

Launch Vehicle Sustainability Rating Development

Entwicklung eines Trägerraketen Nachhaltigkeitsrating

Bachelorarbeit von
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IRS-23-S-025

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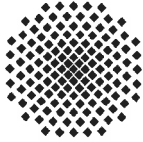
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Universität Stuttgart

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Bachelor Thesis Work
of Mr. Dominik Alexander Gentner
Entwicklung eines Nachhaltigkeitsratings für Trägerraketen
Launch Vehicle Sustainability Rating Development

Motivation:

eSpace has been selected as the organization taking over and putting in place the Space Sustainability Rating, a system that will evaluate the level of sustainability of satellite missions. It has been developed in the last three years by a consortium of organizations including the WEF, ESA and MIT. The objective of the SSR is to push forward sustainability in the space sector and reward operators whose missions comply with the sustainability norms and guidelines, mainly related to space debris mitigation.

It has been shown that the impacts of the launch vehicle (LV) were not easily captured by the current version of the rating. Moreover, the responsibility for sustainability in space is for now mainly put on spacecraft operators and there is little incentive for LV providers in this field. On the other hand, rocket bodies are dominating the current total fragmentation risk and the new space mindset could see many more (micro) launchers produced and launched, which could increase the problem of space debris.

Project scope:

During this project, the development of a new rating formula will be continued, dedicated to the launch vehicle's orbital stage impacts on the space environment. The student will be provided with a list of identified significant parameters and the first iteration of the rating formula. Based on that, the student will bring his own knowledge and research work to develop a coherent and applicable rating system for launch vehicles' upper stage impacts. The focus of this bachelor thesis is first on space debris mitigation, with possible extension depending on the students interests. During the project, there is the opportunity to present the work to the SSR team at eSpace. If the results are convincing, it will also be possible to present it to the SSR advisory board, a group made of companies active in the space sector and/or to the SSR consortium.

Task description of the Bachelor thesis work:

- Understand the Space Sustainability Rating concept
- Assess the development status of the LVSR
- Perform a literature review on rating systems development to define a methodology to create a coherent scoring formula
- Collect data from launch vehicles providers and refine the selection of parameters depending on data availability and on interactions (beta tests)
- Iterate on the LVSR modules' scoring formulas
- Analyse the outcomes of the module with the collected data and rank several launch vehicles, and create guidelines for spacecraft operators to select launch vehicles based on environmental impacts
- Documentation

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Starting date: 01.03.2023

Submission until: 30.06.2023

Acknowledgement of receipt:

I hereby confirm that I read and understood the task of the bachelor thesis, the juridical regulations as well as the study- and exam regulations.

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Abstract

The launch of spacecraft into space has significant global-scale environmental implications, encompassing emissions in atmospheric spheres, resource extraction and utilization, pollution on flora and fauna, potential debris and collision risks, infrastructure development, airspace closures, and restrictions on astronomical observations. This Bachelor thesis aims to address these environmental concerns by analyzing sustainability aspects of launcher systems and identifying key variables that influence their viability so these can be implemented into a launch vehicle sustainability rating.

This research emphasizes the importance of factors such as vehicle reusability, propellant selection, infrastructure requirements, and launch location in assessing the sustainability of launcher systems. Notably, the disposal of launchers after completing their missions and the cohesive environmental impacts that remain insufficiently studied yet are critical aspects. However, these aspects also present substantial potential for the development and improvement of environmental, economic, and social equity.

To facilitate a comprehensive evaluation of launcher sustainability, the study proposes the development of a sustainability rating system that highlights the most efficient pathways for improvement. Although the rating system is a future prospect, it aims to address various aspects crucial to enhancing the environmental and socio-economic performance of launcher vehicles.

Therefore, development of an End-Of-Mission part that will be included into a sustainability rating provides a manageable approach to assessing the overall sustainability of a launcher system. Through this process, significant aspects that warrant attention and improvement have been identified, drawing upon documented feedback and reflection to minimize potential biases.

Further, a background research on sustainability aspects of launcher systems has been conducted. The results of this research are then compared with the latest version of the Launcher Vehicle Sustainability Rating, short LVSR, as of March 2023. This thesis explores new ideas and endeavors to incorporate as many relevant sustainability aspects regarding launcher vehicles as possible.

Throughout that development, challenges in developing new, succinct research questions have been encountered. identified and addressed as far as possible. Furthermore, a weighting methodology utilizing a questionnaire has been developed, but its refinement is required for future research.

Finally, while beta test reviews were not included due to limited feedback from respondents and time constraints, their incorporation in future studies could provide valuable insights.

Kurzfassung

Der Start von Raumfahrzeugen ins Weltall hat erhebliche Auswirkungen auf die Umwelt auf globaler Ebene. Dazu gehören Emissionen in der Atmosphäre, Ressourcengewinnung und -nutzung, Verschmutzung von Flora und Fauna, potenzielle Trümmerteile und Kollisionsrisiken im Orbit und auf der Erde. Weiterhin auch die Entwicklung der erforderlichen Infrastruktur, Luftraumschließungen und Einschränkungen bei astronomischen Beobachtungen.

Diese Bachelorarbeit zielt darauf ab, diese Umweltbedenken zu adressieren, indem Nachhaltigkeitsaspekte von Trägersystemen analysiert und Schlüsselvariablen identifiziert werden, die ihre Machbarkeit beeinflussen. Diese werden dann in ein Bewertungsverfahren der Nachhaltigkeit von Startfahrzeugen implementiert.

Diese Arbeit legt den Schwerpunkt auf die Bedeutung von Faktoren wie Wiederverwendbarkeit des Fahrzeugs, Auswahl des Treibstoffs, Infrastrukturanforderungen und Startort, um der Bewertung der Nachhaltigkeit von Trägersystemen beizutragen. Insbesondere die Entsorgung von Trägersystemen nach Abschluss ihrer Missionen und die kohärenten Umweltauswirkungen sind noch unzureichend erforscht, jedoch kritische Aspekte. Gleichzeitig bieten diese Bereiche auch erhebliches Potenzial für die Entwicklung und Verbesserung von ökologischer, wirtschaftlicher und sozialer Nachhaltigkeit und Gerechtigkeit.

Um eine umfassende Bewertung der Nachhaltigkeit von Trägersystemen zu ermöglichen, schlägt die Studie die Entwicklung eines Nachhaltigkeitsbewertungssystems vor, das die effizientesten Wege zur Verbesserung aufzeigt. Obwohl das Bewertungssystem eine zukünftige Aussicht darstellt, zielt es darauf ab, verschiedene Aspekte anzusprechen, die für die Verbesserung der Umwelt- und sozioökonomischen Leistungsfähigkeit von Startfahrzeugen entscheidend sind.

Die Entwicklung einer End-of-Mission Komponente, die wie der Name sagt, sich mit der Nachhaltigkeit eines Trägersystems nach Missionsende beschäftigt, bietet einen überschaubaren Ansatz zur Bewertung der Gesamtnachhaltigkeit solch eines Systems. Im Rahmen dieses Prozesses wurden bedeutende Aspekte identifiziert, die Aufmerksamkeit und Verbesserung erfordern. Dabei wurden dokumentiertes Feedback und Reflexionen genutzt, um mögliche Verzerrungen zu minimieren.

Zusätzlich, wurde eine Hintergrundforschung zu Nachhaltigkeitsaspekten von Trägersystemen durchgeführt. Die Ergebnisse dieser Forschung werden mit der neuesten Version des Bewertungssystems für die Nachhaltigkeit von Trägersystemen, dem Launch Vehicle Sustainability Rating, kurz LVSR, vom März 2023, verglichen. Diese Arbeit erforscht neue Ideen und bemüht sich, möglichst viele relevante Nachhaltigkeitsaspekte von Startfahrzeugen einzubeziehen.

Darüber hinaus wurden bei der Entwicklung prägnanter Forschungsfragen Herausforderungen identifiziert und soweit wie möglich angegangen. Außerdem wurde auch eine Gewichtungsmethodik entwickelt, die auf einem Fragebogen basiert, jedoch eine Überarbeitung für zukünftige Forschungen erfordert.

Obwohl Beta-Test Bewertungen aufgrund begrenzten Feedbacks von Befragten und zeitlicher Beschränkungen nicht einbezogen wurden, könnten diese in zukünftigen Studien wertvolle Erkenntnisse liefern.

Contents

Abstract	IX
Kurzfassung	XI
1 Introduction	1
Motivation	1
Main Objective	4
Research Questions	4
State of the Art	5
Sustainability Rating	5
Launch Vehicles	5
Life-Cycle-Assessment	5
LVSR	6
LVSR as part of Space Sustainability Association	8
Existing Questions	8
Reducing Technological Bias	9
2 Theory	11
2.1 Expendability	11
2.2 Reusability	11
2.3 New proposed modules of the LVSR	12
2.3.1 Logistics	12
2.3.2 Resources	14
2.3.3 Manufacturing	16
2.3.4 Active Use	18
2.3.5 End-Of-Mission	20
2.3.6 Reentry	23
2.3.7 Reuse and Recycle	25
2.4 Questionnaire	26
2.5 End-Of-Mission Questions	26
3 Methodology	29
3.1 Development Process of the EOM Module for the LVSR	29
3.1.1 Comparison to Current Core Modules	30
3.1.2 Focus on the End-Of-Mission Module	30
3.2 Questionnaire tree diagram	31
3.2.1 Expendability versus Reusability	33
3.2.2 Expendability on Earth	34
3.2.3 Expendability in space	36
3.2.4 Reusability on Earth	38
3.2.5 Reusability in space	40
3.3 Questionnaire	42
3.4 Weighting Process of Questions	42

4	Evaluation of Results & Discussion	53
4.1	Feedback on the Questionnaire	53
4.1.1	Analyzing Results	53
4.2	Challenges Developing Questions	54
4.3	Evaluation of the questionnaires Beta tests	54
4.4	Evaluation of the Weighting Process	54
4.5	Including EOM into the Questionnaire	54
4.6	Discussion on a Future LVSR	54
5	Conclusion and Future Outlook	57
5.1	Conclusion	57
5.2	Future Outlook	57
6	Appendix	59
6.1	Abbildungen	59

List of Figures

1.1	Increasing area of objects in orbit; Probability x Severity [9]	2
1.2	Cumulated fragmentation risk index; Probability x Severity	3
1.3	Fraction of MRO Release Events by Source	3
1.4	Core modules of the LVSR	6
1.5	LVSR tier scores	7
1.6	Correlation between SSR, LVSR, ACT, LCA	8
2.1	Logistics	13
2.2	Resources	15
2.3	Manufacturing	17
2.4	Active use	19
2.5	End-Of-Mission	22
2.6	Reentry	24
3.1	Legend of the decomposition of the questions in the diagrams 3.2, 3.3,3.4, 3.5, 3.6, 3.7	32
3.2	Upper questions	32
3.3	Expendability	33
3.4	Reusability	33
3.5	Expendability on Earth	35
3.6	Expendability in space	37
3.7	Reusability on Earth	39
3.8	Reusability in space	41
6.1	LVSR in development	60

List of Tables

2.1 Advantages and disadvantages of an overall and broad or a specific and detailed questionnaire	26
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Nomenclature

Abbreviations

ACT	Assessment and Comparison Tool
AOCS	Attitude and orbit control system
EOL	End-of-life
EOM	End-Of-Mission
ESA	European Space Agency
IADC	Inter-Agency Space Debris Coordination Committee
ISRO	Indian Space Research Organisation
ISRU	In-situ-resource-utilisation
LCA	Life-Cycle-Assessment
LV	Launch vehicles
LVSR	Launch Vehicle Sustainability Rating
NASA	National Aeronautics and Space Administration
OOS	On-orbit-servicing
SSR	Space Sustainability Rating

1 Introduction

This thesis deals with the subject of the Launch Vehicle Sustainability Rating, the LVSR. The LVSR is a research project done in partnership with the Space Sustainability Rating, SSR, association [28]. It is used to analyze the sustainability of launcher systems and display that in a final score. Therefore, it covers the logistics, resource management, manufacturing, the active mission, and the end of the mission that also includes a potential recovery or reuse of the launcher system.

As the LVSR says in its name, it deals with launcher vehicles and their correspondent systems. Launcher vehicles are vehicles that are able to take off a celestial body and are able to put a payload onto a specific desired orbit around the celestial body. In this thesis, Earth and its orbit are the only ones taken into account. Examples for these are rockets, like the Saturn V, the Space Shuttle, the SpaceRider, the Falcon 9 rocket by SpaceX or the Ariane 5 rocket by the ArianeGroup [14, 2, 29].

Motivation

The motivation behind this thesis can be summarized into the following aspects.

Firstly, mitigation of space debris. As seen in 1.1 a significant area in orbit is being accounted for by rocket bodies, RB, in orange. These are in fewer number than other space debris. Due to their higher mass and overall bigger structures, they pose almost two thirds of cumulated fragmentation risks. This can be seen in figure 1.2 where they take up 66% of the described risk. As more and more debris accumulates in orbit this can also lead to a chain reaction of out-of-control collisions which is called the Kessler Effect. [13, 36] Additionally, another aspect is that high cost to counter space debris with evading maneuvers, de-orbiting debris and its potential crashes and loss of material compared to implementing strategies to prevent debris in the first place. This can also decrease accessibility to space for institutions and organizations with lower budgets in the future.

Secondly, space missions require a high amount of limited resources as metals, but also energy and clean water. Therefore, it is only beneficial to reduce the necessary resources and therefore reduce waste and costs. Regarding future development and the increasing surge of orbital launches, this is not only important to reduce resource consumption on Earth but also in space when developing in-space manufacturing, no matter when using in-situ resource utilisation, ISRU, on the Moon or another celestial object or when recycling debris in space. Related is also a substantial decrease in lower visibility regarding astronomical observations from Earth's surface as spacecraft and therefore also debris reflect sunlight. This is especially true during sunset and sunrise and occurs when spacecraft reflect sunlight back to Earth to telescope observatories [26].

Thirdly, as mentioned before, the need for resources is currently increasing [5]. To sustain long-term space exploration, it is not only crucial to decrease its initial resource requirements but also to decrease ongoing consumption of energy and replacement parts during operation of spacecrafts and launcher systems to increase sustainability. Additionally, this can also open up new possibilities for disadvantaged organizations to access space operations through lower prices.

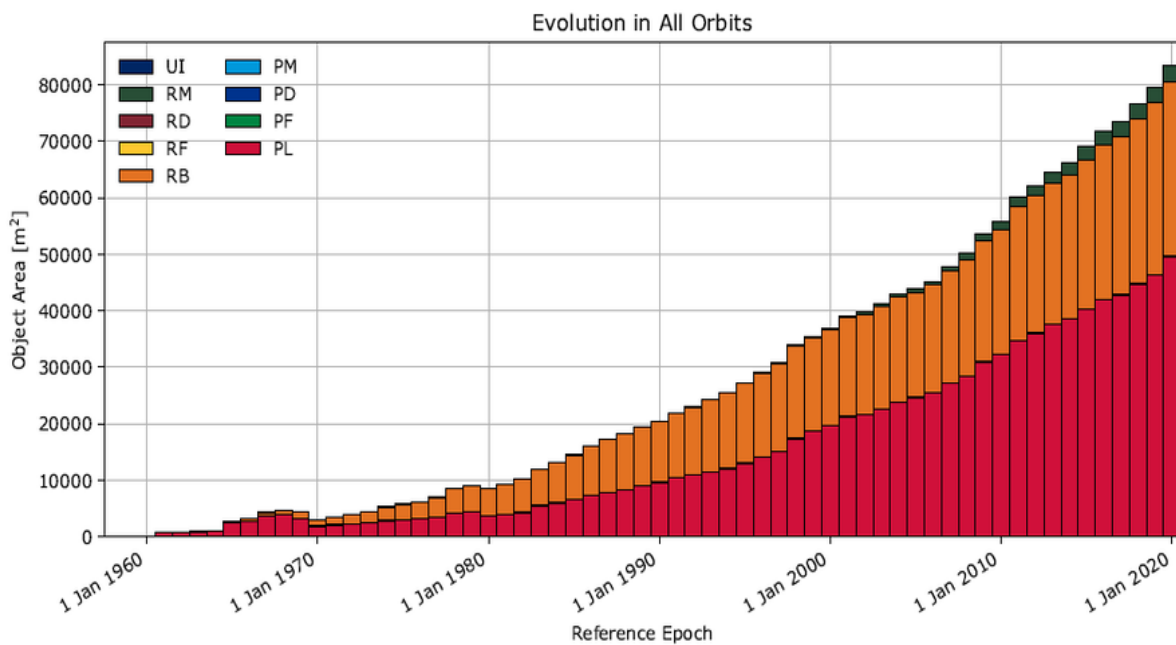
1 Introduction

Moreover, while improving the sustainable development of launcher systems for the reasons mentioned, this can also contribute to environmental friendly development on Earth; be it reducing the space industries impact on climate change or tackling extreme weather events with the help of technology developed for space applications [12].

Finally, another motivational aspect for this thesis is the increase of international cooperation that also helps to increase social equity. International cooperation increases through sustainable development of the space industry and vice versa as international cooperation offers more possibilities and a wider range of perspectives regarding space technologies.

These risks and aspects of environmental impact by launcher systems can be read more in detail in ESA' annual report [9].

Such a sustainable development leads to environmental, but also economic viability and increased social equity.



(c) Evolution of area.

Figure 1.1: Increasing area of objects in orbit; Probability x Severity [9]

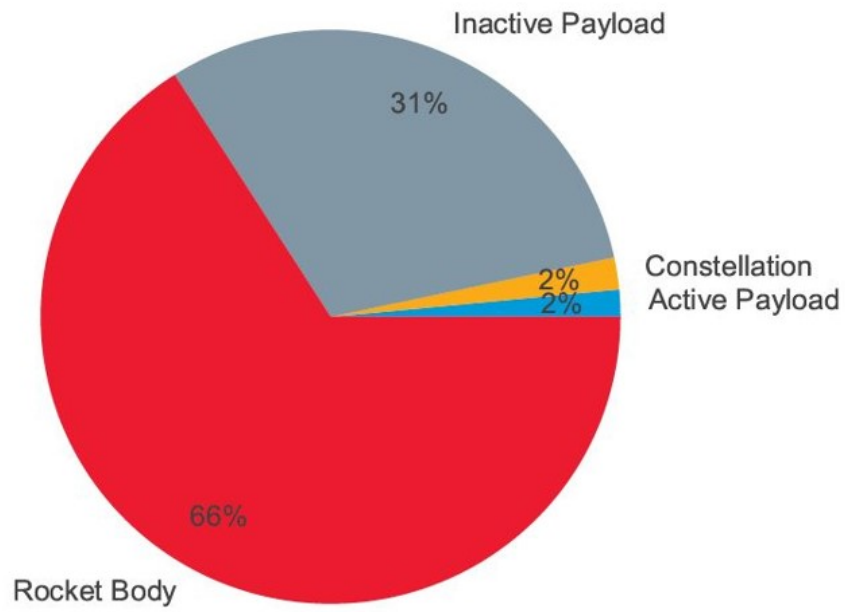


Figure 1.2: Cumulated fragmentation risk index; Probability x Severity

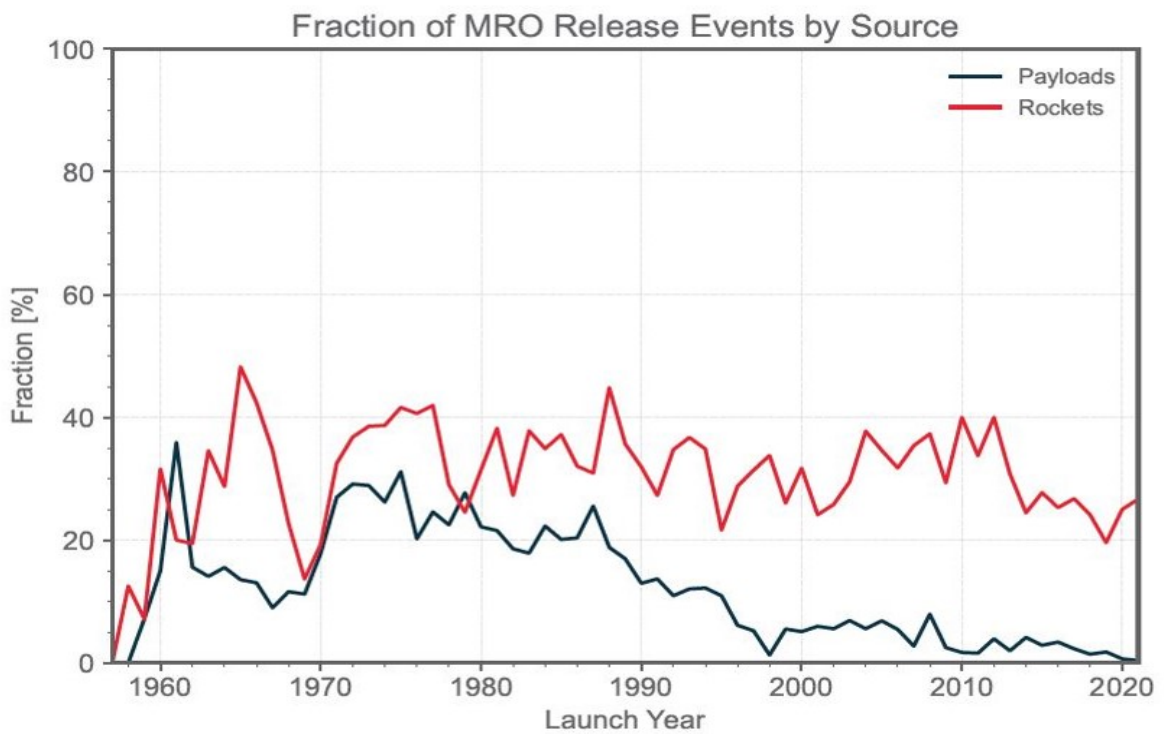


Figure 1.3: Fraction of MRO Release Events by Source

Main Objective

The main objective of the LVSR is to increase the sustainability & safety of launcher systems while rating the real systems and comparing these to the rating of optimized launchers. Therefore, it will be possible to hand out recommendations to improve the current systems. This will be done while advising about the sustainability aspects with the highest impact on the specific system. The results of these ratings are aimed to be reported to the applicant who also decides how to communicate those. Publicly available will be the methodology of the rating on the Space Sustainability Association, SSR, website [28]. Though, publicly published results by companies themselves will help to incentivize action in competitive launch providers.

The focus of this thesis is on understanding the Space Sustainability Rating concept and assessing the current development of the LVSR. Further, also to perform a literature review on rating systems development to create a defined and coherent scoring formula; collect data from launch providers and refine the selection on parameters through the beta tests. In addition, an iteration on the LVSR modules' scoring formulas and finally analyse the outcomes and create the possibility to refer to new guidelines to help spacecraft operators in choosing launch vehicles based on environmental impacts.

Research Questions

Regarding the LVSR, the final aim is to make space missions more sustainable. For this to happen, the sustainability of LV has to be analyzed first to communicate specific recommendations about aspects with the highest impact to the respective launch provider so viable actions can be undertaken and introduced in the future. It is optimal to advise on aspects with the highest impact and those that can be implemented in a facile way.

For this, it is beneficial to explain what sustainability means for space missions and what the most important aspects for sustainable launcher systems are. To accomplish this and explain and elaborate on the findings a rating is a way to progress. In this case it is the LVSR. For this, it is necessary to clarify how a reasonable rating can be accomplished. Such a rating has to include all major sustainability aspects that are called modules in this thesis. These are covered in 3.1.2.

As this requires a high amount of effort and broad research to commence, which results in a high workload, it will not be completely covered during this thesis. For this reason, this thesis focuses on the End-Of-Mission module that is being explained later in more detail in 2.3.5 and 3.1.2.

The EOM module has been chosen to be focused on during this thesis most importantly due to a high possible impact on sustainability of launcher systems. Examples that can potentially increase its sustainability are reusable rocket launchers or open publication about the systems location and data while many factors have to be considered.

Thus, a viable way to rate a launcher vehicle's, sustainability at end of mission has to be developed. In this case this follows a path to construct a questionnaire, that can later be implemented in a user-friendly form.

Therefore, in this Bachelor thesis, answering the following main research questions is undertaken.

- What are main sustainability aspects in the End-Of-Mission phase for launch vehicles?
- Which of these aspects have the biggest impact on sustainability regarding launcher vehicles?

State of the Art

State of the art concepts and systems include newly flight proven LVs, a current design of the LVSR and relating systems. These are introduced in this section.

Sustainability Ratings

A sustainability rating serves the analysis of products and their impact on the environment. For this it is important to clarify what sustainability is. Most commonly it is defined as quoted by the UN World Commission on Environment and Development: "sustainable development is development that meets the needs of the present without compromising the ability of future generations to meet their own needs". This also means that sustainable development relies on three aspects, the environmental, the economical and the social equity aspect. [35]

It is important to differentiate between those three aspects common aspects used in conjunction with sustainability and to keep in mind that it is necessary to take all three into account during a design process to ensure a viable development.

It is for this reason aimed to improve sustainable design processes which can be done with the help of an environmental sustainability rating that serves to find out major and most efficient improvement recommendations.

Launch Vehicles

Launch vehicles are vehicles that take of a celestial body and transport their payload into an orbit around the celestial body they launch from or even further. These are commonly rockets, like the Saturn V, the Falcon 9, the Ariane 5 or the Geosynchronous Satellite Launch Vehicle, GSLV [29, 2, 20]. Space planes like the Space Shuttle or the SpaceRider are also being described as launcher vehicles. Finally, there are launcher systems in development to provide access to space for satellite providers with a centrifuge and a minor rocket for the final ascension like the SpinLaunch company is working on [31].

Currently, these systems are being developed further by various start-ups around the world to improve their efficiency and create launchers for more specific and smaller payload missions than currently provided by SpaceX. As these technologies make access to space becomes more accessible with an increasing number and more frequent orbital launches. Due to this, the sustainability of LVs has an increasing impact on Earth's environment, astronomical observations and a viable development in the industry.

Important to mention is that state of the art are not only reusable launcher systems but also expendable one as the Ariane 5 that has a high safety and success rate in comparison with other systems [2]. Also, different chemical propulsion systems are in development and future prospects include the mentioned SpinLaunch development but also air to space launches from a balloon or a plane and not necessarily a vertical take-off from ground.

Life-Cycle-Assessment

Life-Cycle Assessment, or LCA, is a systematic approach used to evaluate the environmental impacts of a product, process, or service throughout its entire life cycle. In short, this involves assessing the environmental inputs, outputs, and potential impacts at each stage of a product,

1 Introduction

including raw or recycled material extraction, manufacturing, transportation, use, and end-of-life management.

The LCA process has been standardized to improve its use commercially and to ensure comparability of different LCA studies. This can be found in the ISO 14040 [18] regarding standard principles and in ISO 14044 [19] explaining standard requirements and guidelines to perform a LCA study.

LVSR

First and foremost, the Launch Vehicle Sustainability Rating, LVSR, is being developed by the Space Sustainability Rating Association.[33]

First introduced by Mathieu Udriot in 2022 [33], the concept is to rate LV on their sustainability looking into 6 different modules. These are, as seen in 1.4, the Life Cycle Assessment, the Ground to Space, the Orbital phase, the Data verification, the Data sharing Transparency and the End-of-life, EOL, Management modules. This design is to be separate to the Space Sustainability Rating, that focuses on spacecraft, satellites and constellations, that are carried by LVs into space to fulfill its mission.

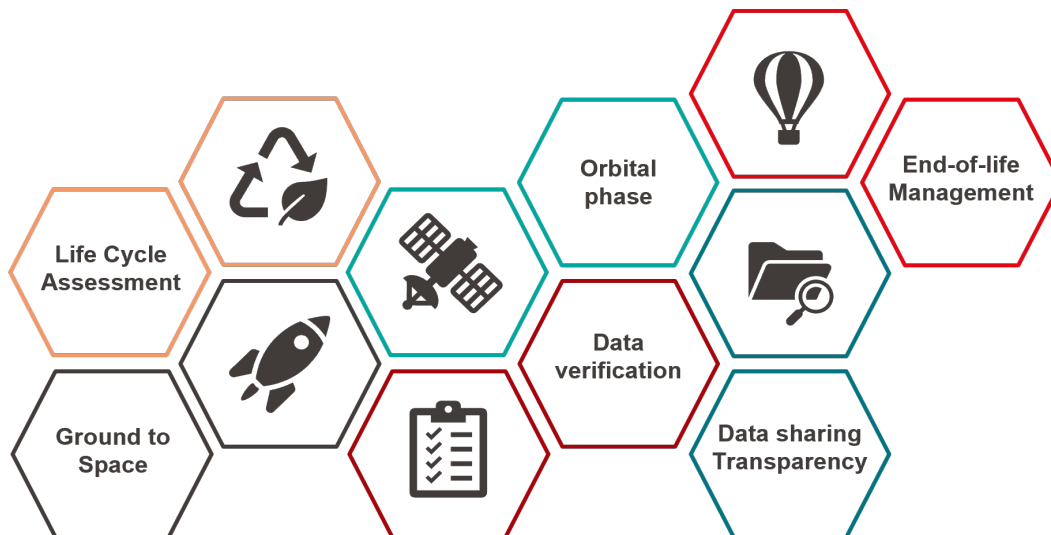


Figure 1.4: Core modules of the LVSR

As the LVSR was envisioned as rating, it also requires to have comparable scores after analyzing the LVs sustainability. These can be seen with examples of two scenarios in figure 1.5. Each scenario ends in a its actual score and the potential optimal score they could have as a result. The scores are combined out of four areas; The ground to space, mission index, EOL management and the data sharing section.

The results are then classified in one of the four final classification; The Bronze, Silver, Gold and Platinum tier scores.

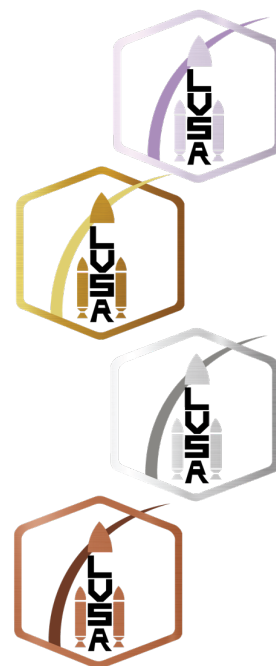
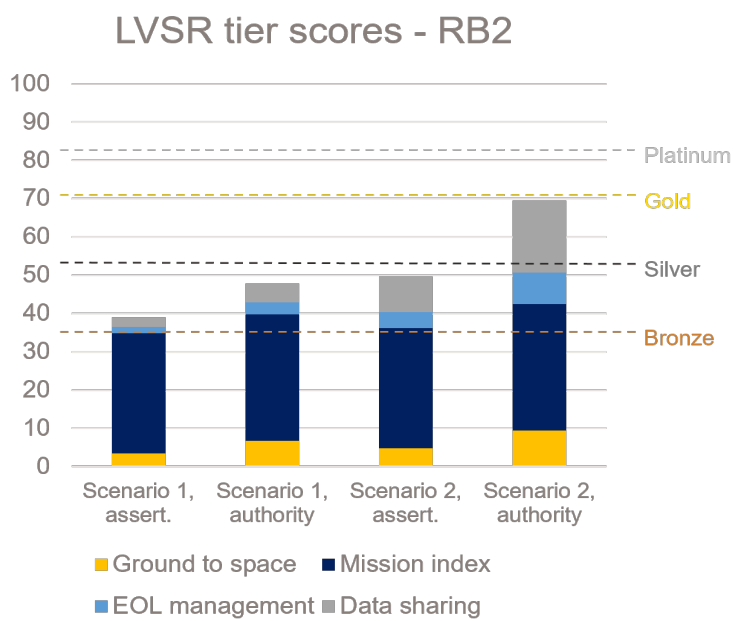


Figure 1.5: LVSR tier scores

LVSR as part of Space Sustainability Association

As you can see in the following figure 4.3, the LVSR is part of the Space Sustainability Rating Association, SSR, and takes into account the Life Cycle Assessment, LCA, that is included via the Assessment Comparison Tool, ACT.

The ACT is a developing software tool to assess and compare the environmental impacts of several space transportation vehicles architectures for a given mission. This is being developed by a consortium of swiss entities lead by eSpace [34].

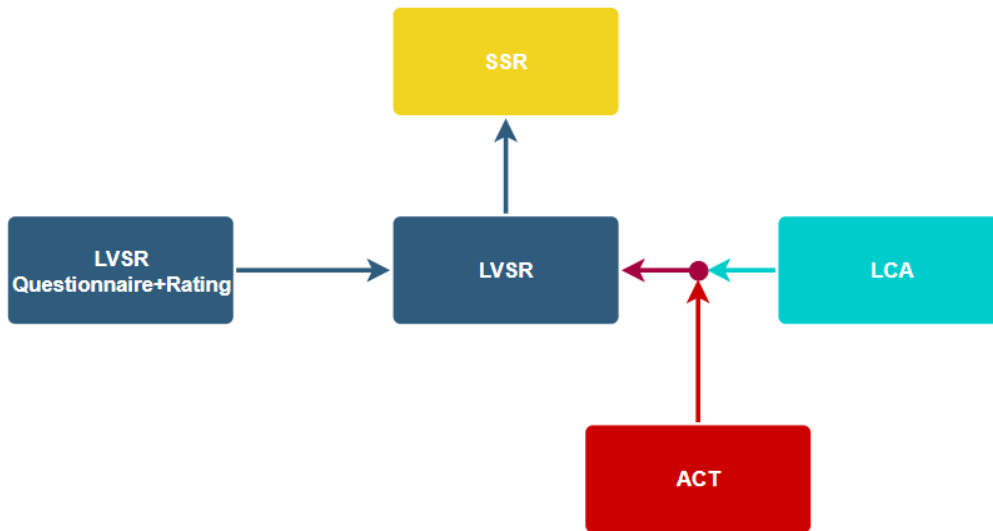


Figure 1.6: Correlation between SSR, LVSR, ACT, LCA

Existing Questions

The following questions have been presented in [34]. These are the questions relating to the end-of-life of a launcher vehicle. These are shown here, due to relevance on the focus of the End-Of-Mission module during this work. Its importance is derived from the inclusion of the end-of-life aspects into the End-Of-Mission area.

Existing EOM questions:

- Do you use a disposal orbit after the end of mission?
- (according to IADC guidelines, section 5.3)
- (Reentry) Do you use a disposal orbit (after EOM with a natural decay;5 years)?
- (Reentry) Do you use a disposal orbit (after EOM with a natural decay;1 year = direct reentry)?
- Do you passivate the propulsion system after the end of mission?
- Do you passivate the Electric Power System after the end of mission?
- (Reentry) Do you satisfy the 10E-4 casualties limit at reentry?
- (Reentry) Is your stage designed for demise? (bonus)
- Do you embed OOS features? (bonus)
- Do you consider in-space manufacturing to reuse the materials of your orbital stage? (bonus)

Reducing Technological Bias

Considerable efforts can be made to minimize impartiality in research. In the realm of bias reduction, various forms of impartiality exist, ranging from technological to political or ideological biases, as well as geographical or demographic biases. It has to be acknowledged that biases can inadvertently influence the research process and compromise the integrity of the findings. To address this, several strategies have been developed.

Firstly, seeking feedback from peers and mentor and reflection on developed research helps to assess possible biases. This also means a careful selection of diverse and representative sources is of importance. Inclusivity also helps in reducing the potential for sampling impartiality. Rigorous research methodologies, such as systematic reviews, or large-scale surveys, should also be employed to prevent biases throughout research.

In addition, transparency plays a crucial role in bias reduction. Transparent documentation of research processes, including design, data collection procedures, analytical methods, and decision-making processes enables others to evaluate and replicate the work, ensuring that biases arising from selective reporting or undisclosed analytical choices are minimized.

Furthermore, external validation through peer review and expert feedback helps identify and address potential biases. By engaging in rigorous review and welcoming external perspectives, it is possible to enhance the objectivity and reliability of findings.

Also relevant is a potential confirmation bias, wherein researchers favor information that confirms their preconceived notions while disregarding contradictory evidence, is a prevalent challenge. In general, selection, publication, or reporting bias, and impartiality arising from funding or conflicts of interest also warrant attention. It is a necessity to proactively address these biases by adopting robust methodologies, transparent reporting practices, and ethical considerations.

For instance, in the context of this research, it is essential to be mindful of potential biases that may arise from personal beliefs, industry influences, or limitations in available data. By recognizing and addressing these biases, it is possible to enhance the credibility and objectivity, enabling a more reliable evaluation.

2 Theory

In the theory section, expendability, reusability, new proposed modules of the LVSR and a questionnaire regarding developed sustainability questions are presented and explained. The focus lies on one of the modules, the End-Of-Mission module. 2.3.5 Additionally, it has to be clear that this development evolved without performing a LCA, see 1, study. Reasons for this decision include the aim to include aspects of environmental sustainability that are not included in an LCA, the vast area of an LCA study and further development to connect the LVSR with the LCA to gain a broader tool for the assessment of a launcher systems environmental viability.

2.1 Expendability

Expendability describes the disposable or replaceable nature of a resource, product, or system. This means the object is being used up or consumed during service. It can also refer to the fact that it is more easy or economic to replace than to rescue, salvage, maintain, or reuse it. [22]

This is relevant to sustainable development as a design strategy for products based on expendability increases the required resources for the production in the long-term, creates unnecessary waste that can not yet be recycled and has an impact on the products disposal environment. Additionally, though expendable product design may be more economic in the short term, it can increase costs due to scarce resource coming from resource depletion, high demand that the production cannot sustain or geopolitical issues covered by the critical raw material analysis [3]. It has a negative impact on social equity as communities with less resources may find it difficulties in funding. Also, the geopolitical aspect is reinforced when the country relying on critical material does not produce these.

2.2 Reusability

Reusability refers to the attribute of objects that can be reused for its purpose multiple times. [23]

Aforementioned is significant for sustainable development as contrary to expendable designs as described in 2.1 reusable design development helps to conserve resources in the long-term and reduces waste as a reusable product can be used instead of multiple expendable ones. Additionally, energy could potentially be preserved and emissions reduced due to lower manufacturing numbers per use of a product due to the same reason resulting in lower demand numbers and due to decreased transportation and logistics emissions. Here, it is relevant to remember that more research need to be done regarding emissions caused by refurbishment, testing and additional logistics from down range recovery to the launch site of launcher vehicles. Thanks to reusable nature of the product or systems, this solution is more economic for customers as can be seen in the development of SpaceX's reusable first stage of the Falcon 9 rocket.[1] This can result in a behavioral change and improved tendency to develop a more circular economy. The latter commonly being the goal for sustainability developments [10].

2.3 New proposed modules of the LVSR

Modules here regarding the LVSR serve to manage all sustainability aspects regarding the LVSR into comprehensible groups. These are the main modules; the logistics, resources, manufacturing, active use, End-of-Mission, reentry, and recycle and reuse modules. These main areas do also have subordinate modules to further elaborate on important parts. The subordinate aspects are described in detail during each main module's elaboration in the following subsections. They explain specific environmental areas relevant to the overhead modules.

2.3.1 Logistics

Logistics in general refer to planning, coordinating, implementing and controlling processes. This module involves the coordination and management of various activities, including transportation, storage, and distribution, to ensure that the right items are delivered as needed for a successfully accomplished task. This can take into account resource like materials, water, energy, time and land. This can be seen in figure 2.1 which also serves to describe this subsection.

The logistics module can be split up into two branches: transportation, and planning the mission's operation and its connected logistical aspects. This can be seen in figure 2.1.

Transportation is divided into five areas, namely materials and resources needed, required infrastructure, the transportation of the crew to needed location, moving the vehicle to test and launch facilities and finally transporting the payload to the launch site.

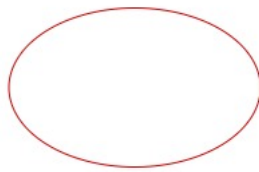
The planning of the operation connects to the mission operation and the logistics of the launch site.

The mission operation discusses logistics regarding safety, like for example no-fly zones, the control center necessary for the mission and the desired orbit for launch.

The launch site combined with the technical specifications of the launcher vehicle restrict the orbital range accessible. Also important to overcome logistical challenges (hurdles?) is the connectivity of the launch site. This includes mainly transportation infrastructure, but also public institutions like hospitals or housing opportunities. These are important as they can have an effect on safety and the environmental impact should the infrastructure be crucial and required to build beforehand.

The environmental impact does not only regard the general LCA of the infrastructure, but also impacts on surrounding national parks, endemic or endangered flora and fauna that are being caused by infrastructure, the launch itself or secondary aspects like impacts on the local industry. This is more relevant for economic and social sustainability than environmental one. Further, it has also been shown that launch areas can suffer from acidification induced by emitted gases and toxicants during the launch. Additionally, a launch impacts regional air space closures that are required to ensure a safe launch. This has impacts on public flight paths and potentially also temporary closures of airports. The relevance for space sustainability regarding the latter argument consists, as safety plays a role in sustainable space development. This is also a part why these logistical aspects are included into the LVSR. One example would be the impact of space launches on maritime and air traffic when announcing no-fly or no-traffic zones to increase safety. Especially, this ever-growing transportation sector has an restricting impact on space launches or vice versa. This can cause delays in traffic or increase safety concerns. [27] [17]

Legend:



Existing parts in the current LVSR



Figure 2.1: Logistics

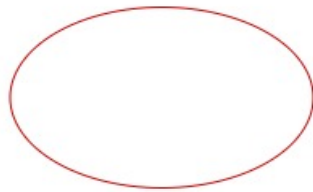
2.3.2 Resources

Resources are available materials, tools, funds, personnel, or other means needed to used to execute a task.

This module is relevant because it includes the extraction of raw materials, environmental impacts of land and energy usage, but also the respective emitted emissions and their toxicity. Additionally, this module can be split in material extraction and energy, but finally mainly the environmental impacts that the energy and material usage evoke/induce.

The material extraction is split up into mining material and using recycled one. Both options impact the environment. The energy, that again has an impact on the environment can be divided into, reusable and non-reusable energy but also the water usage during assembly or manufacturing for example. These branches are shown in figure 2.2. While infrastructure that is part of the Logistics module has an environmental impact, it clearly impacts land usage, regarding transportation infrastructure or a necessary no flight zone for example. Apart from land usage, also the usage of non-recyclable materials and emissions, where the latter is bisected into the greenhouse gases and toxicity induced, have an environmental impact seen in figure 2.2.

Legend:



Existing parts in the current LVSR

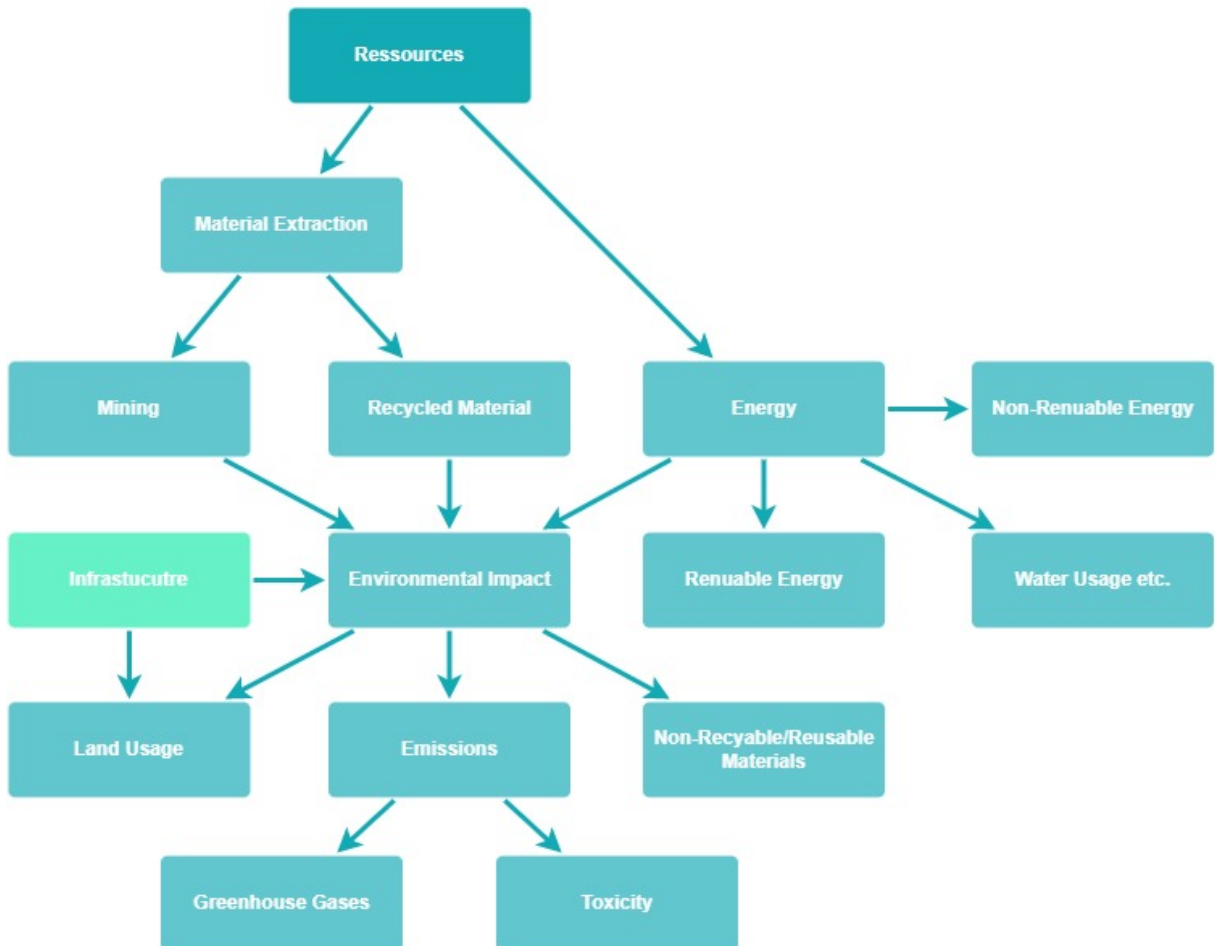


Figure 2.2: Resources

2.3.3 Manufacturing

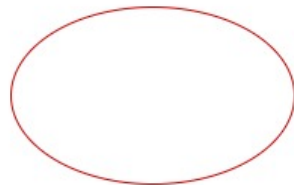
Manufacturing is the process of converting raw materials, components, or parts into finished products through various methods, techniques, and operations. This commences with processing raw or recycled materials into other assets that are finally converted into the end products.

Regarding a launcher system, this takes into account its development phase, its testing, manufacturing including all necessary steps to construct flight hardware. This is crucial as these aspects that have a high impact on the launchers performance and CO₂ footprint.

Here, the manufacturing module has been split up in mainly three sub-modules, the research and development module, R&D, a module regarding processes used in material processing and construction of various parts and the Testing sub-module. These distinctions are made as they have different environmental implications and also impact each other. R&D is commonly done with little to no manufacturing, but impacts the manufacturing processes. For example, specific materials and structures can be designed, but that choice impacts required manufacturing processes and their energy usage. Additionally, the more thorough the research and development has been done, the issues or late changes arise. On the other hand, testing influences R&D, as results can influence the design of the LV.

The R&D module is connected to the Resources and Logistics module as these have an influence on the research and development of a launcher vehicle. The Processes module also involves the logistics but also the energy usage that is part of the Resources module. Finally, the Testing module includes real life subsystem and complete system tests, but also simulations and the usage of a digital twin to reduce emissions in testing which is a sustainability benefit. Apart from that, a digital twin is also more cost efficient than test on hardware, as it reduces the amount of hardware that has to be manufactured and tested before certification.

Legend:



Existing parts in the current LVSR

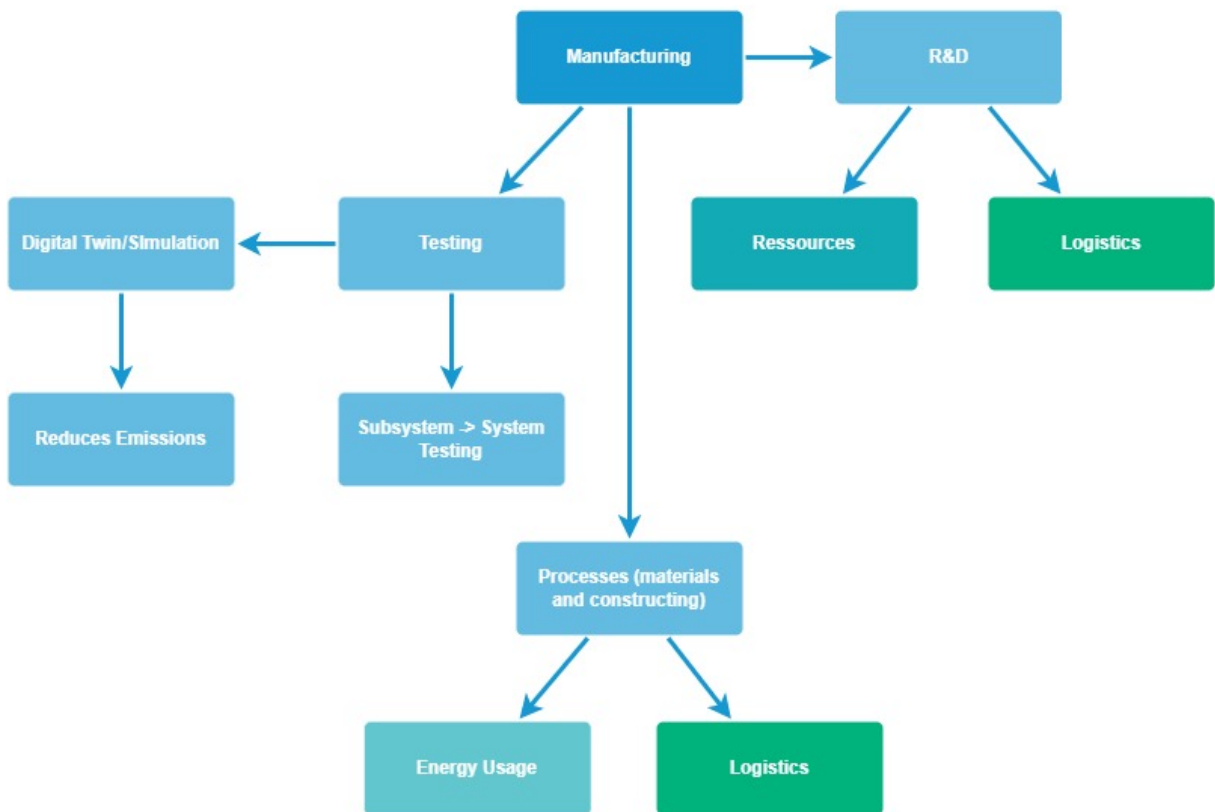


Figure 2.3: Manufacturing

2.3.4 Active Use

The active use mission phase starts when the a vehicle, spacecraft or other machine is being prepared for it mission until the end of its operational mission duration. To clarify, this module does not include reentry or demise of the launcher system to improve the overview over all modules.

This is an important part of the LVSR as this phase takes into account the sustainable use and use according to international norms and regulations. Also, this is the phase with a possible negative effects on the space environment regarding possible debris creation and potential collisions.

Active use can be divided into the preparation and active launch modules as seen in figure 2.4. The preparation phase regards transportation and infrastructure needed for the launcher, payload and the crew involved. These are part of the logistics module as elaborated before.

The actual launch consists of orbit safety, altitude and orbital control systems, short AOCS, where both have already been included in the current LVSR, and the pollution module. Pollution refers to noise pollution, emissions that are already part of the manufacturing module 2.3, infrastructure that is part of the logistics module and potential debris in space or on Earth, whereas the latter aspect is part of the current LVSR as seen in figure 2.4.

The AOCS can be split up into three groups, namely active AOCS, passive AOCS and no AOCS at all. Especially, the latter can create potential collisions and therefore also unnecessary debris in orbit. Unnecessary debris can also be the vehicle itself as it stays in space for a longer duration when it does not have an AOCS that could divert its orbit to for example a reentry into Earth's atmosphere.

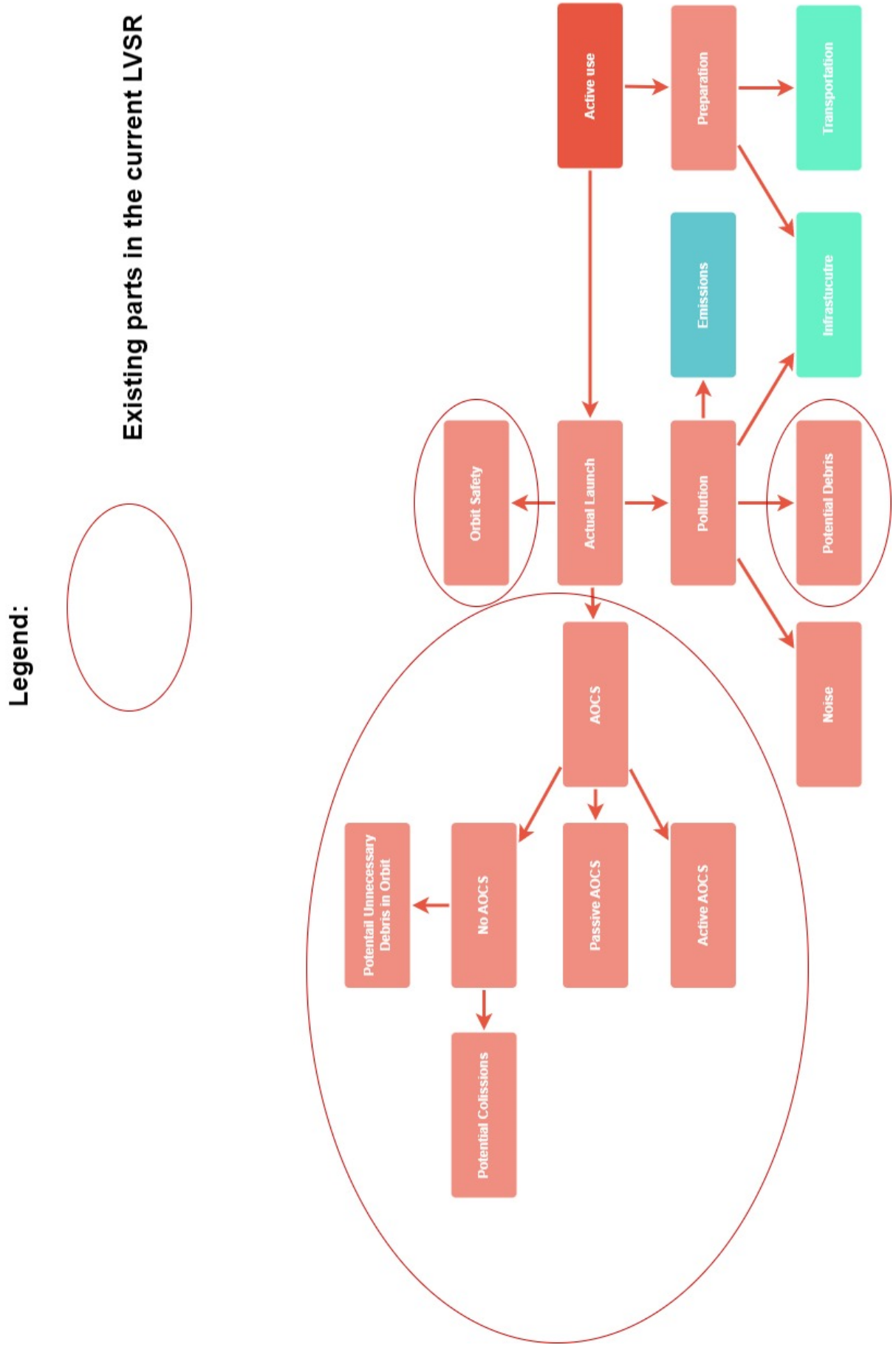


Figure 2.4: Active use

2.3.5 End-Of-Mission

The End-Of-Mission, EOM, module relates to the mission phase after the active mission concludes or a product has outlived its usefulness.

This module is relevant for the LVSR, because it helps to rate the sustainability of a launcher vehicle regarding reusability, expendability, recycling, recovery, gathering atmospheric data while descending to Earth, a possible burn-up of the vehicle in the atmosphere, debris risks and a potential reuse or recycling in orbit.

Space debris mitigation and recycling or reusing the launcher vehicle are main parts of the EOM module while the module can be mainly split up into reusable launch vehicles and expendable ones as seen in the figure 2.5 while these have already been partly included in the current LVSR.

For both, it is necessary to consider the reusability for each stage. Also, available AOCS are a necessary feature for sustainability to avoid collisions and to serve end-of-life manoeuvres de-orbiting the vehicle so it does not become a debris.

Among others, reusable launch vehicles take into account needed infrastructure to sustain reusable launcher systems. This is connected to the logistics module. Also, economic viability that has been proven by the latest developments in rocket launchers is an aspect necessary to consider. This is connection point to another module, in this case the resources module.

There are currently at least three possible ways for a launcher to reenter Earth's atmosphere. These are a parachute recovery, gliding back to an airfield like the Space Shuttle and the space rider with a parafoil [14] or a self-propelled return to the launch pad like the SpaceX's Falcon 9 first stage [29]. For the first two options a secondary transportation to the launch pad has to be considered, though for all three options refurbishment of the vehicle could be necessary. Therefore, checks have to be taken into account to ensure safety and sustainability of the launcher system. Regarding this, required energy and time make an impact on the sustainability of the launcher vehicle. This can especially be seen when looking into the refurbishment, as potential transportation infrastructure but also the refurbishment center itself have to be available. Should the refurbishment also require a clean room, the energy usage can increase even more as extensive filter and air conditioning systems may be needed.

Expendable launcher vehicle that are not staying in orbit and have been adapted to the IADC guidelines according to section 5.3 can be split up into three options as seen in figure 2.5. Burning-up in the atmosphere, crashing into a common location, crashing into a recovery location or an uncontrolled crash.

A crash into a recovery location increases risk on ground infrastructure that is connected to the reentry module, but also creates the potential of material recovery and recycling that decreases environmental hazards created by debris and reduces the environmental impact of sourcing the materials needed for the launcher system. A crash into an ocean opts for a potential recovery of the material as long as the launcher is not designed to sink as soon as possible to decrease marine traffic closures but also to decrease environmental risks in the upper water layer [27]. A crash on land would have similar implications though the known environmental hazard would be higher [4]. Recovery of the parts would in most cases be easier to carry out.

A burn-up in the atmosphere would decrease the risk on ground infrastructure, compared to the previous options, especially when a 100% burn-up is aimed for. This could also be achieved if the expendable vehicle does not stay in a LEO or GEO orbit but would divert to a graveyard orbit, another orbit acceptable for debris or the Moon [11].

While a burn-up of the vehicle in the atmosphere decreases risk on ground infrastructure, it

impacts Earth's atmosphere due to emissions in upper atmospheric layers. These emissions have an impact on the climate but have not yet been studied sufficiently to understand the exact changes that could conclude. Due to occurring particle emissions during an atmospheric reentry which highly depend on the used material, this is connected to the resources module through its environmental impact [4].

As the EOM also includes the de-orbiting of a launcher, it is therefore also connected to the reentry module.

2.3.6 Reentry

The reentry module takes into account the reentry of spacecraft into Earth's atmosphere. In this case the de-orbiting of a launcher vehicle. Moreover, after standing alone, this module has been incorporated into the EOM module as the reentry is commonly undergone after the desired operational mission. As this section includes reentry and demise, though these topics overlap and are well connected with the EOM module, the whole Reentry module will be included into the End-Of-Life module further in this work as in section 2.3.5.

Relevance of this module can be found in the emitted emissions of gases and particle during reentry, possible uncontrolled debris impacts on Earth and the potential to accomplish a reentry where the LV sustains the possibility of reuse. The emitted particles can have an impact on the toxicity of the environment but do have negligible effect on the ozone layer depletion regarding a single reentry event. [7]

In the figure 2.6, the specific modules that are part of Reentry can be seen with their connections. This forms sustainable potential to gather atmospheric data during reentry. This is benefiting environmental development as it serves research on emissions during reentry, but also generally research on atmospheric layers. Further, there is the module regarding separation of mechanical parts during a descent. Impact risks on Earth are connected to the segmentation. Further, there are the emissions connected to the reentry of a vehicle due to at least a partly burn-up of it's materials. This module is part of the Resources module, but is clearly connected to the reentry. Apart from that, the module regarding potential debris, that is part of the End-Of-Life module, but clearly connected to the impact risk and segmentation of a launcher vehicle, as the segmentation of a vehicle during descent increases potential debris on Earth.

After comparison with the already developed LVSR, it can be seen that the whole Reentry module has already been taken into account and implemented to a certain degree.

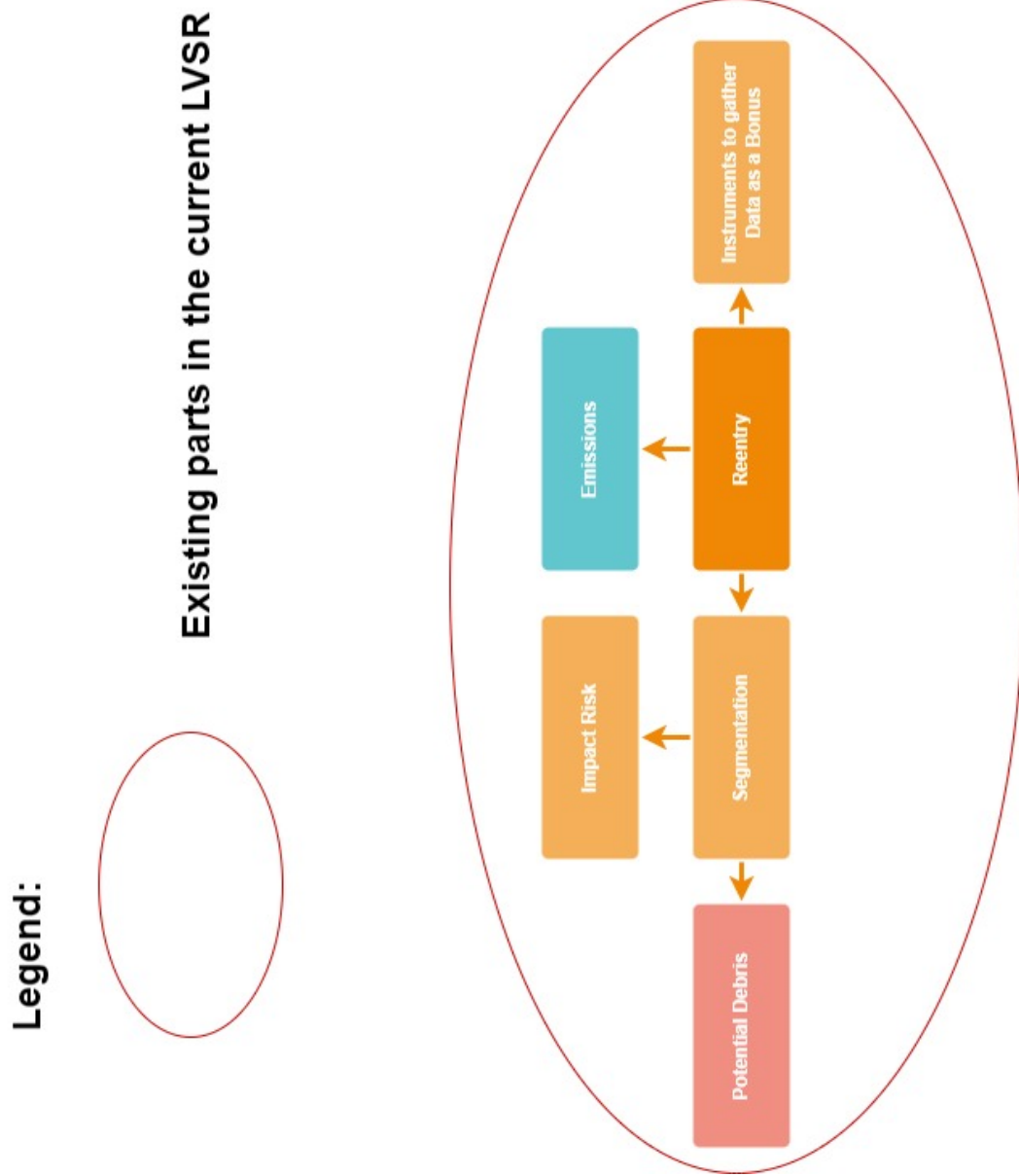


Figure 2.6: Reentry

2.3.7 Reuse and Recycle

The reuse of products and in this case launcher vehicles has been elaborated upon in 2.2. Also, its potential and importance are explained in that section.

Recycling of products or its debris is the process of converting waste materials into reusable materials to minimize the consumption of new resources, reduce waste generation, and mitigate environmental impacts.

Therefore, recycling is a critical practice for promoting environmental sustainability, conserving resources, reducing waste, and mitigating the environmental impacts of human activities. It contributes to creating a more sustainable and circular economy that supports viable long-term environmental activities. This is particularly crucial in the space industry as rare or high value materials are often used for space missions. Apart from Nickel, Aluminium and Steel, rare materials such as Tantalum and Niobium or Lithium are used in spacecraft. [21, 30] Additionally, should in this case a launcher vehicle be reused or recycled in space to serve another mission, this also decreases the number of required orbital launches. Relevant representations in the module map are located in the End-Of-Mission area. 2.5 This module is entwined with the Active Use and End-Of-Life and only a prospective module for future development. This means it will be developed in the future and be partly included in the EOM module. Therefore, this one is not as broadly covered and serves as an extension not a completely separate module. The following notes have been taken.

An advantage reusing or recycling a launcher in space would be for example that materials used in the launcher's upper stages would not have to be explicitly transported to space for manufacturing but could be recycled and reused in space, reducing potential transportation costs and atmospheric emissions during ascent and reentry of the stages. Additionally, this would decrease risks on infrastructure on Earth due to debris due to reentry.

Disadvantages include that not every material can be viably recycled and that the materials used for upper stages are not necessarily useful for in-space production. Further, this could potentially be exploited by launch vehicle providers, should this be technically or economically more viable than for example refurbishing or reusing a rocket. Therefore, it has to be kept in mind to incentivize providers not to use that technique to increase their sustainability but leave the unused parts in orbit as debris. This could be avoided by (inter-)national regulations to remove debris in within five years after service.

In summary, the reuse or recycling of upper stages in space can potentially bring high value in the future as long as required legislation would be adopted. (if the de-orbiting deadline is 5 years then also the removal from orbit to recycle should be the same)

2.4 Questionnaire

This section considers how to make a questionnaire specific enough for any launcher system while being able to fairly compare different ones.

Reasonably, there are two main possibilities of the attributes of a questionnaire. On the one hand, a questionnaire can be made out of overall broad question. These do require broad background knowledge, but are easy to answer as they do not involve any details. Therefore these are straight forward questions relating to any launcher system. Limitations thus prevail regarding specific insights into the sustainability of a LV. This format is easy to compare but has restricted capacities in regard of useful conclusions. As for the simple comparison, this facilitates a clear weighting of the questions. The wide range of covered topics helps to yield a tendency or overall strategy to chose as a launch provider to increase a missions environmental sustainability. This is summarized in table 2.1.

On the other hand, a form can consist of specific questions. This implies detailed background knowledge and therefore a longer duration to answer. Another drawback of this method is the increased difficulty in regard of the weighting. Benefits do arise due to the more in depth questions; The results are more exact and of higher value as conclusions tend to be more specific. This can help to define specific task to be encouraged to aim for by the launch providers to increase the vehicles sustainability. This is summarized in table 2.1.

Questionnaire	Advantage	Disadvantages
overall and broad	easy to answer simple weighting of questions well comparable	requires broad knowledge neglect of details limited insight
specific and detailed	detailed and therefore fairer specific results and conclusions	requires detailed knowledge longer duration to answer more complex weighting

Table 2.1: Advantages and disadvantages of an overall and broad or a specific and detailed questionnaire

Accordingly, it is desirable to create a questionnaire with the advantages of both the general and the specific questionnaire type. This results a set of questions that are simple to answer while also going in depth regarding the launcher system. Thus the aim is to conclude valuable insight to grow the sustainability of launchers. This is aimed for with the questions comparability.

As this is a challenging task to do, problems are explained in section 4.2.

The developed question are included in the section 2.5. Further a detailed questionnaire is elaborated upon in the methodology section 3.3.

2.5 End-Of-Mission Questions

As explained in paragraph 1, this work focuses on the EOM area due to a broad research area and consequently a high workload. Therefore, other areas of the LVSR are aimed to be further developed after future research.

New questions to rate the environmental sustainability part of the EOM module have been developed and can be split into two parts; Expendability 2.1 and reusability 2.2 of a launcher vehicle. These can again be split up in two geographically separate areas respectively; Expendability

of a LV on Earth, but also expendability in space and reusability of a LV on Earth and in space. This is shown in figure 2.5.

This is visualized in a question tree in 3.2 where it is also elaborated upon the development process. This means the methodology and process of creating the sustainability questions presented is explained in section 3.2.

As can be seen in the mentioned figure 6.1, there are general questions that are above the four just described sections 2.5 . These general questions have to be answered, too. Reason for this is that these general questions are relevant for any launcher vehicle and therefore independent from the more specific sections.

The general questions include:

- Number of orbital stages part of the launcher system
- Number of suborbital stages part of the launcher system
- Repeat for each stage from here on
- Is data about the stages mission being shared publicly?

Questions relevant to expendability on Earth are presented here:

- Do you gather data on the atmosphere during reentry to provide data for sustainable research?
- Percentage burning up
- Do you satisfy the $10E-4$ casualties limit at reentry?
- Is the trajectory publicly available?
- Is a commonly used debris crash location being used?
- Is the stage designed to sink into the ocean?
- Is the risk of starting wildfires mitigated?
- Is this publicly shared how to allow for an open discussion on the used methods?
- Will the material be recovered to decrease potential environmental hazards?
- Are parts designed to be recycled at the end of their lifetime?
- Percentage of the mass being recycled

These are required to take into account LVs that descend to Earth but will not be reused. The importance of these aspects arises due to a high potential of debris landing on Earth and due to atmospheric emissions during reentry.

Questions regarding expendability in space:

- Is the trajectory being openly published during ascent and on orbit?
- Time staying in orbit before removal/deorbit
- Does this satisfy the IADC guidelines according to section 5.3?
- Will the debris be removed in the future?
- Are parts designed to be recycled at the end of their lifetime?
- Percentage of the mass being recycled

The relevance of these questions lies in the debris field created by spacecraft out of service or

ones that have not been placed in a graveyard orbit and therefore pose a potential risk to active spacecraft in orbit and to the safety of future launches of LVs.

Questions including LVs reusable on Earth for future launches:

- Do you gather data on the atmosphere during reentry to provide data for sustainable research?
- How often can the stage be reused?
- Are checks necessary?
- Is the refurbishment process standardized?
- Does the launcher require refurbishment?
- Does the refurbishment take place at the launch location? (or external)
- Percentage of the mass being refurbished
- Does the vehicle use active propulsion for descent?
- Does the vehicle use passive propulsion for descent?
- Are parts designed to be recycled at the end of their lifetime?
- Percentage of the mass being reused

Importance of these questions represent rockets and other launcher systems that return to Earth after a successful launch to space and are then reused multiple times for this purpose. This is environmentally beneficial due to an increased sustainability. This results due to lower manufacturing numbers as well as a reduction of transportation requirements. Examples of such systems are SpaceX's Falcon 9 reusable first stage or NASA's Space Shuttle program. [29]

Finally the questions with regard to reusability in space:

- Do you use a disposal orbit after the end of mission? (according to IADC guidelines, section 5.3)?
- Do you intend to reuse or recycle the vehicle in the given 5 years after EOL?
- Is there a plan put in place to reuse the vehicle even before the launch of the mission?
- Does the launcher require refurbishment?
- Is the refurbishment process standardized?
- Percentage of the mass being refurbished
- Are parts designed to be recycled at the end of their lifetime?
- Percentage of the mass being recycled
- Does the vehicle use active collision avoidance?
- Does the vehicle use passive collision avoidance?
- Does the vehicle use passive collision avoidance reliant on an external system?

The necessity of these questions arises with the development of in-space-manufacturing, but also multi purpose vehicles and ride-share capabilities of LVs. These can either be reused on orbit for repurposed for a different mission.

As mentioned at the beginning of this section, the development process of these questions is explained in 3.2.

3 Methodology

The methodology describes on the research process how the results have been obtained. In short, this has been done with a combination of literature research, new ideas and feedback gathered.

Due to the high quantity of work regarding only one module and the amendment of the questionnaire, this work focuses on the EOM module. 2.5 This part is includes the Reentry module, regarding the way the launch vehicle is being reused or discarded after the mission phase.

3.1 Development Process of the EOM Module for the LVSR

The development process of the different modules of the LVSR has begun with a background research like a paper on the previously developed LVSR at eSpace [34] or Professor Neumann's dissertation regarding environmental LCA studies of space transportation [25], but also a paper on environmental impacts of space transportation systems published by the Institute of Space Systems at the University of Stuttgart [15] and a paper about Eco-design of future reusable launchers published at the EUCASS conference in 2022 [8].

Thereafter/thenceforth, a mind-map, which is now the LVSR module map 6.1, has been created through brainstorming. This has been updated and amended with time up to the final figure shown in this thesis 6.1. The creation of a mind-map using brainstorming raises potential bias due to the researchers knowledge and creativity. Hence, to decrease research bias the results have been compared and confirmed with further research.

Further, the work has been presented to experts at a mid-term presentation. These experts from eSpace, the University of Stuttgart and the University of Strathclyde have given valuable feedback to improve and continue the work.

The implementation can be seen in the development of the LVSR module map, that has been amended to be more detailed and organized, especially in the area of EOM. Thus, also including recycling and reuse into the EOM module, while adding the need for AOCS for a controlled atmospheric descent. Additionally, the reuse of LVs in space has been brought up as relevant for future missions.

Subsequently, a question tree has been developed. 6.1 Feedback from the thesis supervisors has been taken into account for improvement. More, the questionnaire tree has been designed so suit a user friendly software design in the future. Therefore, the questions ought to be specific and easy to answer, as elaborated in 2.4. It is aimed to design questions that can be answered with a number regarding an unit or a yes or no respectively. This simplifies the final scoring of launcher vehicles regarding their sustainability. Therefore, there are mainly three different question types; Pathway questions that divide the questionnaire in different areas, scoring questions that are crucial for the sustainability analysis of a LV and questions that require a number for a unit that also suit the latter reason. This is noted in the diagrams legend. 3.1

Further, the implementation of experts' feedback can be seen in the development of the questionnaire's visualization 6.1. Namely, has the feedback steered the way to split it up into the four areas

described in 2.3.5 and took into account the reusability of launcher vehicles in space while this technology is still in development.

Consequently, the developed questions have been implemented in a questionnaire to weight them. This is made in an Excel format. Therefore, all the four main areas and the overall questions as explained in 2.4 are weighted in five separate weighting matrices .

Afterwards, this weighting questionnaire has been sent to ten experts at the Institute of Space Systems at the University of Stuttgart, at eSpace and to an expert from the TU Delft. This approach aims to reduce research bias regarding the questions and to discover potential problems in answering the questionnaire. This approach is similar to the DELPHI method used in Professor Neumann's dissertation. [25].

Unfortunately, there have been multiple unclear aspects about the weighting matrices. Apart from the design, that has to be improved, it also occurred to take more than the expected 15 to 20 Minutes into account to answer the document. It can also be concluded that a detailed and broad background knowledge is required to answer the form. This is so, because knowledge about for example specific IADC rules but also de-orbiting spacecrafts is required.

Afterwards prospective work for the future is being suggested in section 5.2.

3.1.1 Comparison to Current Core Modules

The modules that have been developed at eSpace before this thesis are: Life Cycle Assessment, Orbital phase, Ground to Space, Data Verification, Data sharing Transparency Standards, Reentry & Recovery & Demisability. This is described in paragraph 1 [34].

As seen in figure 6.1 and explained in section 2.3 the LVSR developed in this thesis aims to include the following areas: logistics, resources, manufacturing, active use, reentry and End-Of-Mission while the reentry module has been included into the End-Of-Mission module after investigation into the prevalent connection. Also the reusability of launcher vehicles is included into the EOM module.

The LCA of the previous LVSR is now included into the resources and partly into the manufacturing module of the latest LVSR. Ground2Space is included in the logistics and active use module, whereas data verification and data sharing transparency standards are now part of the logistics module. Finally, the reentry, recovery and demisability module are split up into the Reentry and End-Of-Life, EOM, modules.

After development, it occurred that the reentry and EOM are highly related and it is, therefore, reasonable to make the reentry part of the EOM module. This follows a reasonable stream of questions that are displayed in the question tree diagram 6.1.

3.1.2 Focus on the End-Of-Mission Module

As described in 2.3.5 the End-Of-Life module focuses on the sustainability of the launcher vehicle after its mission ends. Its significance regarding sustainability is justified by the impact that launcher systems have on their environment. This takes into account various aspects that are relevant for environmental and economical sustainability but also social equity. These highlights the reasons for the focus on the EOM module apart from the exceedingly wide range of topics regarding the whole LVSR as mentioned in paragraph 1.

These aspects seven main that the EOM is made of are reusability, expendability, recycling and recovery of the launcher vehicle, gathering atmospheric data while descending to Earth, a

possible burn-up of the vehicle in the atmosphere, debris risks and a potential reuse or recycling in orbit. These aspects stood already out after a review of Professor Neumann's doctoral thesis and Mathieu Udriot's master thesis [25, 33]. Gathering atmospheric data is a possible contribution to improve sustainability in the future. All these aspects have an influence on the the environment.

The reusability can increase not only the economical viability of launchers, as explained in 2.2, but also decrease the environmental impacts as the reuse decreases the quantity of manufactured parts [32, 1]. Expendability of launcher systems can, as explained in 2.1, increase emissions due to manufacturing and a burn-up on the reentry into Earth's atmosphere which has an impact on its composition and can therefore impact regional and global climates. Depending on the kind of de-orbit of upper launcher stages influences the possibility of reuse or recycling. Additionally, this is also the phase where valuable scientific data can be gathered that is still lacking regarding specific about upper atmospheric phenomena.

Recovery of the spacecraft can be in space and back to Earth's surface. With the latter a de-orbit is necessary, no matter is the vehicle is deemed to disintegrate in the upper layers of the atmosphere and then burn-up at least partly or if it is supposed to land back on Earth in a controlled manner.

To reuse a launcher vehicle it needs to be reused in space or arrive on Earth's surface. The latter can currently be done with a parachute system, with a design similar to space plane or with an active propulsion system to slow it down and potentially land vertically like the current first stage of the Falcon 9 rocket. [29]

How launcher systems influence the environment in the long-term future is not yet clear. Theories vary from amplifying climate change to being used as a possible way to counter global heating. Launcher systems counter global heating through the distribution of specific particles in the upper atmosphere that dissipate during a reentry of the vehicle suited to reflect sunlight. What is certain, however, is that launching spacecraft into orbit have an effect on the environment and therefore also on climate change. Additionally, intoxication of natural habitats and acidic rains are realistic risks [4].

3.2 Questionnaire tree diagram

To elaborate on the advantage of future development and understanding of the LVSR including the creation of the questionnaire tool, the questionnaire tree diagram as seen in figure 6.1 has been developed.

To be able to rate launcher systems on sustainability general questions, found in section 2.5 and seen in figure 3.2, it has to be answered first if the rated launcher is an expendable and reusable system. This helps to then rate the systems more in detail. These emerged after the creating the question tree, as they were repeatedly noted in every area. Though, the development of the diagram in general has been a top-down approach. This means, first general questions have been noted and then the topics were split up to make the figure more tangible and clear. Therefore, the separated areas 2.4 have been developed as specific as possible while still being tangible enough to answer simply.

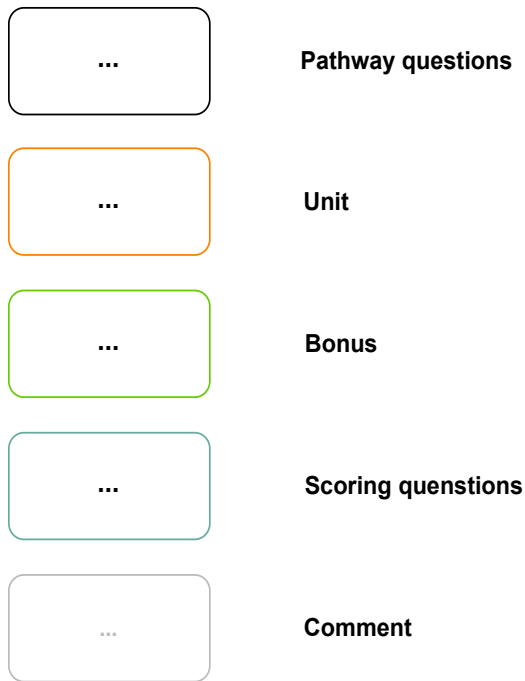


Figure 3.1: Legend of the decomposition of the questions in the diagrams 3.2, 3.3, 3.4, 3.5, 3.6, 3.7 and 3.8

For clarification frames are colored as described in the legend 3.1. This serves to give a better overview but is not crucial for the diagram. Pathway questions serve to split the questionnaire in more tangible parts, unit questions demand a number as an answer and scoring questions together with the unit questions suit calculating a final score of the sustainability of a launcher vehicle as already described in 3.1. Further, bonus questions take into account possible improvements of LVs in their environmental sustainability, but are not necessary to gain a good score. The reason for this is a future possible development of the launcher system's capabilities that are not necessarily required to achieve a sustainable mission. Though, these would benefit future development, safety, or other than environmental sustainability like social equity that still improve the development of launchers. In grey colour, some minor comments have been made on the questionnaire tree to make it more comprehensible for its future implementation into a user-friendly form.

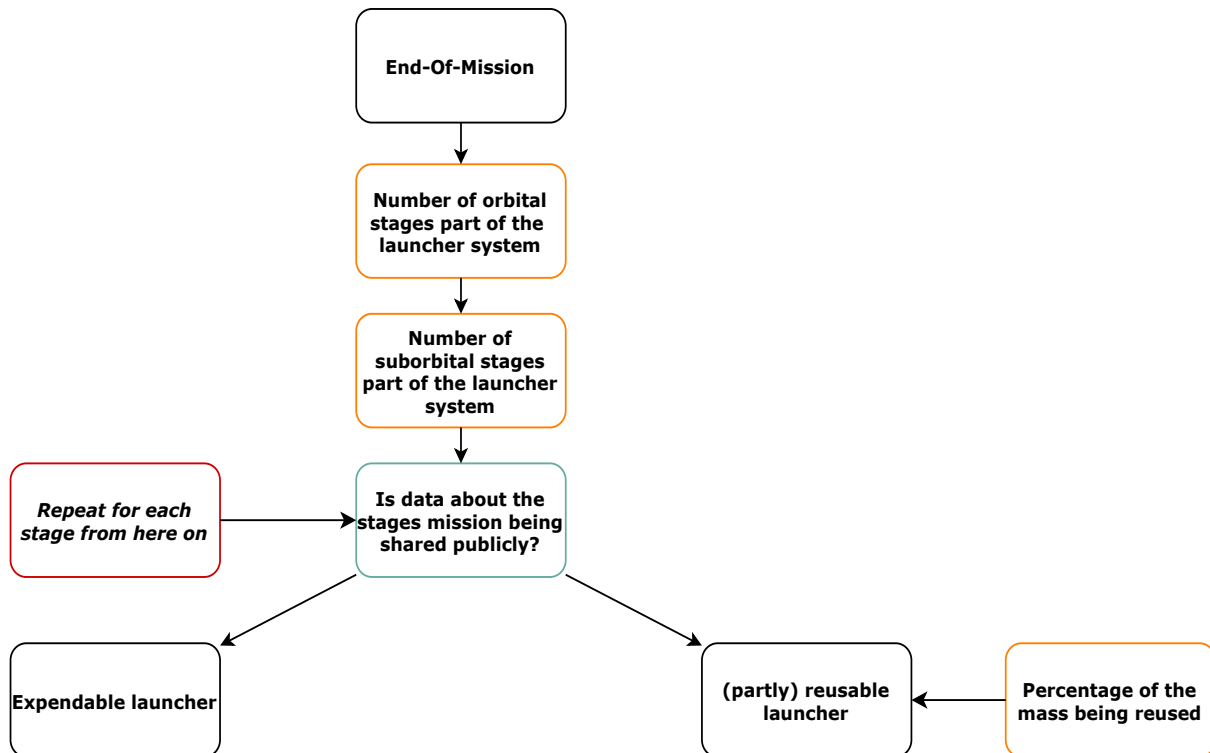


Figure 3.2: Upper questions

3.2.1 Expendability versus Reusability

In figure 3.2 it can be seen how the question tree is split into expendable and partly reusable launcher systems. This resulted in the geographical distinction of where the debris has the most impact.

Expendability, see 2.1, of spacecraft, in this case of launcher systems, means that no parts of the launcher are reusable after the end of their mission. The potential to recycling stays open. Figure 3.3 shows how the expendable launcher is split into disposal in space and reentering Earth's atmosphere. Whereas, the former then raises the bonus question on an openly published trajectory to ensure safe operations on orbit. However, the latter raises the bonus question in regard to gathering atmospheric data during its reentry to benefit future research and development.

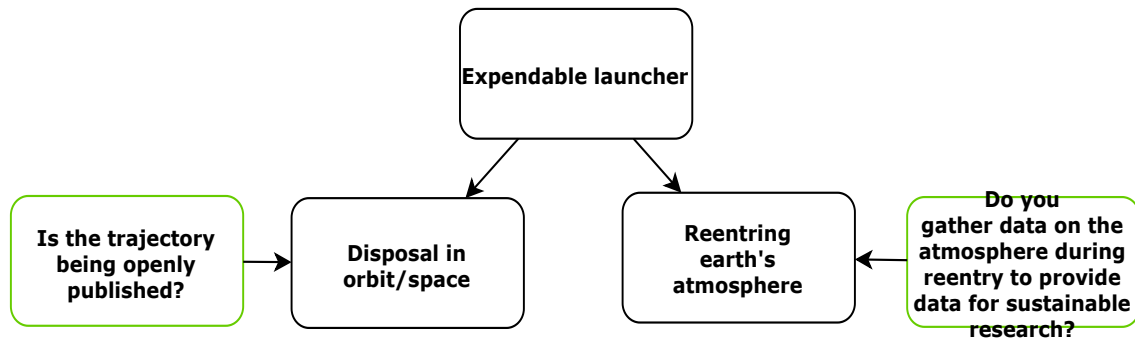


Figure 3.3: Expendability

Reusability on general means that a tool or machine is capable of being used again or repeatedly.[23] Also see 2.2. This means that the launcher vehicle can be reused after its mission. Should it not be fully reusable, the possibility of recycling the expendable parts stays open. Additionally, the potential to recycle the vehicle should it not be reusable anymore at some point in time stays open. As seen in the figure 3.4 reusable launchers are split into two categories. the reuse on Earth and the reuse in space. An important question regarding reusability is how much of the launcher system is being reused. This can be measured in a percentage of its reused mass.

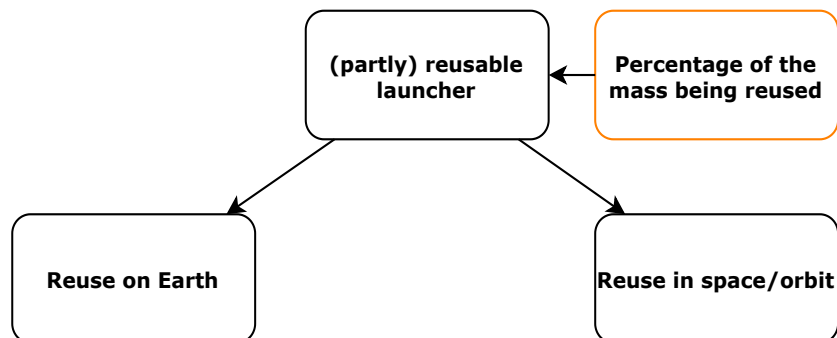


Figure 3.4: Reusability

3.2.2 Expendability on Earth

Expendable launchers on Earth refer to launcher systems or stages that reenter Earth's atmosphere or do not leave it. Consequently, these will be discarded on Earth so this is also where the debris or emissions have an impact.

During reentry, launchers can either burn up or they can land or crash on Earth's surface. The former implies a 100 percent burn-up. The former burns up to a specific percentage. Further, apart from a specific percentage, it is a relevant question whether the trajectory is publicly available and if the limit of 10^{-4} casualties at reentry is satisfied. Both serve to ensure public safety and the possibility to take necessary safety precautions on Earth, if necessary. A bonus of a launcher system to increase the future sustainability of these vehicles is the implementation of instruments to gather atmospheric data during the reentry.

A further question has been concluded relevant after research on crash landings. Namely, the question in regards to a commonly used debris crash location like the so called point Nemo [6]. To ensure sustainable expense of the launcher, the following topics have been met with suitable questions. No matter if the LV comes down over an ocean or land, it is important to know if the LV is being recovered to decrease environmental hazards. Then, also if the parts are designed to be recycled to create a more circular economy, as the material can then be used for future manufacturing again. Therefore, it is necessary to know, what percentage of mass is being recycled. Consequently, should the launcher not being recovered and land in the ocean, a system design to make it sink as fast as possible is relevant to decrease a negative environmental impact on the ocean habitat. This is so, as the parts will not spread far in distance once they reach the bottom of the ocean, due to a high pressure and lower water circulation. Similarly, it is important to mitigate the risk of wildfires and other impacts on the surrounding of a launchers touch-down site on land. In both cases, independent of the crash or landing location, it is beneficial to have a public discussion on used methodology to decrease negative environmental impacts and share these methods to improve other designs, too.

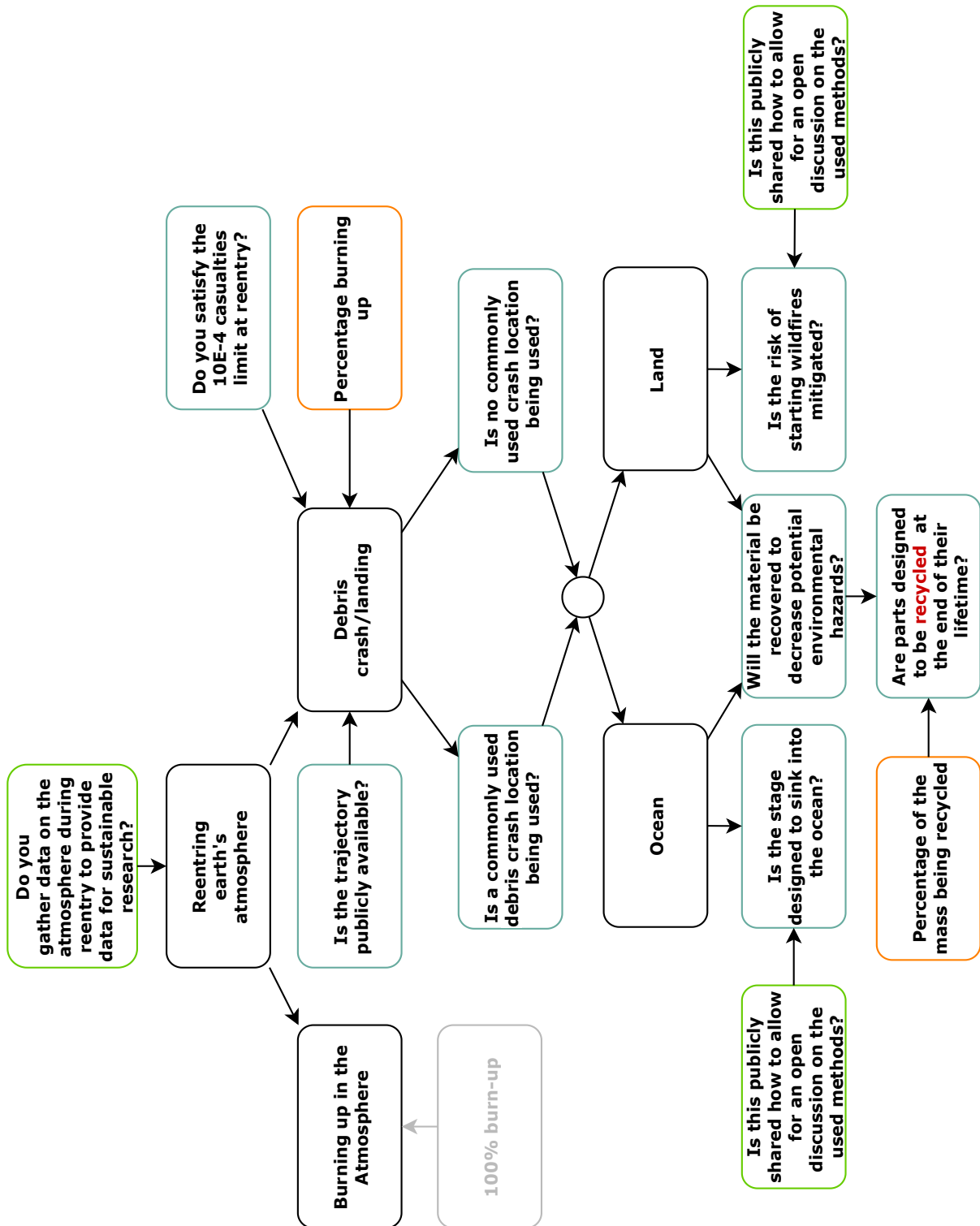


Figure 3.5: Expendability on Earth

3.2.3 Expendability in space

Expendability in space refers to launcher vehicles that stay in orbit or more general in space after their mission duration and cannot be reused. Therefore, these impact possible astronomical observations [26] and can potentially block specific orbits and increase the probability for debris collisions for future missions [13].

When disposed in space LVs commonly stay in a graveyard orbit. This is already an improvement to a random disposed structure passing through space as it is better coordinated and minimizes potential collisions with active spacecraft [11]. In regard to that, it is important to know how long it is planned for the vehicle to stay in a graveyard orbit before it is removed or de-orbited to ensure a sustainable space environment. This is relevant as also graveyard orbits fill up with time and still represent collision risks. As advised by the IADC guidelines regarding the demise of spacecraft, it can be chosen to help improve a launch mission's environmental impact. This is visualized in figure 3.6.

Apart from a graveyard orbit, also the expense of a launcher onto the surface of the moon at a specific location can be considered. This is a futuristic approach and is prone to require a higher amount of energy due to transportation. Therefore, this is included but not further investigated. Nevertheless, this can offer a viable way to remove debris from orbit, which materials can later be reused for other applications after collecting.

Regardless of the choice between those two options and similar to the prospected time in orbit, it is significant if the debris is being removed after a set amount of time. This can serve to recycle the launcher. To ensure high environmental sustainability, it is meant to be aimed to recycle the highest possible percentage of the vehicle. In addition, a bonus to increase sustainability for future space missions is to publish the trajectory of the inactive launcher. This aims to prevent further debris created by collisions with other spacecraft and is especially helpful if the launcher is not easily well visible to other tracking systems like for example telescopes on Earth. [13]

To ensure a sustainable demise of the launcher, the just explained aspects have been met with appropriate questions. Further, the figure 3.6 has been included to improve understanding.

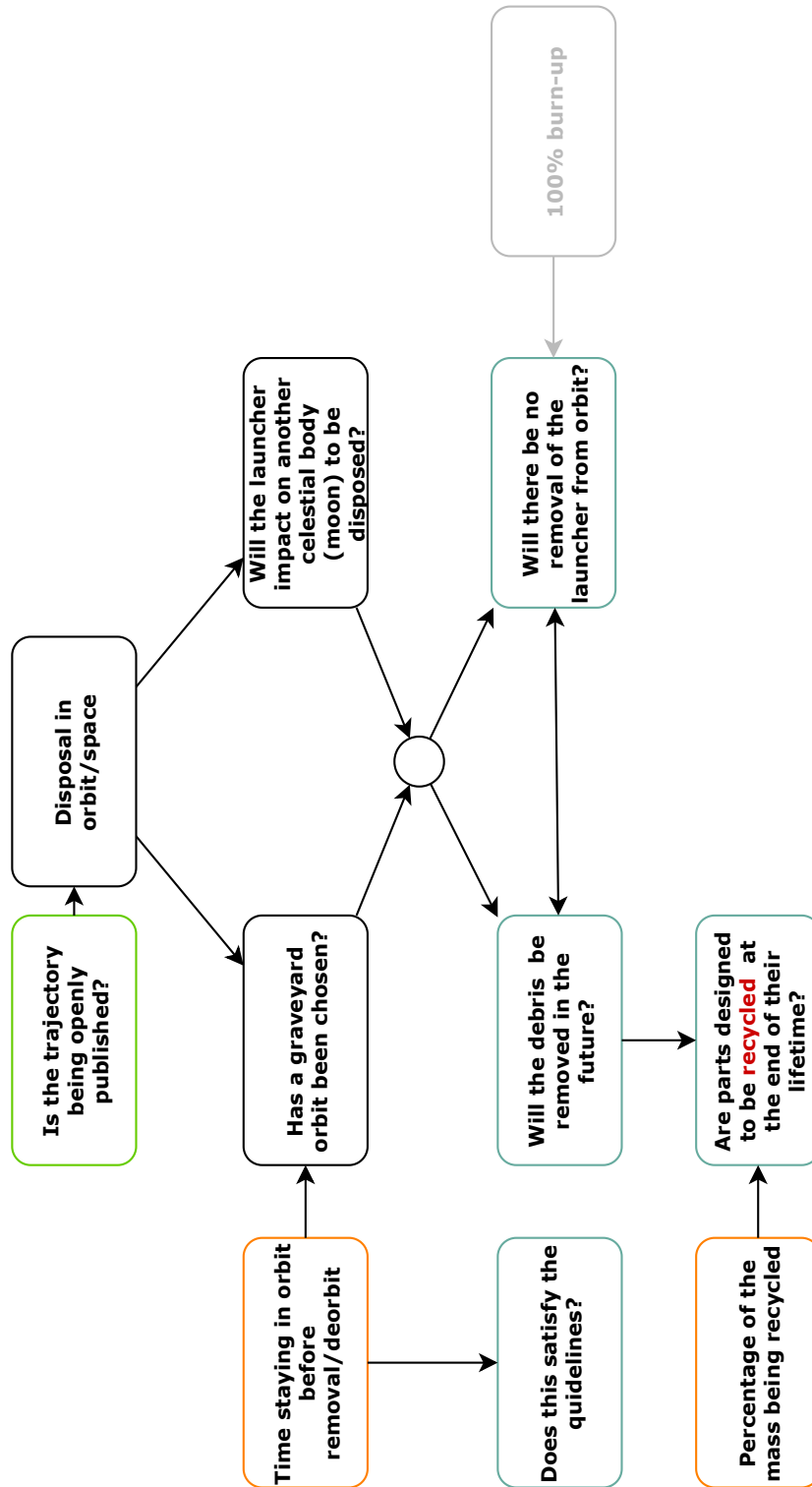


Figure 3.6: Expendability in space

3.2.4 Reusability on Earth

Reusing space vehicles on Earth commonly refers to the reuse of rocket stages like the Falcon 9 rocket or space vehicles like the SpaceRider. [29, 14] Though, it can also mean the reuse of ground infrastructure for space applications or the reuse of a satellite or telescope for multiple and different missions.

Important questions that come up regard a potential direct reuse of the launcher or a reuse after refurbishment. Similarly, it is relevant how often a launcher can be reused on average. In addition, a standardized refurbishment process can decrease the need for excessive testing which can reduce required resources. For this, it is crucial what percentage of the vehicle's mass is being refurbished. Decreasing transportation and logistics needs is environmentally beneficial. Hence, the sustainability of the mission is increased should the refurbishment process take place at the launch location instead of an external one that requires extensive transportation and corresponding infrastructure. This question process is visualized in the figure 3.7.

Without regard to a direct reuse or one after refurbishment, the environmental sustainability of the launcher increased with the use of a passive propulsion system for descend to Earth. The SpaceRider with its parafoil for steering and slowing down takes advantage of that. [14] An active propulsion system would for example be considered a rocket engine as the Falcon 9 first stage uses to securely land. [29]

As also in 3.2.3 and 3.2.2, it helps to boost environmentally viable actions and recycle the vehicle after it cannot be reused anymore. To decrease waste, it is aimed to recycle as much as possible of the launchers mass.

Further, at reentry, as also included in section 3.2.2, it is a bonus of a launcher system to increase the future sustainability of these vehicles is the implementation of instruments to gather atmospheric data during the reentry.

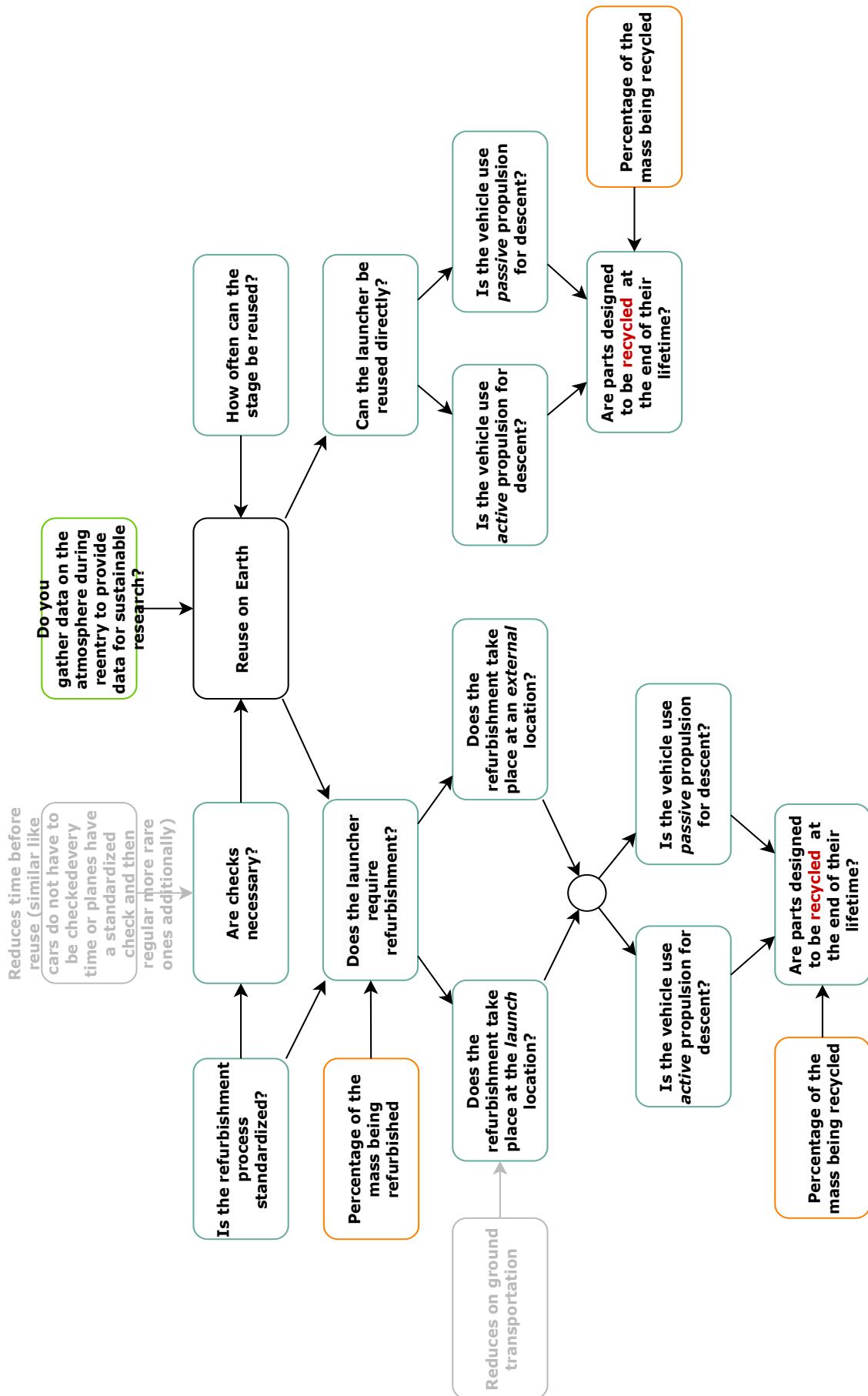


Figure 3.7: Reusability on Earth

3.2.5 Reusability in space

Reusing launcher vehicles in space is not yet a common practice. In this case it takes into account reusable launcher vehicles, for example the Space Shuttle [24] that could be reused to repair the Hubble telescope, or other future multi use in space transportation systems, but can also take into account other space systems like satellites used for multiple missions. This means, that launchers do not have to be reused for the same purpose of launching payload into space, but an orbital stage could be used as a passive attitude and orbital control system, AOCS for other spacecraft or as a transportation system in space.

For in space activities, it is important to be sure that IADC guidelines are met to sustain sustainable development [16]. Therefore, this also implies the question if it is intended to recycle the vehicle in 5 years after the end-of-life. As seen on figure 3.8, it is a bonus if there is a plan in place to reuse the vehicle even before its nominal end-of-life.

Important, as mentioned also in section 3.2.4, with reusability, the question arises if refurbishment is required or not. Consequently, the lower the mass percentage of the LV that has to be refurbished the more sustainable it is. Similar to 3.2.4, a standardized process can increase environmental viable behaviour as it can be optimized and can reduce the need for detailed tests.

Furthermore, it is important to consider collision avoidance systems. A spacecraft can rely on a passive external system or on its own AOCS. If a vehicle has an AOCS, this can be one with an active propulsion system or only a passive one. These three categories are distinct as they offer diverse degrees of sustainable operations. This is visualized in figure 3.8. Currently, it is common for a vehicle to have an active AOCS and less common to rely on a passive system that will move the spacecraft into position. To consider is the possibility of a more efficient operation using a passive system to move the spacecraft into orbit and optimizing this process as this will serve multiple vehicles and therefore benefit from a modular design.

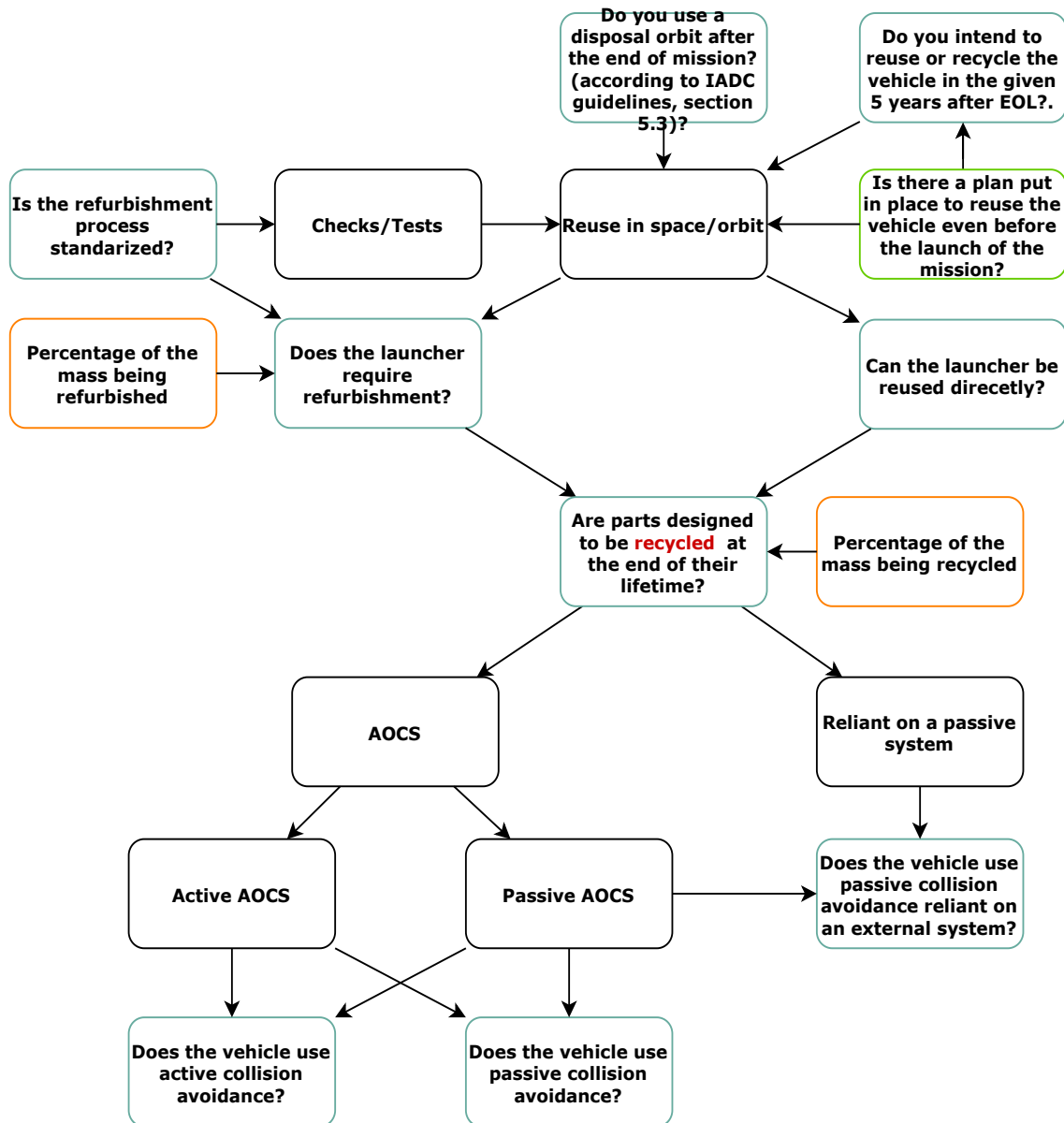


Figure 3.8: Reusability in space

3.3 Questionnaire

The questionnaire including the developed EOM questions 2.5 serves to weight those aspects. The weighting is based on the environmental sustainability impact of launcher systems. This is done using multiple weighting matrices commonly used to help in decision making. Those questionnaires are split into the same areas as the questions in regarding the EOM are. 2.5 In addition, general questions, see 2.5, are rated in a separate matrix. Further the questionnaire incorporates a short introduction page on the thesis and comments above each matrices to elaborate on questions that require further detail or are cannot fit into the prospected line. This has been done in an Excel format. The reason for this choice is a wide usage and therefore available help in online forms. This makes for simplicity while using it. The questionnaire has been amended slightly due to questions that exclude each other. In such a case only one question has been taken into account as the result implies the answer to both aspects.

This is presented in the figures 3.4 to 3.4. To increase readable of the separate pages and include those into the thesis, those pages have been slightly amended and split in two.

3.4 Weighting Process of Questions

The weighting matrix

The weighting form consists of an Excel document with five different weighting matrices. One for the overall upper questions^{3.4} as described in 2.5, two matrices regarding questions about launcher systems expendable in space 3.2.3 seen in 3.4 and on Earth 3.2.2 seen in 3.4 and therefore also two question matrices regarding questions about launcher systems reusable in space 3.2.5 as presented in 3.4 and on Earth^{3.2.4} that can be seen here 3.4.

To weight the questions, the Excel forms need to be answered by experts. These are experts on sustainability rating, LCA or a related area at eSpace, at the EPFL, at the Institute of Space Systems at the University of Stuttgart or the TU Delft. The forms have then been send to those experts with a short personal introduction and context. Afterwards the filled out forms and feedback or just one of those has been send back to this thesis author.

Launch Vehicle Sustainability Rating (LVSR)

Who I am

I am Dominik, currently in the final stage of writing my bachelor thesis. I am an Aerospace Engineering B.Sc. student at the University of Stuttgart though on my exchange semester at the EPFL this summer semester.

Bachelor Thesis

Launch Vehicle Sustainability Rating aims for the assessment of the sustainability of launch vehicles (rockets, space planes and other more novel techniques), by means of a questionnaire to be able to recommend practices improving sustainability in the future.

This questionnaire helps to weight the different additional questions for the End-Of-Mission part of the LVSR.

The different answers will be evaluated and compared afterwards.

Task

Please fill out the weighting matrices as described next to them.

This should take no longer than 15-20 minutes.

Deadline

19.06.2023

Email: dominik.gentner@epfl.ch

General Question

Introduction:

The following questions are general questions to split up End-Of-Mission into expendable and reusable launcher systems. In the future questionnaire design, these filter which questions are relevant for a launcher system.

Therefore there are only a few relative to the other more detailed sections.

The third question regarding data-sharing regards any mission data to increase safety, security and finally also to diminish problems with the missions.

For the last question data takes into account anything from the flight trajectory, total mass of the launcher system, mission goal and duration, collision avoidance strategies and means to mitigate environmental impacts as well as impacts on astronomical observations.

Weighting of Evaluation Criteria

Only change numbers above diagonal line

Markings:

- + 3 = Y is much more important than X
- + 2 = Y is more important than X
- + 1 = Y is slightly more important than X
- + 0 = Y is as important as than X / Not Applicable
- 1 = Y is slightly less important than X
- 2 = Y is less important than X
- 3 = Y is much less important than X

	Number of orbital stages part of the launcher system	Number of suborbital stages part of the launcher system	Is data about the stages mission being shared publicly?	SUM COLUMN
Number of orbital stages part of the launcher system				0
Number of suborbital stages part of the launcher system				0
Is data about the stages mission being shared publicly?				0
SUM LINE	0	0	0	

General Question

Introduction:

Expendable launchers on Earth refers to launcher systems that reenter Earth's atmosphere or do not leave it. Therefore, these will be discarded on Earth so this is also where the debris or emissions have an impact. The question in line 12 regarding the common crash location regards the commonly chosen location for satellites and other space vehicles to crash into. This is a point on the south Pacific Ocean between New Zealand and Chile. It is also being called "Point Nemo" near the New Zealand's Bounty Islands. (approximately at 47°24'42"S 177°22'45"E) The question in line 15 takes into account methods to mitigate environmental impacts and potential catastrophes like a chemical leak or a wildfire.

Weighting of Evaluation Criteria

Only change numbers above diagonal line

Markings:

- + 3 = Y is much more important than X
- + 2 = Y is more important than X
- + 1 = Y is slightly more important than X
- + 0 = Y is as important as than X / Not Applicable
- 1 = Y is slightly less important than X
- 2 = Y is less important than X
- 3 = Y is much less important than X

	Do you gather data on the atmosphere during reentry to provide data for sustainable research?	Percentage burning up	Do you satisfy the 10E-4 casualties limit at reentry?	Is the decent trajectory publicly available?	Is the descent controlled?	Is a commonly used debris crash location being used?	mitigate the risk of a potential wildfire? Depending on the crash location	Is this publicly shared how, to allow for an open discussion on the used methods?	Will the material be recovered to decrease potential environmental hazards?	Are parts designed to be recycled at the end of their lifetime?	Percentage of the mass being recycled	SUM COLUMN
Do you gather data on the atmosphere during reentry to provide data for sustainable research?												0
Percentage burning up												0
Do you satisfy the 10E-4 casualties limit at reentry?												0
Is the decent trajectory publicly available?												0

Is the decent trajectory publicly available?

General Question

Introduction:

Reusing space vehicles on Earth commonly refers to the reuse of rocket stages or space vehicles similar to the Space Shuttle like the SpaceRider. Though, it can also mean the reuse of ground infrastructure for space applications or the reuse of a satellite or telescope for multiple and different missions.

Weighting of Evaluation Criteria

Only change numbers above diagonal line

Markings:

- + 3 = Y is much more important than X
- + 2 = Y is more important than X
- + 1 = Y is slightly more important than X
- + 0 = Y is as important as than X / Not Applicable
- 1 = Y is slightly less important than X
- 2 = Y is less important than X
- 3 = Y is much less important than X

	Percentage of the mass being reused	Do you gather data on the atmosphere during reentry to provide data for sustainable research?	How often can the stage be reused?	Are tests necessary before the next launch?	Does the launcher require refurbishment?	Is the refurbishment process standardized?	Does the refurbishment take place at the launch location?	Does the vehicle use active propulsion for descent?	Are parts designed to be recycled at the end of their lifetime?	Percentage of the not recycled mass being recycled	SUM COLUMN
Percentage of the mass being reused											0
Do you gather data on the atmosphere during reentry to provide data for sustainable research?											0
How often can the stage be reused?											0
Are tests necessary before the next launch?											0
Does the launcher require refurbishment?											0
Is the refurbishment process standardized?											0
Does the refurbishment take place at the launch location?											0
Does the vehicle use active propulsion for descent?											0
Are parts designed to be recycled at the end of their lifetime?											0
Percentage of the not recycled mass being recycled											0

General Question

Introduction:

Reusing launcher vehicles in space is not yet a common practice. In this case it takes into account reusable launcher vehicles, for example the Space Shuttle that could be reused to repair the Hubble telescope, or other future multi use in space transportation systems, but can also take into account other space systems like satellites used for multiple missions.

With the use of an external system mentioned in the last question, transportation vehicles in space are those that can (re-) position a satellite without an AOCSS to another orbit.

Weighting of Evaluation Criteria

Only change numbers above diagonal line

Markings:

- + 3 = Y is much more important than X
- + 2 = Y is more important than X
- + 1 = Y is slightly more important than X
- + 0 = Y is as important as than X / Not Applicable
- 1 = Y is slightly less important than X
- 2 = Y is less important than X
- 3 = Y is much less important than X

	Do you use a disposal orbit after the end of mission? (according to IADC guidelines, section 5.3)?	Do you intend to reuse or recycle the vehicle in the given 5 years after EOL?	Is there a plan put in place to reuse the vehicle even before the launch of the mission?	Does the launcher require refurbishment in space?	Is the refurbishment process standardized?	Percentage of the mass being refurbished	Are parts designed to be recycled at the end of their lifetime?	Percentage of the mass being recycled	Does the vehicle use active collision avoidance?	Does the vehicle use passive collision avoidance?	Does the vehicle use passive collision avoidance reliant on an external system?	SUM COLUMN
Do you use a disposal orbit after the end of mission? (according to IADC guidelines, section 5.3)?												0
Do you intend to reuse or recycle the vehicle in the given 5 years after EOL?												0
Is there a plan put in place to reuse the vehicle even before the launch of the mission?												0
Does the launcher require refurbishment in space?												0

4 Evaluation of Results & Discussion

This chapter evaluates the weighting questionnaire feedback. Also general recommendations for improved work in the future is discussed. This includes the development of LVSR modules, questions and the format of the questionnaire.

4.1 Feedback on the Questionnaire

Results on the questionnaire include mainly feedback on it from multiple experts, see 3.1, shows some common advise regarding the weighting questionnaire 2.4 due to difficulties in answering the document. Specific results of the questionnaire have not been compared are are seen as of low value due to the issues arising in answering the form.

Problems and challenges regarding the questionnaire and the included that have been mentioned by respondents are the following ones:

- Broad and detailed expertise is necessary to weight the different aspects.
- Contradicting or exclusive questions cannot be weighted against each other; Therefore, weighting is dependent on the specific mission.
- Topic overreaching questions and ones dependent or influenced cannot be compared reasonably.
- Questions relying on knowledge regarding official guidelines or other background knowledge require references or a detailed description.
- Developed questions must to be specified in more detail to avoid unclarity.
- Unclear definition regarding the topic; Launcher systems need to be specified in more detail to for example clarify if ground infrastructure is included or not.

Additionally, suggestions have been brought up by the respondents to improve the weighting process:

- Research analysis on the questions during a review has more potential for a reasonable weighting of the aspects instead of a form like the questionnaire, that experts answer
- Specify and elaborate questions more in detail
- Development of more distinct questions

4.1.1 Analyzing Results

The results suggest that the weighting procedure has to be amended as explained in 4.1. Further, they show that there is high potential behind a LVSR, though further detailed research has to be done one its main modules to clarify specific topics. This can be read though the feedback noted in 4.1.

The application of the weighting questionnaire has to be reconsidered as it does not seem to bring forward valuable conclusions that would help to add a weight to the various areas. This

for, suggestions have been made 4.1. These consider to change the weighting process completely and base it not on a form questioning experts, but found it on more research and an analyse that. The analysis would be in regard to the environmentally sustainable development of a launcher vehicle.

4.2 Challenges Developing Questions

A challenge developing questions during this work has been creating specific questions. These are aimed to deliver valuable conclusions useful to the development of more sustainable launcher systems. Important is also that these developed questions are comparable so most relevant sustainable areas are recognized. Another demanding feat is to chose questions that are not only useful in a sustainability rating but also simply answerable to experts who they are aimed for. This means the questions need to be specific, but brad enough to be answerable without a huge personal background research required by respondents. This has also been described in section 2.4.

4.3 Evaluation of the questionnaires Beta tests

Further review due to late replies from companies and not a sufficient number of feedback to have a fair and broad view. Therefore not included in this work in detail.

4.4 Evaluation of the Weighting Process

Improvements have to made to the weighting process of different sustainability aspects. As described in 4.2 and 4.1 it is a suitable option to re-asses the methodology and base the weighting process on a research analysis instead of a questionnaire, as this is difficult in its realization while providing a fair and unbiased approach.

4.5 Including EOM into the Questionnaire

The current sustainability form on the LVSR developed before this Bachelor thesis has to be amended to include newly developed environmental aspects. To help in this process the question tree including the EOM module was created 6.1.

A separate section for the EOM part will have to be added while further modules, described in 2.3, are being developed.

4.6 Discussion on a Future LVSR

Tho overcome difficulties in data gathering for specific questions and reducing biases. It is crucial to implement feedback obtained from the Beta tests to improve the project. The implementation of the EOM is also necessary. Furthermore, it is important to refine and meticulously implement all main modules. Another task involves amending the methodology of weighting to enhance accuracy. To gain a comprehensive understanding of the project's environmental impact, a thorough LCA should be conducted with the assistance of the ACT.

Additionally, the development and full implementation of core modules such as logistics and active use are essential. Lastly, logistics, resources, manufacturing, and recycling should be included in the LCA to evaluate their impact on overall sustainability.

5 Conclusion and Future Outlook

Here the conclusion of the work done is summarized. In addition, a future outlook is discussed and presented.

5.1 Conclusion

The LVSR is a launch vehicle sustainability rating that aims to compare different systems and identify major environmental areas of launcher systems impacting their sustainability. It has been focused on the life cycle assessment, ground to space area, the orbital phase, flight data verification, data-sharing transparency and the end-of-life management. In this work an amended approach has been created focusing on the sustainability modules of logistics, resources, manufacturing, active use of launcher, their End-Of-Mission phase, a potential reentry into Earth's atmosphere and the vehicles reuse. This work focuses on the End-Of-Mission module and the detailed parts included as seen in section 2.3.5.

After literature research, brainstorming and gathered feedback on the work after a mid-term presentation, a question tree diagram was made to point out main questions that help to rate a launchers environmental viability. The diagram was first split into reusability and expendability and secondly into both these aspects on Earth and in space as described in section 2.5. Then a questionnaire in form of weighting matrices on Excel sheets had been created and the responses taken into account as feedback on the work as seen in 4.1. There challenges in the weighting process were identified and a new approach to a literature research based development on the questions weighting is suggested.

Finally, sustainability aspects with relevant environmental impact during the End-Of-Mission phase of launch vehicles were identified as described in section 2.3.5. Due to challenges in the weighting process as elaborated in paragraph 4.2, the weighting of aspects regarding their impact on launcher vehicles' sustainability are not clearly identified.

5.2 Future Outlook

Regarding a future outlook on the LVSR, it needs to be said, that such a rating will only increase in importance the more space launches there are.

The strategy to gain knowledge about various important factors with the help of research, brainstorming and open discussions is useful for the development of a LVSR. Though, the application of a weighting questionnaire should be reconsidered and methodology should be chosen due to the vast area of importance in a sustainability rating.

Further, future work on the SSR includes the LVSR. Beta-tests will have to be reviewed in detail, implemented and expanded to more recipients. That will help to create a questionnaire that companies can answer and therefore this also results in a more concise form to answer on which data is available.

5 Conclusion and Future Outlook

Additionally, developing and implementing all modules of the LVSR, like the EOM module, fully into the rating and generating a user friendly application out of it is crucial for improvement and progress on a user focused tool to examine a space missions sustainability.

In regard to the modules, some parts of the EOM module will be transferred to the LCA part, see 1.6. For this, all other modules have to be finished first as mentioned. This will require extensive research. It can be considered to require approximately at least one semester project worth of work per module. This is considering semester projects at the EPFL. Then, the EOM and other modules, see paragraph 2.3, have to be integrated into the questionnaire form. The questionnaire tree, explained in section 3.2, will be useful to save time on rethinking the questionnaires structure.

Concluding, progress on the LVSR and its important parts to improve the rating to finally increase the sustainability of launcher vehicles is ongoing and will require further research to finalize and optimize. Relevant is also that the LVSR will have to amended in regard to future technological development.

6 Appendix

6.1 Abbildungen

The LVSR module map diagram to give an overview. It has been elaborated and shown in the theory section to be readable and in better detail. 2.4

A simple visual overview of the question tree diagram that is explained and in a readable format in the methodology section 3.2.

Is the BDS being passivated?

Are chemicals being passivated?

Are chemicals being passivated?

Are chemicals being passivated?

Legend

Scoring/ratio questions

...

...

...

...

...

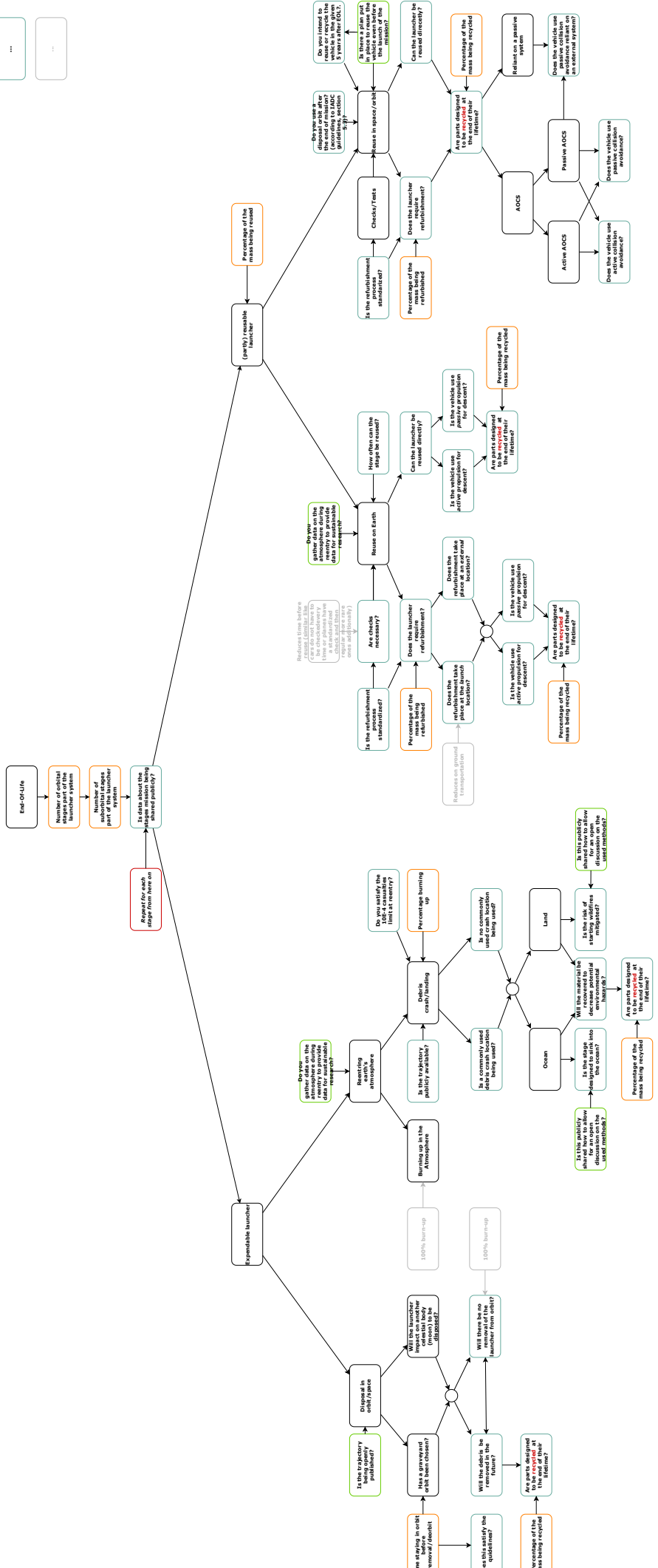
Pathway questions

Unit

Bonus

Scoring questions

Comment



Legend

Scoring/ratio questions

...

...

...

...

Pathway questions

Unit

Bonus

Scoring questions

Comment

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