

### Space sustainability beyond 'zero debris': from orbital safety to circular materials

Corresponding Author: Dr Axel Solt-Rindler

**This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.**

Version 0:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

This commentary article hits on a critical topic, challenging current end of life practices which have become commonplace within the space industry due to the unintended consequences this practice may pose to the terrestrial environment. The idea of using wood as an alternative is an interesting concept, although it's not the first time that I've heard of such a proposal.

I think this manuscript is worthy of publication as a commentary article because, although it does not pose anything that is particularly 'new' to the field, the current non-linear approach of dealing with space systems at present is wholly unsustainable and needs to be questioned.

In terms of areas of improvement within the manuscript itself, I think the article generally would benefit from a little more specificity in places. For example, in lines 39-46, there's a lot of non-quantified terminology used (e.g. "may persist in the stratosphere for years" - are we talking 5 years, 20 years, 100 years). Even an order of magnitude estimation would be appreciated here. Similarly, line 55 mentions the ECSS framework without explaining which specific standards are being referred to.

Moreover (and possibly most importantly), I think the article needs a direct link to the use of Life Cycle Assessment (LCA) for quantifying environmental impacts of space missions. This is the most widely accepted method for doing that at present, and with it having not been mentioned in this manuscript seems a significant omission. The authors may want to consider how that could be used as part of the new space sustainability paradigm they outline.

Nonetheless, an enjoyable read and well done to the authors on bringing such an important issue to the forefront of the engineering community.

Reviewer #2

(Remarks to the Author)

The Comment titled "Space sustainability beyond 'zero debris': from orbital safety to circular materials" stems from important observations for the space sector: its rapid growth together with the "design for demise" principle yield increasing burden on the atmosphere. The atmospheric impacts are not well understood, but based on multiple recent studies, a couple of which are cited in the Comment, the impacts may be non-negligible in the future. The authors argue that circular economy principles and the use of biomaterials may alleviate the atmospheric burden and claim that wood could be a worthwhile option to investigate as a (potentially secondary) material for spacecraft.

The Comment highlights an important topic given the projected space activity in the coming decades. I have a few comments and questions listed below. I think the Comment will warrant publication to Communications Engineering, should the authors be able to address these.

- Lines 80-82: on the potential atmospheric impacts on wood re-entry, it would be helpful if the authors could back the statement with either further explanation or cited literature.
- Lines 88-90: could the authors mention what type of subsystems they have in mind with this statement. For the bigger

picture, it would be helpful to estimate what might be the maximum addressable mass that may be viable for substitution such that eventual impact of such an approach can be estimated.

- Given the title of the comment, are there any other examples of circular materials that may be good candidates, beyond wood?

Version 1:

Reviewer comments:

Reviewer #1

(Remarks to the Author)

I'd like to thank the authors for addressing my concerns so thoroughly. I think the article is now much stronger and more specific. Well done to the authors on this article - I now happily recommend it for publication.

Reviewer #2

(Remarks to the Author)

I'd like to thank the authors for addressing my comments. I do not have any further comments.

**Open Access** This Peer Review File is licensed under a Creative Commons Attribution 4.0 International License, which permits use, sharing, adaptation, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license, and indicate if changes were made.

In cases where reviewers are anonymous, credit should be given to 'Anonymous Referee' and the source.

The images or other third party material in this Peer Review File are included in the article's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the article's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

To view a copy of this license, visit <https://creativecommons.org/licenses/by/4.0/>

## Point by point response to reviewers' comments - COMMS-26-0520-T v1.0

Thank you for the opportunity to revise our manuscript "Space sustainability beyond 'zero debris': from orbital safety to circular materials" (COMMS-26-0520-T v1.0) for Communications Engineering. We are grateful to you and the two reviewers for their constructive and encouraging comments. We have revised the manuscript to address every point raised and provide a point-by-point response below. Changes in the manuscript are highlighted in the marked-up version; line numbers refer to the original submission.

### Reviewer #1

***Comment 1: "In terms of areas of improvement within the manuscript itself, I think the article generally would benefit from a little more specificity in places. For example, in lines 39-46, there's a lot of non-quantified terminology used (e.g. 'may persist in the stratosphere for years' – are we talking 5 years, 20 years, 100 years). Even an order of magnitude estimation would be appreciated here."***

Response: We agree and have quantified this statement. We now specify that satellite launch activity (number of objects placed in orbit, most of which are small satellites) increased by over 250 % between 2020 and 2025, and that re-entry-derived alumina particles may persist in the upper atmosphere for years to decades, with estimated sedimentation times of up to approximately 30 years before reaching the stratospheric ozone layer. We have added a supporting citation (ref. 4, Gunter's Space Page chronology) for the launch-rate figure.

***Comment 2: "Similarly, line 55 mentions the ECSS framework without explaining which specific standards are being referred to."***

Response: We have replaced the generic reference to "the ECSS framework" with the specific applicable standards: ECSS-U-AS-10C Rev.2 (adoption of ISO 24113:2023) for debris mitigation, re-entry casualty risk and design-for-demise; ECSS-Q-ST-70-02C for thermal-vacuum outgassing; ECSS-Q-ST-70-06C for particle and UV radiation resistance; and ECSS-Q-ST-70C Rev.2 for atomic oxygen resistance in LEO.

***Comment 3: "Moreover (and possibly most importantly), I think the article needs a direct link to the use of Life Cycle Assessment (LCA) for quantifying environmental impacts of space missions... The authors may want to consider how that could be used as part of the new space sustainability paradigm they outline."***

Response: We thank the reviewer for this important suggestion and have added a new paragraph introducing LCA as the established, ISO 14040/44-based method for quantifying environmental impacts across the mission life cycle, including its adaptation by ESA for space systems. We further describe a recent extension combining the Environmental Footprint 3.1 method with a dedicated Space Debris Indicator, enabling comparison of end-of-life scenarios (natural re-entry, controlled re-entry, graveyard disposal) across terrestrial, atmospheric and orbital impact domains (new ref. 10). We also link this framework explicitly to our wood case study by citing a CubeSat LCA example illustrating addressable structural mass.

## Reviewer #2

***Comment 1: "Lines 80-82: on the potential atmospheric impacts on wood re-entry, it would be helpful if the authors could back the statement with either further explanation or cited literature."***

Response: We have added new experimental evidence from plasma-wind-tunnel testing under representative LEO re-entry conditions, showing that a beech-balsa panel completely demises in under 30 seconds at temperatures up to 2000 K, with predominantly CN, CH, C<sub>2</sub>, Na and K detected among the ablation species and no metal oxides observed (new ref. 13). This directly substantiates our claim regarding wood's favourable, low-metal-oxide re-entry signature relative to conventional aluminium structures.

***Comment 2: "Lines 88-90: could the authors mention what type of subsystems they have in mind with this statement. For the bigger picture, it would be helpful to estimate what might be the maximum addressable mass that may be viable for substitution such that eventual impact of such an approach can be estimated."***

Response: We have specified that near-term applications include secondary structural panels, brackets and housings. To ground the scale of potential impact, we now cite a recent 5-kg 3U CubeSat case study in which the aluminium structure accounted for 60% of total satellite mass, illustrating that even partial substitution of suitable structural components could address a meaningful fraction of demisable mass (ref. 10).

***Comment 3: "Given the title of the comment, are there any other examples of circular materials that may be good candidates, beyond wood?"***

Response: We agree that the original text was too narrowly focused on wood given the broader scope implied by the title. We have added a passage identifying other circular material classes meriting parallel consideration, including natural-fibre-reinforced composites and thermosets/thermoplastics derived from renewable or waste feedstocks, such as biodegradable polymers like polylactic acid (PLA). We also note that high-performance thermoplastics such as PEEK can support design-for-demise, citing recent work showing improved demisability of composite fasteners relative to steel or titanium baselines (new ref. 9).

We believe these revisions have substantially strengthened the manuscript by quantifying previously qualitative claims, grounding our argument in the established LCA framework, broadening the discussion of candidate circular materials, and providing new experimental support for wood's demisability. We hope the revised manuscript now meets the requirements for publication in Communications Engineering and look forward to your response.

Yours sincerely,

Axel Solt-Rindler  
(on behalf of all co-authors)

Tulln, 21.08.2026