan, C., Kaur, P., Kraus, S. and Dhir, A. (2022). Drivers and barriers of circular economy business models: Where we are now, and where we are heading, 2022. Journal of Cleaner Production, Volume 333, 2022, 130049, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.130049.

Kessler, D., Nicholas, L. J., Liou, J.-C. and Matney, M. (2010). "The Kessler Syndrome: Implications to Future Space Operations", 2010. Presented at the 33rd Annual AAS Guidance and Control Conference, Paper AAS 10-016, Breckenridge, CO, February 6-10, 2010. To be published in Volume 137 of Advances in the Astronautical Sciences, pp 47-61.

Kirchherr, J., Reike, D. and Hekkert, M. (2017), Conceptualizing the Circular Economy: An Analysis of 114 Definitions (September 15, 2017). Available at SSRN: https://ssrn.com/abstract=3037579 or http://dx.doi.org/10.2139/ssrn.3037579

Koch, F. (2021), Orbital Recycling, A BUSINESS CASE FOR SPACE DEBRIS EXECUTIVE SUMMARY, ESA, Orbital Recycling 2021.

Lawrence, A., Rawls, M.L., Jah, M. et al. (2022). The case for space environmentalism. Nat Astron 6, 428–435 (2022). https://doi.org/10.1038/s41550-022-01655-6

Leonard, R. and Williams, I. D., 2023. Viability of a circular economy for space debris, Waste Management, Volume 155, 2023, Pages 19-28, ISSN 0956-053X, https://doi.org/10.1016/j.wasman.2022.10.024.

McDonough, W., and Braungart, M. (2002). Cradle to cradle: Remaking the way we make things. New York: North Point.

Miraux, L. (2021). Environmental limits to the space sector's growth, Science of The Total Environment, Volume 806, Part 4, 2022, 150862, ISSN 0048-9697, https://doi.org/10.1016/j.scitotenv.2021.150862.

Münster, M.B., Sönnichsen, S.D. and Clement, J. (2022), Retail design in the transition to circular economy: A study of barriers and drivers, Journal of Cleaner Production, Volume 362, 2022, 132310, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2022.132310.

Moreno, M., De los Rios, C., Rowe, Z. and Charnley, F. (2016). A conceptual framework for circular design. Sustainability 8. https://doi.org/10.3390/su8090937.

Murray, A., Skene, K. and Haynes, K. (2017). The Circular Economy: An Interdisciplinary Exploration of the Concept and Application in a Global Context. J Bus Ethics 140, 369–380 (2017). https://doi-org.proxy.lib.ltu.se/10.1007/s10551-015-2693-2

NASA (2003), Spacecraft classification, (2003). Via https://www.nasa.gov/audience/forstudents/postsecondary/features/F_Spacecraft_Classification.html.

NASA (2016). NASA’s In Space Manufacturing Initiative and Additive Manufacturing Development and Quality Standards Approach for Rocket Engine Space Flight Hardware, Additive Manufacturing for Defense and Aerospace 2016 Summit March 29-30, 2016, London, United Kingdom, via: https://ntrs.nasa.gov/api/citations/20160004218/downloads/20160004218.pdf.

Sassanelli, C., Urbinati, A., Rosa, P., Chiaroni, D. and Terzi, S. (2020). Addressing circular economy through design for X approaches: A systematic literature review, Computers in Industry, Volume 120, 2020, 103245, ISSN 0166-3615, https://doi.org/10.1016/j.compind.2020.103245.

Suppipat, S. and Hu A. H., (2022). A scoping review of design for circularity in the electrical and electronics industry, Resources, Conservation & Recycling Advances, Volume 13, 2022, 200064, ISSN 2667-3789, https://doi.org/10.1016/j.rcradv.2022.200064.

Salvador, R., Barros, M. V., Freire, F., Halog, A., Piekarski, C. M. and De Francisco, A. C. (2021). Circular economy strategies on business modelling: Identifying the greatest influences, 2021. Journal of Cleaner Production, Volume 299, 2021, 126918, ISSN 0959-6526, https://doi.org/10.1016/j.jclepro.2021.126918.

Umeda, Y., Kondoh, S. and Sugino, T. (2005). PROPOSAL OF “MARGINAL REUSE RATE” FOR EVALUATING REUSABILITY OF PRODUCTS, DS 35: Proceedings ICED 05, the 15th International Conference on Engineering Design, Melbourne, Australia, 15.-18.08.2005, 385-386 (exec. Summ.), full paper no. DS35_247.81.

Waste360 (created: 10-02-2021). Designing through the Lens of Circularity. [online] Informa PLC. Available at: (https://www.waste360.com/sustainability/designing-through-lens-circularity) (Nov/20/2022).

Webster, K. (2021). A Circular Economy Is About the Economy. Circ.Econ.Sust. 1, 115–126 (2021). https://doi.org/10.1007/s43615-021-00034-z

Weiss, B. M., Clauss, M., Rönnbäck Öhrwall, A., Laufer, R. and Losch, A. (2022). Creaternity Space: In Search of Circularity for Reuse of Spacecraft Materials. IAC 2022 Congress Proceedings, 73rd International Astronautical Congress (IAC), Paris, France. Presented at the 73rd International Astronautical Congress

(IAC), Paris, France, September 18-22, 2022. Retrieved from http://urn.kb.se/resolve?urn=urn:nbn:se:ltu:diva-93493

Zikopoulos, C. (2022). On the effect of upgradable products design on circular economy, 2022. International Journal of Production Economics, Volume 254, 2022, 108629, ISSN 0925-5273, https://doi.org/10.1016/j.ijpe.2022.108629.

APPENDIX

Interview

	Question	Aim of question
1	Tell us about your company and your mission/vision.	Background: company.
2	Your product enables the space industry to ….	Background: product.
3	What is your take on reuse or recycling of materials and components in space? What is the difference between reusing and recycling?	Background: reuse of space hardware.
4	What are benefits to reuse materials or components in space?	Benefits.
5	How difficult is it to reuse materials or components in space?	Challenges.
6	Would it be easy to sort materials and components in space?	Challenges.
7	What do you think are the best options for materials and components to be reused in space?	Drivers: materials and component prioritization.
8	Are there any materials and components that cannot be reused in space?	Barriers: materials and components to be neglected.
9	What challenges must be overcome to increase the reuse of materials and components in space?	Barriers.
10	What are the top three “missing” technologies or practices to be able to reuse materials or components in space?	Drivers and barriers: missing technologies and practices.
11	What is the aim of a spacecraft design?	Background: design of spacecraft.
12	How would reuse change the certification of materials or components?	Background: certification.
13	How would you design a spacecraft (satellite)?	Individual opinion.

Expert Information

No	Background	Main Area	Obstacle (to reuse)	Benefit (of reuse)
E1	senior level engineer, space agency	Innovation, Space Missions	"Parameters not known".	Efficiency vs. melting.
E2	senior level engineer, space agency	In Situ Resource Utilization, Space Missions	Design for one mission, infrastructure missing.	Enable space exploration.
E3	senior level engineer, research institute	Space Sustainability	Capture / repairability.	Sustainability.
E4	senior level engineer, private company	Reuseable Electronics	Standardization.	Cost driver and less waste.
E5	senior level engineer, private company	CubeSats	Modularization, cost.	Cost driver (decrease).
E6	University professor	Sustainability, waste management	Knowledge about materials and components.	System reliability, production in space decreases cost.

https://doi.org/10.1017/pds.2023.126 Published online by Cambridge University Press