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Development of a launch vehicle sustainability rating

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Abstract

The largest contributors to debris risks on orbit are mission-related objects and rocket bodies generated by launch vehicles (ESA Space Debris Office, 2022). Passivating and deorbiting upper stages are thus critical to safeguard valuable orbits, even more since some end up crossing crowded low Earth orbits (LEO) and geostationary orbits (GEO), threatening many operating satellites. The number of launches per year is bound to increase in the coming years, driven notably by the democratization of the access to space. Consequently, this will likely increase material consumption and emissions, especially those during launch events, directly in all layers of the atmosphere.

After the successful development of a Space Sustainability Rating (SSR), operationalized in 2022 by eSpace - EPFL Space Center, a new formulation focusing on the sustainability of launch vehicles is proposed. The SSR is a notation system that characterizes the impacts of a space mission and highlights areas of possible improvements. The idea of a Launch Vehicle Sustainability Rating (LVSR) emerged following discussions about the SSR with different stakeholders in the space domain, and is motivated by several facts. In the same mindset as the SSR, the goal will be to incentivize launch vehicle providers to implement sustainable design and operational decisions, to reduce environmental impacts and space debris risks.

This paper will describe the process followed to elaborate the first version of this new rating. First, a list of significant parameters to account for is defined and discussed. The parameters cover all phases of the launch vehicles' life cycles and allow to rate different architectures depending on their impacts on the space's and Earth's environments, including the atmosphere.

Secondly, these impacts are grouped in five technical modules and the LVSR takes advantage of the verification process already used in the SSR. One module focuses on sustainability on Earth, with a score based on a rapid life cycle assessment study. Other modules follow the general concept of operations of a launch vehicle by assessing the ascent trajectory (including jettisoned parts), the orbital stage (including mission-related objects, disposal and passivation strategies), and the reentry phase (including the demisability). A last module rewards launch service providers' transparency and adhesion to international guidelines.

Finally, a formula to grade a launch vehicle by aggregating the modules' individual scores will be presented. The next steps will include the validation of the LVSR approach by applying the rating to vehicles during a beta testing phase.

Keywords: Space Sustainability Rating, Space Debris, Space Environment, Long-term Space Sustainability, Launch Vehicle, Space Debris Management

Acronyms/Abbreviations

ACT	Assessment and Comparison Tool
ADR	Active Debris Removal
EOL	End-of-Life
EOLM	End-of-Life Manoeuvre
EPFL	Ecole Polytechnique Fédérale de Lausanne
GEO	Geostationary Orbit
GTO	Geostationary Transfer Orbit
IOS	In-orbit servicing
LEO	Low Earth Orbit
LCA	Life Cycle Assessment
LV	Launch Vehicle
LVSR	Launch Vehicle Sustainability Rating
MRO	Mission related objects
PMD	Post-Mission Disposal
RB	Rocket Bodies
SSO	Sun Synchronous Orbit
SSR	Space Sustainability Rating
STV	Space Transportation Vehicle

1. Introduction

1.1 The Space Sustainability Rating

The concept of a Space Sustainability Rating (SSR) first emerged within the World Economic Forum's Global Future Council on Space. In 2019, they appointed a consortium including BryceTech, ESA, the Massachusetts Institute of Technology, and the University of Texas at Austin to develop the SSR. The consortium has designed and formulated the rating system for over two years and has selected in 2021 the EPFL Space Center (eSpace) to conduct the transition from fundamental research to a real product [1, 2]. The rating was officially launched in June 2022.

The rating is composed of seven modules, six of them capture important parameters that impact the definition of space sustainability as defined by the consortium, and the seventh allows to weight the confidence the issuer has on the provided input data (see more in section 3).

Now established, the team working on the Space Sustainability Rating is conducting research projects to identify and test potential extensions or improvements to the rating. The team is exploring the development of potential additional modules, like one that will focus on the impacts of space missions on astronomical observations. They are also considering ways to enhance the existing modules and even create new rating formulas for other space mission segments.

This paper will first present a review of the current state of affairs regarding the applicability of the SSR and space debris guidelines to launch vehicles. After a review of current practices in the industry, the motivations for a Launch Vehicle Sustainability Rating (LVSR) will be explained. In section 4, the five modules included in the LVSR formulation will be detailed, and used with a formula defined in section 5 to assess several test cases in section 6. Finally, a discussion of the results will allow to highlight the next steps required in the development of the LVSR.

1.2 Current state of affairs for launch vehicles

1.2.1 Launch Vehicles in the current version of SSR

During the development of the SSR, the idea of dedicating a module to the impacts of the launch vehicle was mentioned but not further investigated [3].

At the moment, some of the SSR modules require input values for both spacecraft(s) and launcher(s). This has the advantage of raising awareness about the Launch Vehicle (LV) impacts to missions' operators. They can thus include stricter requirements when selecting a launch vehicle for their mission. Following the same logic, the Space Safety Coalition best practices state that "in selecting launch service providers, space operators should consider the sustainability of the space environment" [4]. But the responsibility should not only fall on the spacecrafts' operators as their choice is often primarily dictated by performance, cost, and availability.

The mission index module used in the SSR is able to rate whole space missions, including the launch vehicles [5]. However, this is not used at the moment due to the possible controversy of being rated based on the impacts of another company.

These reasons and other motivations explained in section 1.3 highlight the need for a separate rating, issued directly to launch vehicles designers and providers.

An early idea in the thinking process for this project was to apply the current SSR to a launch vehicle alone and consider its upper stage like it was a spacecraft. However, this idea was turned down because some modules would not be applicable to LVs. Moreover, the SSR is focused on the impacts on the space environment and misses atmospheric impacts and other effects that apply to the Earth biosphere.

Thus, the idea to create a Launch Vehicle Sustainability Rating, to incentivize more sustainable design choices and operational behaviours, also of this segment of a space mission. It was first proposed during a master thesis at EPFL [6] and it is planned to continue its development by involving students and professionals from the SSR network. As discussed before, some of the input parameters of the current rating can serve as a basis for new modules [6] and the process will be detailed further in sections 4 and 5. The following sections provide an overview of existing guidelines and current practice that will influence the definition of the LVSR.

1.2.2 Space debris guidelines applying to launch vehicles

Space debris mitigation guidelines exist to detail sets of good practices to limit any associated risks.

The Inter-Agency Space Debris Coordination Committee (IADC) guidelines [7] often use the terms "spacecraft and orbital stages", recognizing that launchers' upper stages must follow the same disposal or passivation constraints as satellites once their missions are over. It is in this set of guidelines that the rule of 25 years or shorter for the expected residual orbital lifetime after end of mission is described. The guidelines are voluntary and use only the verb *should*, defining only goals and not binding requirements.

ISO standard 24113 [8] has been adopted by the European Cooperation for Space Standardization (ECSS) for space debris mitigation requirements. Some of its listed requirements are very similar to those of the IADC guidelines but they may have more weight if required in a contract as they are norms Moreover, ISO 24113 uses the verb *shall*, putting more emphasis on the required nature of these mitigations.

Several of those requirements also apply to launch vehicles.

The UNCOPUOS guidelines [9] list similar mitigations as the ones cited above but using a broader (and less technical) wording so their voluntary document can also be used by policy makers. The same main guiding principles are always present: protect the LEO and GEO regions by removing spacecrafts (satellites and LV's upper stages alike) that are no longer operational, build international cooperation and raise awareness, lower risks of debris generation and reentry casualties.

Several requirements apply to any mission but some will differ based on a mission's objectives and architecture. For instance, the orbit to which the payload must be delivered has a large impact on the disposal strategy and different requirements applied in LEO or GEO [7, 8]. These differences must be accounted for in a rating system so the results are fair for any architecture.

1.2.3 Review of providers' current practices

In most of the recent launch vehicles' user guides, the notions of passivation, deorbitation and the efforts to limit the number of debris released during nominal operations, are mentioned. Sometimes the documents refer to the guideline(s) on space debris mitigation that are followed. But the level of details is low, and the wording can sometimes let the readers think that the measures are optional for the spacecrafts' operators rather than a mandatory step of the concept of operations. For instance, from its user manual, Vega C's upper stage "*typically* conducts a deorbitation or orbit disposal manoeuvre" [10] (§2.3.3).

It is in fact in the interest of both spacecrafts' operators and launch service providers to keep Earth's orbits sustainable, to ensure long-term use of the space environment. There has been changes of mindsets in the industry in the past years, for example at United Launch Alliance (ULA) between 2006 to 2021. In 2006, a catastrophic event occurred during the deorbiting manoeuvre of a Delta 4, creating at least 62 pieces of debris [11]. At the time, a vice-president of ULA said "How often we can [...] deorbit the stage in the future depends on the performance margin we have for future missions". Deorbiting was a nice-to-have option and performance was the most important factor. In 2021, during a hearing in front of a committee of the United States House of Representative, space debris are explicitly cited in a paragraph called "Protecting Earth Orbit – A Natural Resource". In this testimony, ULA's president says that they are proactive in debris pre-emptive actions "by safely disposing of our second stage rockets by placing them in a graveyard orbit or conducting a controlled reentry [...]" [12].

1.3 Motivations for a Launch Vehicle Sustainability Rating

The guidelines cited above are valuable and can serve to disseminate knowledge about best practices for space objects to avoid more debris. But they remain voluntary and updating them is a long process. The Space Sustainability Rating is also performed on a voluntary basis, but rewards better design choices and better orbital behaviours, and accompanies applicants with technical advices, which incentivize more operators to apply for a rating. It is imagined that the same business model could be applied with launchers' providers. As highlighted by their current practices (section 1.2.3), launcher providers are aware of the space debris risks but are not yet fully transparent or committed to reducing longer-term risks.

Research is being conducted at EPFL to develop a proof-of-concept of an LVSR and later integrate it to the SSR portfolio after a validation by the consortium. This process ensures that the modifications are fair and robust before their implementation. On top of the motivations given above, others related to the launchers themselves are explained below:

Firstly, rocket bodies (RB) already on orbit are the largest contributor to the cumulative fragmentation risks in the space environment [13] (see Fig. 1). Much more than inactive and active payloads, assuming the latter is able to manoeuvre. This shows that without proper disposal strategies, rocket bodies are and stay dangerous for a long time.

The risk highlighted previously may be due in large part to the fact that LV upper stages are massive (a large cross-sectional area and mass of several tons) and sometimes left on special orbits. Highly elliptical geostationary transfer orbits (GTO) are particularly dangerous as they mean the objects can impact both high Geostationary Orbits and Low Earth Orbits.

The difficulty to comply with the 25 years guideline (e.g. from GTO) is one reason why upper stages and payload adapters are good candidates for active debris removal (ADR) missions. In this case, standard interfaces and markings to facilitate the capture would be an asset and should be rewarded by a rating (see 4.3).

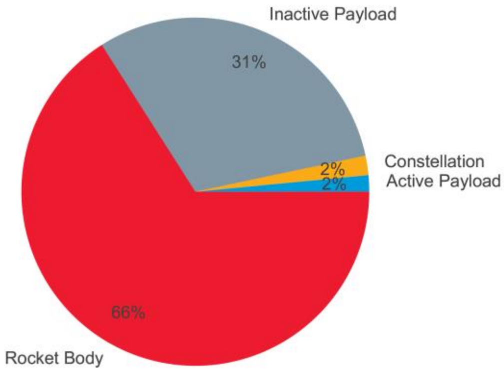

Fig. 1. Contribution to the cumulative risk index by category of object currently in space (2022) [13].

Secondly, the number of launches is increasing to meet the growing demand to access Earth's orbit. Especially in LEO, where many new micro launchers could be use to put payload in space. If larger providers are starting to commit to international guidelines to manage the end-of-life of their spacecrafts, micro launchers have yet to prove they will also implement those guidelines. With the New Space approach, the manufacturing rate, especially in the launcher sector will increase and be closer to a mass-producing industry. This will mean more raw material consumption, more regular emissions and debris generation.

Finally, in terms of environmental impacts on Earth, launch vehicles have particularities that can only be assessed with specific knowledge. One of the reasons ESA has developed an adapted methodology for the life cycle assessments (LCA) of its missions was that projects in the space industry were different than elsewhere [14]: Materials and processes can be very specific to the space industry. Requirements on the purity of the propellants, the cleanliness level and the number of tests mean the production can require a lot of energy and materials.

Looking at atmospheric pollutions, launch vehicles are the only human-made objects that inject particles, gases, and ozone destroying compounds directly in all layers of the atmosphere and their effects are hard to quantify directly. Space technologies are also exempt from several regulations on environmental protection, probably because space access is so strategic to every nation in the world, and also due to the lack of data on their real impacts.

In the case of a propulsive recovery to land, some propellant is also used during the descent phase, again in several layers of the atmosphere. It also consumes material to refurbish and reuse parts of the LV, though probably less than producing new part from the beginning.

Assessing those impacts in the LVSR would be a way to increase the scope of the rating, not only looking at space debris risks. There are ongoing projects at eSpace and in Europe to better model and assess them. All this information shows that an LCA module, as proposed in section 4.5 would take a lot of time to develop. The LVSR should take advantage of other projects that are trying to simplify the environmental impacts assessment of LVs, and incorporate them into its rating formula.

2. New Rating System for Launch Vehicles

The creation of a new rating that would be issued to launch services providers could answer the need to incentivise launch vehicle providers to design and operate their product in a more sustainable way. But the score may be too dependent on their customers' requirements and the type of mission (payload mass and target orbit(s)). Issuing a rating for every launch mission would be an operational burden for the issuer since there are more than one hundred launches per year and this number is increasing. But rating a launcher system only once would not make sense either because mitigations will highly depend on the mission's target orbit [7, 15] and mission [16]. For these reasons, it is proposed that a rating could be applied for each *type* of mission. Some launchers target only LEO but some have different configurations to also access GEO on a GTO trajectory, or deep space for instance. While ridesharing missions can include several payload adaptors and release mechanisms, increasing the risk of releasing mission-related objects (see Fig. 3) compared to single launch configurations.

A second idea, discussed in [6] states that the rating should be weighted by the performance (payload mass in kg) of the launcher. Indeed, a launch vehicle with a high fragmentation index, highly increasing the debris risks, used only to bring a few CubeSats on orbit is less optimized than a LV with a larger capacity, with the same impact on the space environment. On the other hand, this weighting factor would favour large providers (in opposition to new micro launchers' providers), creating an imbalance in the rating. On top of that, larger companies may have more resources to allocate to sustainable design than start-ups, this weight could therefore penalize the latter with no option to improve, so it is decided not to include it in the first iteration of the rating formula.

One also has to keep in mind, the rating must be made in a way that data is available for a fair rating to be issued.

3. Verification

In the SSR, a verification factor is applied to all inputs provided by the operators [1]. Ranging from "assertion", penalizing the score with a factor of 0.5, to "authority", adding no penalty, when a neutral third party can review the input (table 1). Indeed, SSR is an initiative aiming at having operators pro-actively work on the topic and answer on a voluntary basis. The inputs may not all be verified independently but the issuer can modify the level of verification in case the supporting documentation is not satisfactory.

Table 1. Verification levels of the SSR.

Levels of verification	Factors
Assertion	0.5
Assertion with technical documentation	0.6
Public release of technical documentation	0.8
Authority - Independent technical review	1

The verification has a great impact on the final score, incentivizing transparency and deeper studies on aspects related to space sustainability. The same verification strategy would be applied to the LVSR as it has been demonstrated to be efficient and well implemented in the SSR [17].

4. Catalogue of significant parameters

A first list of significant parameters, gathered during a literature review, tested with several industry and academia stakeholders and refined accordingly, is detailed below. The parameters are grouped in themes that could turn into separate modules within the LVSR (figure 2).

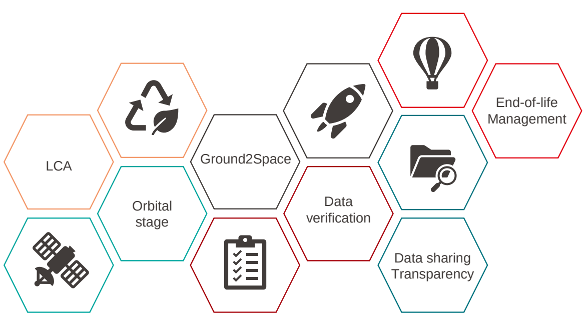

Fig. 2. The six modules (themes) proposed for the Launch Vehicle Sustainability Rating.

4.1 Ground to Space

This module aims at recognizing providers that make the best efforts to make sure no incident happens on the way up to space. For launchers, this is generally well implemented already as it is in the interest of the companies to get their payloads on orbit safely. This would justify a low importance weight on the module in the final formula (see section 5). Efforts shall also be made to avoid damages and casualties on the ground. The same risk threshold as for reentry risk is applied here [18]. Table 2 provides the input questions which are explained in more detail below.

Table 2. Input parameters for the Ground to Space module with associated maximal number of points, and the points for the scenarios that are used in section 6.

Ground to Space	Max points	Scenario 1	Scenario 2
Do you satisfy the 10E-4 casualties risk limit during ascension?	1	1	1
Do you perform conjunction risk assessment with manned objects?	3	3	3
Does your product create mission related objects during nominal operations? (e.g. from deployment mechanisms)	1	0	1
Do you comply with the maximum number of deployment debris as per ISO 24113 [8]? (1 for a single launch, 2 for a dual/multiple launch)	1	1	1
Do you embed on-orbit collision avoidance capabilities?	1	0	1
Do you use a low or seldom-used initial operations' orbit for demonstration flights? (bonus)	1	0	1

Ascent trajectory risks include disruption to maritime and air traffic, and debris fallout on populated areas in case of unexpected events, but also during nominal operations. Some parts are jettisoned during the ascent phase and fall down into the ocean without being demised like during reentry. Some can be recovered, for instance some EAP (*étage d'accelération à poudre*) boosters from Ariane 5 that have been recovered for structural analysis. But for others, they are designed to sink as fast as possible to shorten the impact on the maritime traffic. This means all the materials and left-over fuel are polluting the oceans and potentially impacting the fauna (this aspect will have to be covered in the LCA module, section 4.5). With the increase of launch events, the question of raising the acceptable risk threshold for shipping lanes might be considered, to limit the impact on global logistics. Large container carriers can have surface areas four order of magnitude larger than a human (which is 0.36 m^2 [18]) but their number is about 10^6 lower. Because the density of ships and planes is especially high along shipping and flying corridors, it should be up to the launch sites' operators to arrange with the maritime and air traffic authorities to manage the risks. So, this impact will not be rated here. The first question in Table 2 therefore uses the same risk threshold for falling objects as computed for reentry [18]. Nonetheless, sharing flight information with the authorities is important and the LV providers will be incentivized to do so in the data sharing module (section 4.4).

Conjunction risk assessment at launch is already performed by operators to make sure they can get their payload onto orbit. Looking to avoid collision risks with the International Space Station (ISS) or other manned objects is a must that shall be rewarded (second question). But NASA estimates that screening unmanned space objects for launch collision avoidance capabilities could impact too greatly the launch windows, even though the cumulative risk of collision is orders of magnitude lower than the risk of a mission failure during operations [19]. Meaning this parameter may be too restrictive for low space sustainability gains and should not be included.

Some separation and deployment mechanisms can release small debris in orbit, called mission-related objects (MROs). Clamp bands, pyro bolts and others, used to separate and inject payloads onto the correct orbit, will generate small debris, but those are still dangerous because they are travelling really fast. More modern separation systems, based on pneumatic forces, exist and do not create any debris during nominal operations [21]. Still, figure 3 shows the number of MROs released by rockets has not improved in the past years. This is not a technical issue but probably a lack of economic reasons to change current systems. Thus question 3 in Table 2 is there to incentive changes. For larger debris, ISO 24113 [8] has clear requirements: maximum one debris for single launches, maximum two for multiple payloads (question 4).

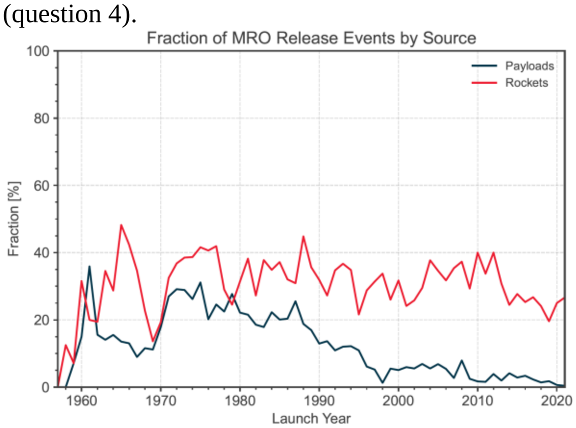

Fig. 3. Evolution of fraction of mission related objects released per year with respect to the total amount of payloads and rocket bodies injected into the space environment during that year [13].

On-orbit collision avoidance capabilities are accounted for in the current SSR formulation and could make sense for the LVSR too (Table 2, question 5). Embedded propulsion is usually used to carry the payload to the desired orbit and avoid collision with the payload once it's separated in a Contamination and Collision Avoidance Manoeuvre (CCAM). But upper stages and kick stages that can be manoeuvred to avoid other space objects during reentry give more freedom and increase safety on orbit. For that, their engines have to be re-ignitable or they shall have a secondary propulsion for collision avoidance manoeuvres.

The initial operations' orbit parameter could reward LVs that aim at a low or seldom-used orbit to start deploying their payloads. In case of a problem that would result in the loss of control of the upper stage or the newly orbiting spacecraft, they would deorbit more rapidly or be in a low satellite density area, with low collision risks. This is of course only possible for payloads with a propulsion system that can propel themselves up to their operational orbit. But this guideline is particularly relevant for new vehicles, during their first orbital flights, before they have proved their reliability. A threshold is set at 200km for LEO insertion because in some literature [20], space debris impacts are only assessed higher (it is assumed object with lower orbit will re-enter really rapidly). Applicants can also score the full point of this bonus question if they insert in an orbit with low density even if they target higher orbits.

4.2 Orbital Stage / ESA Mission index

Just like the current version of the Space Sustainability Rating, this module would take advantage of the mission index that has been developed by ESA [5]. It captures the fragmentation risk of the mission, meaning both risks of explosion and collision, looking at the probability of a fragmentation event to happen, and the consequences it would have on the space environment and other operational spacecrafts.

The inputs are metrics of the launcher: mass, cross-sectional area, operational and end-of-life (EOL) orbital parameters, and mitigations parameters like the Post-Mission Disposal (PMD) success rate and the mitigated collision risk percentage. With those parameters, ESA computes the index score along the mission's lifetime with a simulation that is then normalized with the space environment capacity to get a score between 0 and 1 [5]. This score can be used with the other modules' scores in the final formula. The score is split into two parts: an absolute score (80% of the module) and a relative score (20%). The latter compares the situation of the mission with a reference scenario based on the 25 years scenario of the IADC guidelines [5, 7].

For now, the index can be computed for circular orbits and an index computation for GTO can only be estimated. Only cases in LEO will be tested in this paper (see section 6) but it would be interesting to expend the index' capabilities to elliptical orbits, in particular GTO ones for launchers.

4.3 End-of-life (EOL) Management

This module includes the scoring of the EOL, either using a reentry in the atmosphere, a graveyard disposal orbit, or at least passivation of the subsystems. The disposal strategy is also reflected in the relative mission index and thus a low weight on the module is justified (see section 5).

The goal of the EOL management is to clear the orbit and passivate all energy sources to avoid the creation of new space debris. For re-entries, it also has to limit the casualty and damage risks caused by the objects that comes down on Earth. Questions are formulated to include any disposal strategy unless written that they apply to a given mission type.

According to the IADC, the remaining orbital lifetime due to natural decay of a spacecraft in LEO should be lower than 25 years [7]. This guideline could be considered as outdated [16, 22] so two additional questions are added in Table 3 to grant more points to operators that deorbit even faster.

Table 3. Input parameters for the End-of-life Management module with associated maximal number of points, and the points for the scenarios that are used in section 6.

End-of-life Management	Max points	Scenario 1	Scenario 2
Do you use a disposal orbit after the end of mission? (According to IADC guidelines [7, 15])	1	0	1
(Reentry only) Do you use a disposal orbit after EOL with a natural decay < 5 years?	1	0	1
(Reentry only) Do you use a disposal orbit after EOL with a natural decay < 1 year or direct reentry?	1	0	0
Do you passivate the propulsion after the end of mission?	2	0	2
Do you passivate the electric power supply after the end of mission?	1	0	1
(Reentry only) Do you satisfy the 10E-4 casualties limit at reentry?	3	3	3
(Reentry only) Is your stage designed for demise? (bonus)	1	0	1
Do you embed IOS features? (bonus)	2	0	0
Do you consider in-space manufacturing to reuse the materials of your orbital stage? (bonus)	1	0	0

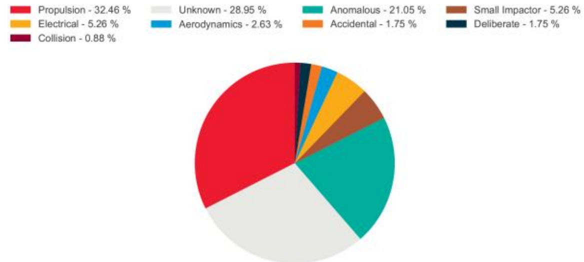

Fig. 4 Causes of fragmentation events in the past 10 years [13].

In the past 10 years, most of the fragmentation events have been caused by the propulsion subsystem [13]. Passivation of the propulsion seems thus more important than for the electrical subsystem. But the graph on figure 4 accounts for any type of spacecrafts, and electrical subsystems of launch vehicles are usually designed for shorter operational lives so there could be more risks [23]. So questions 4 and 5 are included in Table 3, with more points put on the propulsion passivation.

Casualty risks include the death or serious injury of someone, with an accepted risk threshold set at 10^4 human casualties per reentry [18]. If the casualty risk is too high, guidelines require the operators to conduct a controlled reentry. Meaning they have to manoeuvre their object so that it falls down in a low-risk area, usually the South Pacific Ocean Uninhabited Area (SPOUA).

Demisability is another key parameter in the EOL scenario, especially for uncontrolled reentry. Some space objects that reenter the atmosphere are not fully demised by the friction and heating of the descent, typically 10-40% of the mass will touch down [24]. It is particularly true for some very resistant material like titanium, and the behaviour of composite materials during reentry is not yet well characterized. Design for demise of the orbital stage will be rewarded in the bonus score (Table 3, question 7) because although it lowers risk for ground casualties it also generates particles at high altitude during the demise. Their impacts are not yet well understood, although preliminary studies have found that they could be modest [25]. Those impacts would have to be considered in the LCA module.

Objects falling down during the ascent phase of the rocket and their associated risks are already covered in the "ground to space" module (section 4.1). For space objects that would land using their propulsion system, the safety and success rates shall be similar to those coming down in free fall or with other means.

For objects that do not come down, embedding in-orbit servicing (IOS) features to facilitate a rendezvous, for instance with a refuelling or repairing spacecraft, or with an ADR mission, is rewarded. The latter being interesting for upper stages that would not have enough fuel to deorbit themselves at the end of their mission or for debris and MROs. An interesting way to reuse the materials of space waste and avoid burning and losing them in the atmosphere would be in-space manufacturing but the technology is still not mature so this last input should be counted only as bonus point.

4.4 Data Sharing

This module is similar to the data sharing one in the SSR [1] and several questions about the launch vehicle are already included. Here the questions of course focus only on the launch vehicle and the shared data will have to target specific audience: SSA providers, air and sea traffic management authorities, other operators and/or operators' network upon request, or the general public. Ideas of types of information that should be shared are shown in table 4, the scores have been decided based on the impact that sharing an information with a target audience has on space safety. The Fibonacci sequence up to 13 is used to rate the score of each cell so to have clear demarcation between levels, but the scores can still be fine-tuned in future revisions.

Table 4. Input parameters for the Data Sharing module. Do you share the information with the relevant audiences? Cells are shaded in yellow when both scenarios 1 and 2 comply, in green when only scenario 2 complies, and are left without shading if the input is not applicable (see section 6).

Data sharing	SSA providers	Air/sea traffic	Operators	Public
Contact information	8	8	13	13
Launch windows time	2	5	1	3
Ascent trajectory (Planned and actual)	2	8	1	3
Upper stage metrics				
Ephemeris	8	0	13	13
Covariance	2	0	5	5
Covariance validation	5	0	3	3
Orbital stage characterization				
Mass	3	0	3	5
Manoeuvrability [y/n]	8	0	8	8
Manoeuvrability capacity	8	0	8	2
Operational status	8	0	8	5
Autonomous system? (bonus)				
Your criteria to trigger a manoeuvre?	5	0	5	5
Planned autonomous manoeuvres?	5	0	5	5
Emergency stop procedures?	2	0	3	3
Others				
Radio-frequency information	1	2	5	8
Stage anomaly information	5	1	5	5
Datasets to support government and academia	5	1	2	5
APIs to automatically access info	2	1	2	2

Applicants can score points in any of the cells, either 0 if the data is not shared or all the points if it is, and the points are cumulative. A verification level is applied for each row of the table. The maximal number of points is 250 and 38 bonus point. By dividing the achieved score by the maximal number of points, one gets a result between 0 and 1 that is used in the final formula.

4.5 Life Cycle Assessment

While the other modules focus on the impacts on the space environment and the risks of space debris, the idea of this module is to also account for the impacts of the launch vehicle on Earth's environment. Life Cycle Assessment (LCA) is a recognized method to capture the environmental footprint of a product. It is said to be multi-step and multi-criteria because the method accounts for impacts along the whole life cycle of a product and outputs the impacts on several issues. The goal is therefore to avoid burden-shifting by reducing the impact during one project phase or in one impact category (indicator) at the expense of others. Typical LCA indicators include Global Warming Potential (GWP, assessed in kg CO_2 equivalent), Ozone Depletion Potential (ODP), Abiotic Resources Depletion (ARD), and many more, in particular those used in the ESA LCA handbook [14].

eSpace leads a consortium of Swiss entities developing a software tool (the assessment and comparison tool, ACT) to assess and compare the environmental impacts of several space transportation vehicles (STVs) architectures for a given mission. Its main goal is to automatize life cycle assessments of STVs, to understand their environmental impacts since early in the design phase. Although assessing an LCA module requires a lot of input data, using the tool developed at EPFL could simplify the rating process.

A single score formula to aggregate the impact indicators and weight them with their importance regarding the definition of "green space" for ESA will be discussed during the 2022 CleanSpace Industry Days [26]. Using this formula, it will be possible to set thresholds that incentivize launcher providers to improve their products' life cycle.

Efforts to limit the impacts of the manufacturing, or the logistics, etc. would help to reduce their overall footprint and thus improve their score. Selecting the source of raw materials, and of energy production depending on their impacts will also improve the LCA score. Finally, key design choices can lower the impacts during operations of the launch vehicles: the propellants type, the engine cycle, as well as the trajectory are the main drivers of the emissions taking place during the propulsive phase(s) of a mission [27, 28]. Recovery of stages and reusability, will reduce the abiotic resource depletion impact but will have to be traded-off with additional emissions for instance. ACT will account for those choices and the output will allow for comparison between several LV architectures to evaluate their effectiveness at reducing impacts.

Important to note that including a module about LCA raises potential issues about the responsibilities of the emissions and other impacts. It may happen that a company's role is to deliver a launcher, but it is the responsibility of another one to launch and operate it. The latter would be responsible for all impacts related to space debris, in orbit. But in this case, the LCA score would have to be assessed with data coming from two companies, which would complexify the life cycle inventory step and the certification process.

5. Rating formula

A complete rating formula cannot be created yet since the scoring of the LCA module is still to be defined. Also, more development is needed on the ESA mission index to accommodate elliptical orbits like GTO. Table 5 summarizes the development status of the modules.

Table 5 Summary of the modules' development status.

Module	Status
Ground to Space	Need validation with real data
Mission Index	Need extension for elliptical orbits
EOL Management	Need validation with real data
Data Sharing	Need validation with real data
Life Cycle Assessment	Need aggregating formula (LCA single score), ACT to compile the inputs, and validation with real data

A basic formula is proposed with weighting factors for the modules described in Table 6. The exact weights will need to be fine-tuned with tests based on real and fictive inputs. This is to ensure the rating is applicable to a wide range of launch vehicles and outputs calibrated results that correctly highlight the better designs and operational choices. For now, the score of the LCA module is not accounted for so the final score is corrected to have it on a scale up to 100%.

Table 6 Weighting factor for each module will depend on their importance.

Module	Importance	Weight
Ground to Space	Low	7.5%
Mission index (absolute)	High	40%
Mission index (relative)		10%
EOL Management	Low	7.5%
Data Sharing	Medium	15%
Life Cycle Assessment	Medium	20%

For each module, the tier points are summed up if the applicant provides a positive answer to the questions, and the sum is divided by the total number of tier points available. The bonus points are summed together across the modules and divided by the total number of bonus points. If an input is not applicable, for instance the question regarding autonomous systems in the data sharing module (table 4), it is removed from the total, so it has no influence on the final score.

As a first assumption, the same thresholds as for the SSR are applied to divide the final score into rating tier levels: bronze (40-55%), silver (56-70%), gold (71-80%), and platinum (81-100%). This has the advantage of keeping the output clear for SSR applicants even though space and launch segments score can not be compared with one another. These percentages can be adapted following beta testing. For bonus points the thresholds are set at quarters of points: 0 star (< 25%), 1 star (25-50%), 2 stars (50-75%), and 3 stars (> 75%).

6. Test cases

In order to try this preliminary LVSR formula and highlight modules or questions that should be improved, some tests were done with mock data found in the literature. For the purpose of the analysis, the verification factors were left at 1 (authority level) or 0.5 (assertion) for all inputs, to see the highest and lowest achieved scores. Two rocket bodies (RB) launched to Sun Synchronous Orbits (SSO) at about 800km, 98.6 degrees are extracted from F. Letizia et alli [5] with their values for the ESA mission index. They are also rated with the questionnaire-based modules with two compliance levels: Scenario 1 is a baseline created with inputs derived from the Ariane 5 user manual [29]. Where no data could be found, assumptions were taken to fill tables 2, 3 and 4. Scenario 2 implements most best practices as defined in the previous sections (4.1 to 4.4). It is made with assumptions for an improved launch vehicle, but still with realistic design choices and operational behaviours, see below. This generates a total of eight test cases by combining the rocket bodies with the compliance scenarios 1 or 2 and with the two verification levels.

For the "ground to space" module (see Table 2), it is assumed that scenario 2 has deployment mechanisms that do not generate debris. It is also assumed the orbital stage has (a) re-ignitable engine(s) that can perform an End-of-life Manoeuvre (EOLM) and collision avoidance manoeuvres.

The target orbits of the rocket bodies were chosen to correspond to a concept of operation from the user manual [29] and to match with mission index scores found in the literature [5]. RB1 corresponds to the first row of Table 5 in F. Letizia et alli [5], RB2 is the 16th row. They were chosen because of the difference between their index scores. The validity of these approximations is discussed in section 7.

Regarding the End-of-life management module, it can be noticed in Table 3 that the baseline scenario scores very little points. This is because the Ariane 5 user manual does not detail the deorbitation strategy, only stating that "deorbitation of the upper stage [is performed] if necessary" [29]. Direct deorbiting technologies were planned on the Ariane 5 ME version, even for GTO mission profiles, before its cancellation [30]. It will now be part of Ariane 6 version. The second scenario gets a lot more points by implementing an EOLM and passivation. This is deemed achievable since some passivation/EOLM strategies are already implemented in the latest Ariane 5 flights [31].

None of the cases implement autonomous reentry so the corresponding cells in Table 4 are left as *not applicable*. For the other inputs of data sharing, it is assumed that the baseline scenario shares all relevant information with an SSA provider, while scenario 2 shares them with all possible audiences, greatly improving transparency.

Table 7. LVSR modules' and aggregated scores. The four test cases of the first rocket body (RB1) are shown.

LVSR modules – RB1	Scenario 1 (baseline)		Scenario 2 (improved)	
Verification level	0.5	1	0.5	1
Ground to Space (%)	35.7	71.4	50	100
Abs. mission index (%)	43	49	43	49
Rel. mission index (%)	0			
EOL management (%)	16.7	33.3	44.4	88.9
Data sharing (%)	13.4	26.8	50	100
LVSR tier score (%)	**28.9**	**39.3**	**39.7**	**61.0**
Bonus score (%)	0	0	20	40
Bonus level (stars)	0	0	0	1

Table 7 provides the results of the modules as assessed for the first rocket body without the LCA module. Fig. 5 shows the cumulated scores considering the weighting factors of the modules, with the tier level thresholds.

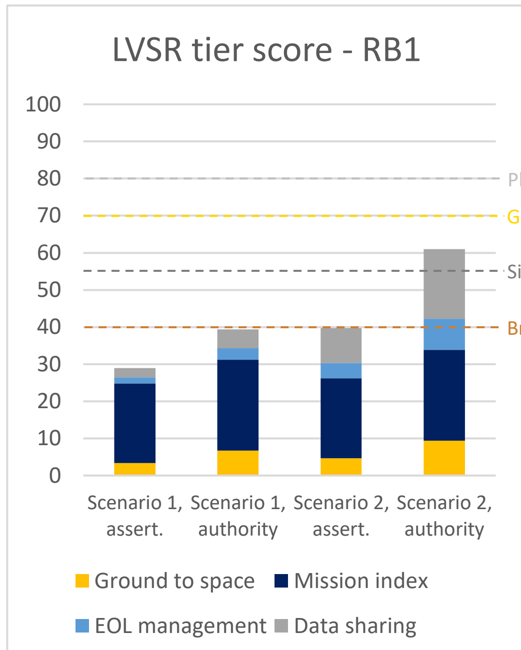

Fig. 5 Cumulated score of each module and tier level reached by the four test cases of RB1.

Table 8 LVSR modules' and aggregated scores. The four test cases of the second rocket body (RB2) are shown.

LVSR modules – RB2	Scenario 1 (baseline)		Scenario 2 (improved)	
Verification level	0.5	1	0.5	1
Ground to Space (%)	35.7	71.4	50	100
Abs. mission index (%)	63	66	63	66
Rel. mission index (%)	0			
EOL management (%)	16.7	33.3	44.4	88.9
Data sharing (%)	13.4	26.8	50	100
LVSR tier score (%)	**38.9**	**47.8**	**49.7**	**69.5**
Bonus score (%)	0	0	20	40
Bonus level (stars)	0	0	0	1

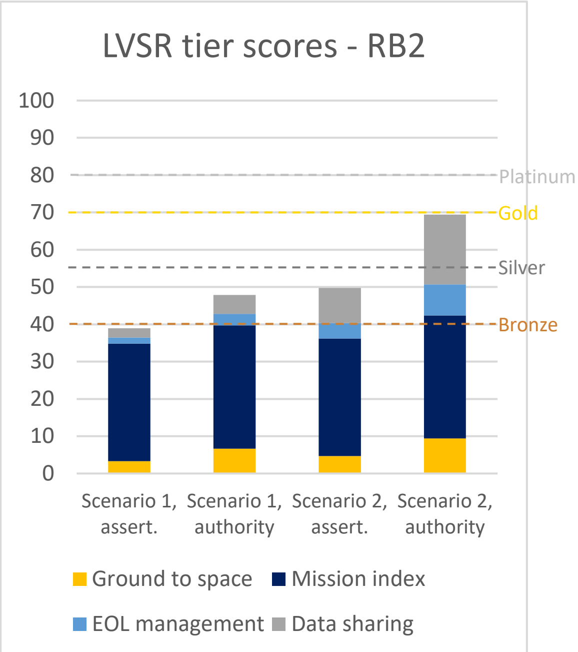

Fig. 6 Cumulated score of each module and tier level reached by the four test cases of RB2.

7. Discussion and next steps

The first results shown in section 6 prove that a Launch Vehicle Sustainability Rating with a similar format as the SSR is possible to implement and makes sense. To score high, LV providers are incentivized both to implement sustainable designs and operational behaviours and be transparent with data relevant to space safety. With the current formulation and weights, it is only in the improved test cases with high verification levels that a launch vehicle can get a good rating.

Of course, assumptions and simplifications mean these scores are not completely accurate and there is still room for improvement for the content of the LVSR modules. In particular for the mission index, which acts as a "score stabilizer" due to its high importance and the little change in its score.

Firstly, the relative mission index is not zero in the improved scenarios but should help getting an even higher score. Indeed, in the EOL management module, the two first questions (see Table 3) provide the information that the natural decay after disposal is shorter than the IADC guidelines [7] for scenario 2. The relative index rewards this by comparing the actual disposal with a scenario based on the 25-years rule with a 90% PMD success rate. For now, only ESA can compute the real values of the mission index, like they do for the SSR. As stated before, for this first iteration, values from literature were used [5], which did not provide relative index scores. Not to guess a wrong value, it was decided to leave the relative score at zero for all scenarios.

Secondly, the real mass of a launch vehicle upper stage, its real cross section, and the mission duration all have an impact on the debris risks assessed with this metric. In these test cases, the masses are 8226 kg (RB1) and 1764 kg (RB2) [5] which contribute to RB1 scoring less overall. The exact values used in F. Letizia et alli [5] are not known for the cross section or the mission duration for instance. In any case, a more precise assessment can be done by using the specific launch vehicles' data.

For now, many modules are assessed with inputs simply defined as true or false. Some inputs already score more points than other depending on their relevance, but using models or more complex combination of information should allow to output more relevant information about space safety and sustainability. Based on the significant parameters described in section 4, and the results of this first analysis, it will be possible to improve the modules by asking for more inputs and aggregating them with more precise formulas.

As seen in the results tables (Table 7 and Table 8), the bonus scores only change slightly between the cases. Some questions might need to be reworked or new questions added, with more points attributed, to have a bonus score that changes more easily. But the objective of the bonus score is to reward providers that go beyond what is now expected so it is fair to keep more demanding scoring criteria.

Finally, as discussed above, this paper provides test cases derived from available literature. But one cannot work on fine-tuning a rating formula without real values provided by companies that would accept to act as beta testers for the LVSR. Following a similar process as the SSR, the EPFL Space Center would sign NDAs with LV providers to test the LVSR with their data and make sure its formulation can be applied to any type of LV while reaching its main goal of reducing space debris risks and environmental impacts.

8. Conclusions

Starting from the finding that launch vehicles providers are not incentivized as much as satellite operators to improve the sustainability of their products, even though they have a large impact, this paper suggests a first simplified formula for a Launch Vehicle Sustainability Rating.

The format of the SSR and space debris guidelines are reviewed to define a list of parameters that are important regarding the sustainability of a launch vehicle. The parameters that are accounted for in the rating formulation are explained, and grouped in five modules covering the phases of a launch vehicle's mission. From the ascent with the "ground to space" module, to the "orbital phase", to "end-of-life management". A "data sharing" module, incentivizing more transparency, and a "life cycle assessment" module to account for impacts on the Earth's biosphere, are also discussed.

Eight test cases are created with mock data that are aggregated into a single score. With the presented test cases and the assumptions taken, it can already be seen that launch vehicles rated with the LVSR can score on the range from below bronze, to higher than gold (see Fig. 5 and Fig. 6). This confirms the validity of the LVSR as a way of rewarding designs and behaviours that improve the mission's sustainability.

The next development step will be to beta test the rating by modelling test cases with real data from launcher providers. It is envisioned to use those beta tests to fine-tune the modules' weights and formulations.

By continuing the development of the LVSR and adding it to its offer, the EPFL Space Center will provide a new metric to assess the sustainability of space actors, and incentivize them to design, share data and behave in accordance with the space environment limitations.

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