Space for Sustainability Award

2023 Edition

# Spacecraft Reentry as a Source of Atmospheric Pollutants

## *Accounting for the Environmental Impact of Spacecraft Demise in the Atmosphere*

At the end of life, space hardware is disposed into the atmosphere. While it is widely understood that most will completely burn during reentry, the impact on atmospheric composition has not been thoroughly studied. As reentry rates tend to massively increase, possible consequences to the ozone layer and global warming remain unknown. ESA's low-fidelity open-source tool for debris survival DRAMA provides an expansion opportunity to provide a first-order estimation of the byproducts generated by spacecraft. As such, a fully-integrated rating system is proposed to support the preliminary design phase of ESA missions, incentivizing environmentally friendly materials when feasible. Full integration of the rating in ESA's engineering workflow is envisioned to 2030.

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# 1. Background

## Context

Earth’s orbit presents around 60 % of mission-related debris, rocket stage remainings, and defunct spacecraft; and 40 % of debris fragments that were primarily originated by any of the previous forms [1]. This is thoroughly explained by a model firstly defined as the *Kessler Syndrome* in the late 1970s [2], bringing to light the need to declutter such environment. Empirical data from 2022 shows that there are more than 34 000 pieces of debris larger than 10 centimeters across – population which is expected to double every 75 years – while reentry rates from Low-Earth Orbit (LEO) were of 146.3 and 162.6 tonnes for satellites and launch vehicles, respectively [3]. Rough estimations point to future reentry rates of 800 to 3200 tonnes per year for satellites, and up to 1000 tonnes per year for launch vehicles [4]. The overall imbalance of launched and reentered objects on a yearly basis can be appreciated in Figure 1, where a clear trend of increasing satellite mass launched is unmatched by the mass fraction reentered.

As the launched mass increases, it is clear that most will eventually reenter in the atmosphere. It is estimated that 51 to 95 % of the spacecraft mass burns in the atmosphere upon reentry [5]. In fact, the U.S. Federal Communications Commission emphasized, in April 2021, the «Potential Effect on Earth’s Atmosphere from Satellite Launch and Reentry» while reviewing Starlink batch 1 modification application [6]. It was argued that such satellites, built from aluminum, could generate aluminum oxides during reentry, which is a climate change potentiator. However, lack of evidence prevented subsequent regulatory actions.

Based on empirical data since 2016 [3], Figure 2 presents an estimation of the anthropogenic injection of aluminum upon reentry from launch vehicles and satellites when compared with that from meteoroids [7]. The satellite-based injection has grown 52 % per year on average, while the launch vehicle reentry rate has only grown by 14 % per year despite being larger in magnitude. In 2022 only, the anthropogenic injection of aluminum in the mesosphere reaches an 87 % excess of that from natural sources.

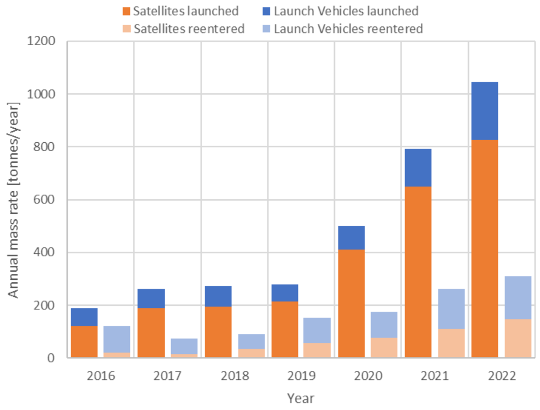

*Figure 1 – Annual mass rate launched to and reentered from LEO (ESA annual report [3])*

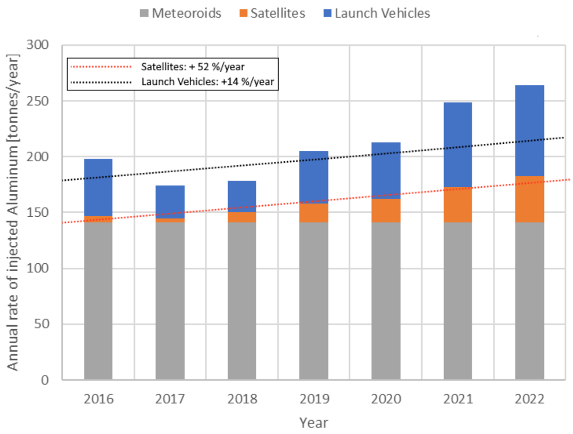

*Figure 2 – Annual mass rate of aluminum from LEO reentries: natural + anthropomorphic sources*

## State of the art

The only observational study representative of a spacecraft reentering from LEO was led by ESA and joined by NASA. This campaign gathered valuable data from the reentry of the ATV-1 resupply vehicle, enabling the development of reentry break-up models and risk analysis tools which heritage lives is today’s ESA software such as SCARAB and DRAMA. That campaign produced one of the most valuable pieces of empirical data to date, showing presence of aluminum and other metals during reentry at an altitude of 74 km [8] as depicted in Figure 3.

In 2021, ESA published 2 computational studies on the assessment of pollutants from spacecraft demise during reentry. The ATISPADE study [9] performed a coarse estimation of atmospheric emissions of a 20-tonne spacecraft, estimating reentry byproducts such as nitrogen oxides and chlorine. The ARA study [10] considered the demise of structural panels during reentry to estimate the byproduct generation of nitrogen, aluminum, and titanium oxides in the mesosphere.

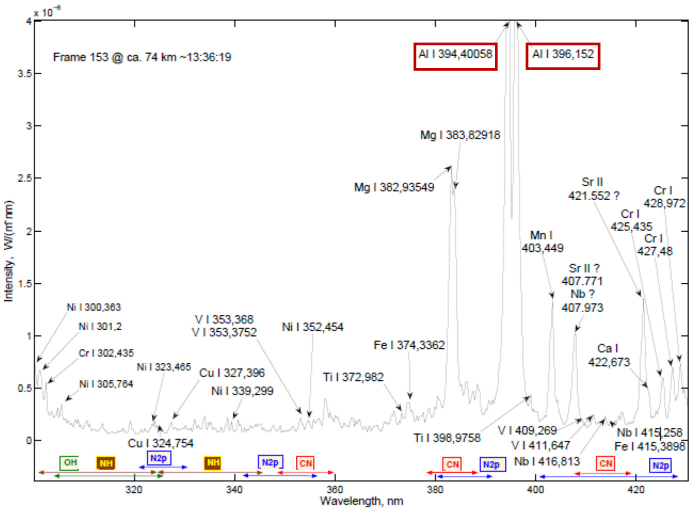

Figure 3 - Spectroscopy measurements of ATV-1 demise [8]

In spite of the polluting potential, ESA concluded that the atmospheric impact of spacecraft reentries is relatively low when compared with aviation or road transportation, although uncertainties on the byproduct generation and transportation modelling persist along with lack of observational data to validate the models.

Notwithstanding, recent studies have shown new evidences on the oxidation process of Aluminum and how nanoparticles are generated during the reentry process, suggesting that byproducts take several decades to reach the ozone layer [11]. Other variables such as the Radiative Forcing (RF) and the Global Warming Potential (GWP) remain unstudied.

## Legal Framework and Rating Systems

The paramount need to control LEO environment may also help with ever-growing increase of post-mission disposal and demise in the atmosphere. In 2002, the Inter-Agency Space Debris Coordination Committee (IADC) published the first set of internationally accepted measures to ensure the mitigation of space debris, recommending a 25-year limit for deorbiting whenever direct reentry or disposal to a graveyard orbit is not possible. It currently solely addresses the environmental impact deorbiting would have on the ground, mentioning that «ground environmental pollution, caused by radioactive substances, toxic substances or any other environmental pollutants resulting from on-board articles, should be prevented or minimized in order to be accepted permissible» [12]. NASA's good practices [13] and ESA's debris mitigation guidelines [14] reflect this concern, along with international standards by ISO [15].

The United Nations (UN) has been a strong advocate for sustainable space activities with the *Guidelines for the Long-term Sustainability of Outer Space Activities*, mentioning the need to measure «risks to [...] the environment associated with the launch, in-orbit operation and re-entry of space objects» [16]. Recently, in June 2023, the *Space Industry Debris Mitigation Recommendations* [17] were announced, in a new industry-led initiative pushing the envelope of what is currently adopted by industry as good practices in the absence of a binding legal framework for space debris and environmental concerns.

Notwithstanding, the Space Sustainability Rating (SSR) is the only reward-based approach currently deployed to promote sustainable practices in space activities. It rewards deorbiting as a means to reduce post-mission residence time by potentially decreasing insurance cost and easing funding conditions. The rating is based on 6 modules under quantitative appreciation: Mission Index; Detectability, Identification and Tracking; Collision Avoidance Capabilities; Data Sharing, Design and Operations Standards; and External Services [18]. However, this rating system solely focuses on in-orbit assessments, neglecting putative environmental impacts on Earth caused by space missions.

## 2. Proposed Solution

This proposal advocates for the creation of a rating system integrated in the design phase of a mission to assess the environmental impact of space activities on Earth. It is conceived to support the preliminary design of ground, launch, and space segments of any mission, including launch vehicles and spacecraft. It is worth noting that launch vehicles may be pollutant during ascension and reentry, while satellites will only pose a potential impact for reentry.

The solution herewith presented solely focuses on the atmospheric reentry of space objects, evaluating each material from a comprehensive standpoint, including technical and ecological concerns. The sole goal is to use this rating methodology in the Preliminary Design stage – which usually consists of Phases 0 to A. This could minimize the environmental footprint of the mission, supporting ESA's goal of *Design for Demise* (D4D). Design decisions should be reflected in the mission requirements, influencing the Detailed Design of the mission – Phases B to C –, and to be verified in the mission milestone of Preliminary Design Review.
As depicted in Figure 4, the process can be described as a closed feedback look and consists of:

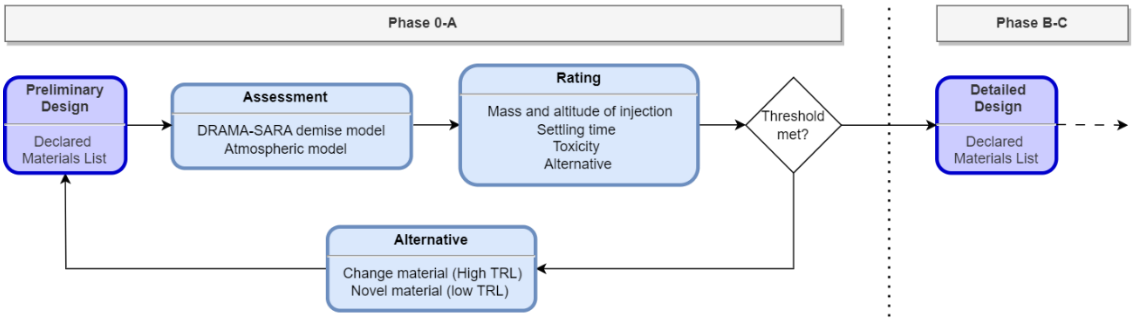

*Figure 4 – Design support system for the environmental impact of space hardware upon reentry*

**Preliminary Design**: within Phases 0 to A, the mission is drafted and components are conceptually designed according to traditional methods and materials. Such are usually reported on Product Assurance documents such as the *Declared Materials List* (DML) as defined in the relevant ECSS standards [19].

**Assessment**: ESA's DRAMA open-source tool allows for debris-related risk measurement upon reentry. This includes the module SARA that estimates debris survival upon reentry and performs a ground-hit risk analysis. The software possesses a data base of core materials developed and updated by ESA for the use case of spacecraft demise from a LEO reentry. It outputs an estimation of the break-up altitude at which fragmentation occurs and the mass fraction lost during reentry. Such results would then be used as an input to atmospheric models used in previous ESA studies such as REPROBUS [9] and ECHAM [10] to resolve the transportation of pollutants through the atmosphere. Alternatively, simplified 1D models such as the U. S. Standard Atmosphere [20] may be considered for cost effectiveness.

**Rating**: a quantitative measure is expected to derive from the analysis of 4 base criterion:

- *Mass and altitude of injection*: DRAMA-SARA is expected to output the mass fraction lost during reentry as a function of altitude for a given material in the catalogue. Benchmarking against natural sources would allow concluding about its significance.
- *Settling time*: based on the mass and altitude of demise and how particles rearrange during descent, determine how long it takes until they affect the atmosphere.
- *Toxicity*: based on the previous point, calculate the Radiative Forcing (RF) and Global Warming Potential (GWP) of byproducts to assess the impacts in the atmosphere.
- *Availability of an alternative material*: assessment based on alternative processes of manufacturing at a Technology Readiness Level (TRL) of at least 7, depending on the component criticality.

**Alternative**: upon definition of a threshold, and should it not be met, further investigate other material alternatives. This may involve a new design iteration using a high TRL solution, or conclude about the low TRL of current alternatives which could boost the investment on such research area by ESA. In the latter, the mission should carry on with the material initially defined while the mission promoter compromises to offset the long-term environmental consequences.

# 3. Implementation

Implementing the proposed solution is enabled by currently available tools that will partake in a development process to enlarge current capabilities. Firstly, the workflow to obtain quantitative outputs supporting the rating systems is presented along with tools to be developed, followed by an implementation roadmap to achieve broad ESA adoption by 2030.

## Workflow

In this section, the inputs and outputs of the closed feedback loop process are presented along with the developments needed to enable the envisioned application. Figure 5 presents key points feeding the rating system and the ones to be developed, clustered in 3 groups:

**Standards**: the DML is the go-to document to gather information about the materials to use in the DRAMA model, with no need to update the reference standard [19].
As new scientific breakthroughs emerge, it is expected that existing standards are updated and a new family of standards related to sustainable practices of space hardware design gets published.

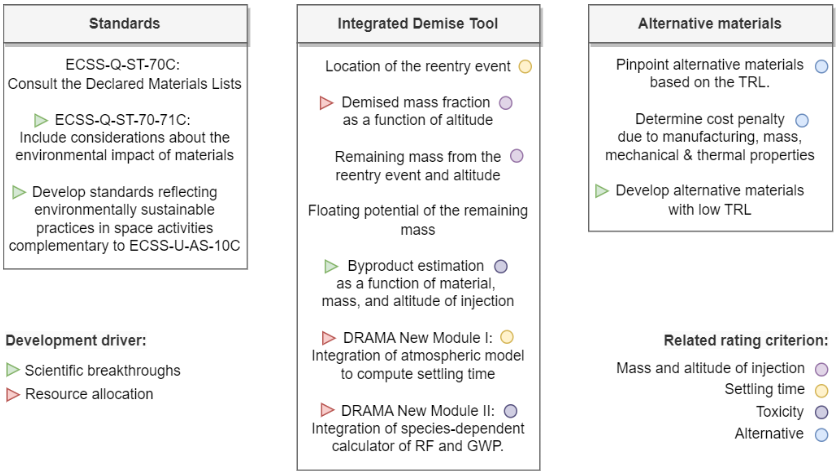

*Figure 5 – List of inputs and outputs supporting the rating system. Solutions to be developed are highlighted with a triangular icon on the left-hand side, and outputs quantitatively related to the rating system present a circular icon on the right-hand side*

**Integrated Demise Tool**: ESA's DRAMA open-source tool would be upgraded to offer new features in existing modules and implement new ones. Although the location of the reentry event, remaining mass and altitude, and floating potential of the reentered body are already provided by the SARA module, a very straightforward addition would allow outputting the mass fraction of demised material as a function of altitude. Scientific breakthroughs such as research done on resolving the chemical mechanisms of byproduct formation upon reentry [11] would provide the information necessary to estimate the byproducts generated from each reentry event. Using that data would allow computing the settling time of such byproducts by implementing a cost-effective atmospheric model in a new module for DRAMA, followed by computing their toxicity by means of the Radiative Forcing (RF) and Global Warming Potential (GWP) in a second new DRAMA module.

**Alternative materials**: a very clear process of identifying putative alternatives for a given material is expected to be developed, along with a practical assessment of the penalty involved in changing the material from both economic and technical perspectives. This would eventually output clear directives concerning research worth developing in the realm of sustainable material sciences.

The diagram presented allows to identify points worth developing to implement this solution. The ones solely driven by resource allocation are expected to be straightforward as no leaps in the understanding of the reentry phenomena are needed for the implementation. On the other side, the ones driven by scientific breakthroughs currently limit the community's knowledge about the subject.

Furthermore, the infographic also enables identifying points in the critical development path when they are simultaneously a development point and a rating criterion. For the criterion points which development is solved by resource allocation, the solution is trivial; however, for the ones relying on the advancement of scientific knowledge, a coordinated approach should be deployed to develop such field as it creates, as of today, a critical development path.

## Roadmap

Following the identification of the development areas that need to be tackled to implement the proposed solution, a roadmap is presented to provide context as to the implementation timeline. This development plan structures actions to implement this process in all ESA missions by 2030, accounting for the scientific breakthrough that will work as enablers. The roadmap is depicted in Figure 6 and can be described as follows:

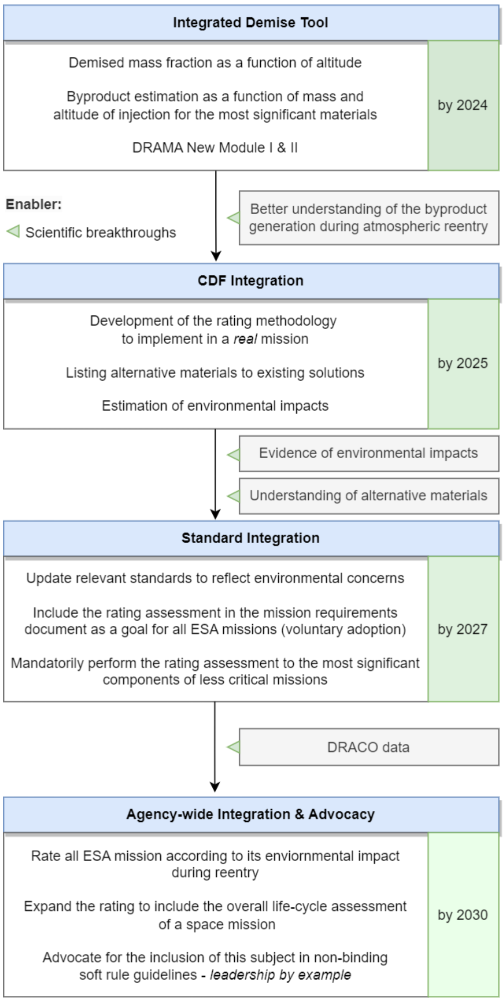

*Figure 6 – Development plan*

**Integrated Demise Tool**: the enlargement of ESA's DRAMA open-source tool is largely dependent upon resource allocation as depicted in Figure 5 and is expected to be concluded by 2024.

**CDF Integration**: as a better understanding of the reentry byproducts arises, the pilot integration on ESA's Concurrent Design Facility (CDF) will allow testing the methodology effectiveness. As the CDF primarily address Phase 0 studies, it is believed that the implementation within CDF can be concluded as early as 2025.

**Standard Integration**: upon advancements on material sciences and evidence gathered of the environmental impacts of spacecraft demise in the atmosphere, existing standards should be updated and new ones developed as suggested in Figure 5. This would leverage the integration of the rating assessment as a mission goal for every ESA mission, which would be seen by the engineering team as an objective to achieve. Furthermore, ESA should target implementation in less critical missions and turn the aforementioned goal into a requirement, making it mandatory. This is to say that, by 2027, ESA may perform this assessment in small science missions, which is something that may learn from the experience of developing the DRACO mission.

**Agency-wide Integration & Advocacy**: the recently announced ESA's DRACO mission will build on the ATV-1 reentry observation study heritage by deploying a controlled reentry capsule to measure its own demise process. Set to launch in 2027, it will allow for validation of the computational models and will resolve, for the first time and *in situ*, the byproducts generated by a representative microsatellite during reentry. This should provide sufficient evidence for ESA to widely adopt this methodology as part of the preliminary design cycle of its missions, further including the whole life-cycle assessment of the launch segment. In this way, ESA will promote with actions its agenda for sustainability, showing leadership by example and advocating for the inclusion of such assessments in non-binding industry-led best practices and in a concise regulatory framework to guide the future development of sustainable space missions.

# 4. Pilot Study

This section intends to showcase how this methodology can be integrated in a timely manner in existing procedures of Phase 0 studies carried out in the Concurrent Design Facility (CDF). In this use case, the subject under analysis is ESA's satellite Sentinel-1B, analyzed using the current version of DRAMA-SARA at a starting altitude of 120 km, inclination of 98 degrees, and at the end of its operational lifetime and extended deorbiting campaign in early 2040.

## DRAMA-SARA assessment

The SARA module within DRAMA allows retrieving very important data from the demise process of the satellite. The computational model is defined in line with the chemical composition of each component. In Figure 7, the first two blue crosses depict the altitude at which the Antenna array and the Solar Panels completely demise, at an altitude of 95 and 93 km, respectively.

The green cross, defined as a *Balooning Point* [21], is a numerical artifact from the demise process and, therefore, the satellite structure can also be considered as completely demised at the altitude of 57 km, freeing the internal components and exposing them to the atmosphere. As a result, all internal components reached the ground, and consulting the *impactingFragments.xml* file allows to assess the *surviving mass* and the *isFloating* flag [22]. In this use case, all components kept their mass, not suffering from any mass loss in the terminal stage of reentry, and all but the Magnetorquers and the Tank stood afloat.

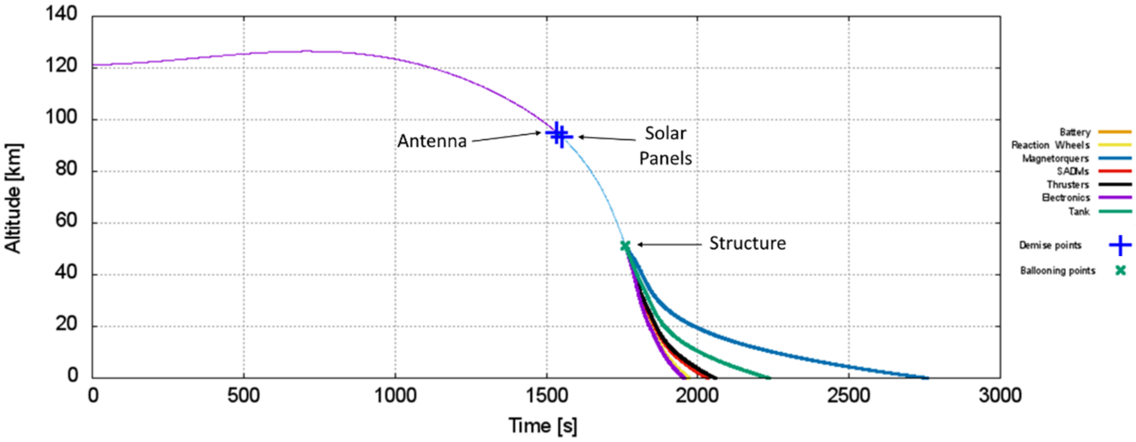

*Figure 7 – DRAMA-SARA demise assessment of Sentinel-1B*

By comparing the surviving mass with the initial component mass, one can conclude the difference was injected in the atmosphere. The altitude of the injection sources may be assumed as the one of the *Demise point*. For components that completely demise, such as the structure, the mass injected in the atmosphere is the total mass of the component. Furthermore, determining whether the object sinks in the ocean or stays a float (eventually being retrieved) may also be used in future environmental assessments.

## Integrated Demise Tool

The Integrated Demise Tool, which would consist of the current DRAMA open-source tool plus 2 additional modules, would allow performing the remaining of the assessment as depicted in Figure 5 and Figure 6. The current SARA module could be easily adapted to output the mass fraction loss as a function of altitude which would allow for a more precise environmental assessment of the atmospheric injection sources. This would enable a better estimation of the byproducts generated as a function of altitude, which would then be integrated in DRAMA New Modules I and II to compute the propagation of pollutants through the atmosphere and estimate their toxicity, respectively.

In this way, the rating computation is finalized by equating the aforementioned parameters along with putative alternative materials, available by 2025. The decision about whether to reiterate the design of the component under analysis would depend on a threshold defined *a priori*, closing the feedback loop and guiding the CDF team throughout the process.

# 5. Potential Risks & Expected Results

Assessing implementation risks allows for a proper identification of critical paths in the development of this rating system. As previously mentioned and highlighted in Figure 5, science breakthroughs is the only development driver with some associated uncertainty as it is not possible to predict how fast knowledge would advance in this domain. However, there are solid indicators that research on the environmental impact of rocket launches in the atmosphere [23], resolution of byproducts of spacecraft atmospheric reentry [24] [11], and in the overall life-cycle assessment of space activities [25] will continue pushing the knowledge envelope past 2025, which is expected to be complemented by valuable data gathered by DRACO mission after 2027.

The expected quantitative results of the rating, eventually applied to an overall life-cycle assessment of space missions, will contribute to reinforce ESA's value proposition concerning Environmental, Social, and Governance (ESG) concerns. Strong ESG propositions lead to value creation through cost reductions, asset optimization, regulatory and legal intervention, productivity uplift, and easier access to funding and partnerships due to meritorious behavior [26]. As depicted in Figure 8, the implementation of such a rating system will empower ESA's voice on the field, which can boost the development of a legal framework to finally regulate the in-orbit economy and the underlying resource exploitation.

| Environmental | Social | Governance |
|---|---|---|
| More conscious management of raw materials and processes<br>Optimize components not only for function but also for demise (Design for Demise - D4D)<br>Lower emissions of GHG & other pollutants incured by space missions | Foster ESA's reputation as a global leader in space sustainability<br>Actor seen as a role model for newer players<br>Positive impact on people's lives by minimizing polluting activities<br>More engaged and cause-oriented workforce | Internal system of practices, procedures and standards implemented towards more sustainable engineering and operations<br>Intervention in multilateral discussions as a subject matter expert on implementing sustainable practices<br>Active voice in contributing to a broader international regulatory framework |

*Figure 8 – ESG value proposition of ESA after rating implementation*

# 6. Conclusion

Atmospheric pollution due to space activities is a growing concern with the advent of reusable launchers that enable a multitude of solutions for a vivid in-orbit economy, ranging from microsatellite mega-constellations to active debris removal. The long-term impacts of such increased activity are very poorly understood, with current leads pointing to potential harm to the stratospheric ozone and increasing of the global warming effect. The proposed methodology implements a rating system to rank materials used in spacecraft and launch vehicles concerning their polluting potential integrated in preliminary design stages of a new mission, incentivizing alternative materials when feasible. The development plan suggests a full integration of the rating in ESA's engineering workflow by 2030, paving the way to a broader agreement on a regulatory framework to limit atmospheric pollutants resulting from space activities.

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