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# Space sustainability in systems engineering and design processes - Industry overview and case study at EPFL

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## Abstract

The increasing cadence of launches, satellite production, and spacecraft atmospheric re-entries prompts the space industry and regulators to better consider the growing environmental impacts of space missions on Earth and on orbital resources. It is known that the largest leverage for impacts reduction is during the early design phases of a new system, which is incentivizing the industry to consider (space) sustainability more closely during the design process. Indeed, it is increasingly being recognized as a critical component of systems engineering for space mission design.

Some actions are already undertaken in industry, but are - so far - too isolated and with limited results. The long-term objective of research around space sustainability is to extend the current design-to-time, design-to-objective and design-to-cost philosophies, by including design-to-environmental-impacts. Indeed, industries have to prepare now to anticipate growing scrutiny from the general public and space agencies, as well as increasing regulatory pressure from national entities and international ones like the European Union. This can only be reached with a workforce that is educated about the challenges of space sustainability, and has the necessary skill set. Although not yet existing everywhere, some educational programs have been developed for active professionals as well as for students who will soon graduate and take up positions in industries.

This paper draws on existing literature and known projects to review current practices and challenges in integrating sustainability in the early design process of space systems. Surveys have been conducted with engineers, practitioners, and managers in the space sector about how they implement sustainability criteria into their design and decision making processes. It was investigated if and what type of guidelines or handbooks they use, as well as whether simplified Life Cycle Assessment (LCA) is applied, and with which data sources. Moreover, survey questions delved into their integration of environmental criteria within design methods. The paper proposes recommendations for the best course of action to improve the synergies between space sustainability and systems engineering. A case study performed in the Concurrent Design Facility (CDF) during a class at EPFL is presented, highlighting practical challenges and potential strategies for embedding sustainability into collaborative design environments. Finally, the paper also emphasizes the critical need for education in space sustainability, in order to prepare the next generation of leaders and to raise awareness amongst the current decision makers in the space sector.

## 1. Acronyms/Abbreviations

Assessment and Comparison Tool (ACT)
Clean Space Industry Days (CSID)
Concurrent Design Facility (CDF)
Concurrent Engineering (CE)
Dark and Quiet Skies (DQS)
Life Cycle Assessment (LCA)
Life Cycle Inventory (LCI)
Life Cycle Impact Assessment (LCIA)
Model-Based Systems Engineering (MBSE)
Systems Engineering (SE)
Space Situational Awareness (SSA)
Space Traffic Management (STM)

## 2. Introduction

Awareness of human activities' effect on the environment has been growing in the past decades. Legislations and regulations emerged and have been strengthened for industries to take on more responsibility and perform actions to mitigate their environmental impacts. The space sector has traditionally been excluded from many such legislations due to its unique and unclear impacts on the environment - e.g. high atmospheric emissions, re-entry emissions, use of space-specific material and use of orbits - its low volumes, and strategic importance.

However, the increased launch cadence, growing number of satellites in production and in orbit and the rise in light pollution are all factors contributing to a tightening of regulations for the space industry. Most particularly in Europe and to a lesser extent globally, space companies are increasingly required to show their environmental consideration and mitigation actions. Guidelines, regulations and legislations are being applied to limit the environmental impacts on Earth, as well as on the orbital capacity.

In particular, companies ought to apply specific methodologies and take certain actions, such as the life cycle assessment (LCA) methodology, ecodesign methodology and debris mitigation actions. However, it is unclear yet how and to what extent the industry applies these methods. Similarly, there doesn't exist a vast amount of data on the preparedness and expertise of the space industry's workforce.

This paper aims to address these knowledge gaps through literature research, direct experience, and surveys to current and freshly graduated students and to space professionals in the field of space sustainability. The general background needed for this paper is summarised in Section 3. Section 4 explores current and ongoing projects known to the authors, as well as answers from the survey on how sustainability topics are applied in the industry. Section 5 provides an overview in a recent practical experience at the EPFL Space Center, on the implementation of sustainability topics in a concurrent design study. Section 6 discusses the needs for education programme to prepare the current and future workforce to tackle these issues.

## 3. Background

There are plenty of ongoing activities in Europe about (space) sustainably. On an industry-level, this includes the creation of the PEFCR4space [18] and the work of ESA CleanSpace office to harmonise requirements and methodologies in ESA projects. There is also ongoing research on the topic in several universities, including EPFL, the University of Stuttgart, the Politecnico di Milano (Polytechnic University of Milan), the University of Strathclyde and ISAE SUPAERO. Even with an increased interest in the topic, several major knowledge gaps remain like the atmospheric impacts of launches and reentries, the definition of an orbital capacity, and large data gaps exist [45].

The EPFL Space Center is a center of excellence in space technologies, research, education and innovation at EPFL, with a research focused on space sustainability. This materialised in the past with the preliminary design work for the precursor of ClearSpace-1, an active debris removal mission developed by EPFL Space Center spin-off Clearspace. In the same field, one can also note the creation of the Space Sustainability Rating that was hosted at the center, as a result of its ongoing research in in-space environmental impacts, mitigations, and good operational behaviour incentives [40]. EPFL Space Center is now involved in projects about environmental life cycle assessment of space systems, especially launch vehicles, and space situational awareness [15], and takes part in several initiatives mentioned above.

### 3.1 Three pillars of sustainability in the space sector

An insightful and well-defined description of the key pillars of sustainability is given by A. Wilson et. al. [48] and is referenced throughout this paper. They suggest that the broad concept of space sustainability can be subdivided in the following pillars:

- Sustainability *from* space, referring to all the data that satellites gather about Earth or other celestial bodies to inform researchers on Earth's climate change and other environmental topics.
- Sustainability *in* space, referring to the issue of space debris and the ongoing efforts to ensure a usability of orbital resources in the future.
- Sustainability *for* space, referring to the environmental impact the space sector has on Earth, as a consequence of its activities throughout all phases of a space mission's life

This paper focuses mainly on the latter two points: sustainability *in* and *for* space. Further emphasis is given on how these two aspects are considered in the design process. Nevertheless, the pillar of sustainability *from* space is also touched upon in the investigation of the need for education.

### 3.2 Sustainability in the systems engineering process

The last two space sustainability pillars ("*in* space" and "*for* space") in the section above are increasingly being integrated in the system engineering process. Commonly, systems engineers take into account solely the system's functionalities, whilst its properties, such as its cost, robustness, flexibility, safety, usability, serve as a list of guiding principles for the design choices throughout the engineering process. More and more system engineers are adding sustainability aspects to this list. As discussed in Section 4 below, particularly the concepts of sustainability *in* and *for* space are integrated in the systems engineering process.

This has been spearheaded by the definition of the Sustainable Development Goals (SDG) by the United Nations (UN) in 2015. These goals provide an explicit foundation regarding the objectives that should be targeted. They can be used to define a basis for a quantitative measure for sustainability. For example, in the work of Richardson [35], a metric of eco-efficiency, shown in equation 1, is produced with the SDGs, with some goals defined as "Levers for transformation". These provide clear incentives on affordability, clean energies (Low environmental impact), innovation, and circular economy, that have positive effects on the environment and other factors.

$$\text{Eco-efficiency} = \frac{\text{Human wellbeing}}{\text{Environmental impact}} \tag{1}$$

To create a link between the complex space mission's systems engineering and the concept of eco-efficiency, one ought to correlate the "Human well-being" in Equation 1 with usability and safety of space systems that provide services. Indeed, some space services can be beneficial for human well-being [21] (s̃ustainability *from* space) and assuring future space missions can operate thanks to sustainability in and for space will continue enabling these benefits. Usability can be translated into operability to be better suited, where it can immediately be linked with the well-known problem of debris. One can also add the factor of resilience, which is compliant with the concept of a lasting system, and correlated with sustainability according to De Weck [11]. Hence, one can define an adapted version of equation 1, tailored for space systems (See equation 2).

$$\text{Space Systems Sustainability} = \frac{\text{Operability} \cdot \text{Safety} \cdot \text{Resilience}}{\text{Environmental Impact}} \tag{2}$$

This equation is of importance in Section 5, where each of its concepts is elaborated further. The operability is discussed in Section 5.1.2, an explanation of the safety and resilience is given in Section 5.1.4. Whilst the section below discusses how one can assess the environmental impact, its meaning in the above equation in the context of the EPFL CDF implementation is detailed in Section 5.1.3.

### 3.3 Life cycle assessment and ecodesign of space missions

To address the environmental impacts of industrial activities and understand them, the life cycle assessment (LCA) methodology is used globally. It is a systematic approach that is international accepted through ISO standards [28], [29]. It requires a definition of the system boundaries and the goal of the assessment, creation of an inventory with all the information, computation of the impacts and interpretation of these results. The results are often shown per impact category, including amongst others climate change, ozone depletion or eutrophication. Space-specific LCA guidelines have been developed by ESA in its Space System Life Cycle Assessment handbook, published in 2016 [16].

When integrating LCA in the design process, one often uses the word "ecodesign". Depending on the project phase, ecodesign can be applied at two levels: first on the overall architecture of the system, with the main design choices driving most of the environmental impacts (e.g. propellant type for a launch vehicle), then to optimise a selected solution. These processes imply performing simplified or full LCAs whilst continuing to design the system, to reflect on the impacts of design choices for the entire architecture whilst mitigating the environmental impacts of identified hotspots. Critical design decisions do come at a cost as the design evolves: the more the system matures and the design freedom reduces, the more any change would be costly in time and money. Nevertheless, the system becomes better known as the design progresses, reducing uncertainties about the LCAs results, increasing confidence in the hotspot identification. Therefore, making architectural changes early on during the ecodesign process may be the least costly with the most effect, but it is often paired with uncertainty in the LCA conclusions. This is schematically shown in Figure 1.

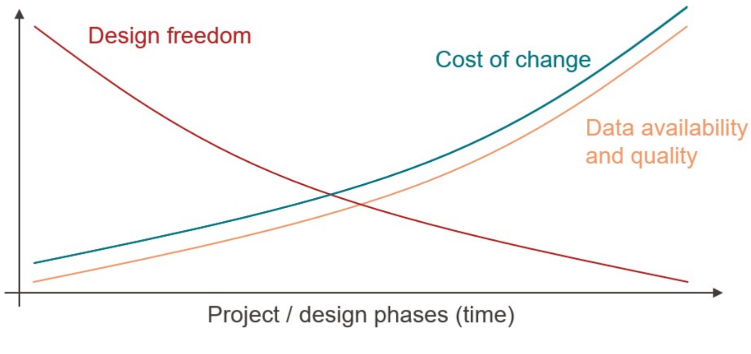


**Figure 1:** Qualitative evolution of key metrics along a project timeline. Adapted from the InnovateDelta.com website.

## 4. Space sustainability in design processes

Cluzel et al. [9] proposed a method to eco-innovate for *terrestrial* complex industrial systems. Space systems share some characteristics with them, especially the large scale in terms of subsystems and components, some unpredictability in the lifecycle, and close interaction with their environment (e.g. vacuum, radiations, micro-debris). But importantly, an identified similarity is the limit to *radical innovation* that is possible in the space sector due to the use of proven technologies (flight heritage). The method [9] includes steps of eco-ideation and eco-selection of R&D projects that can improve environmental performance and be acceptable for customers (e.g. with respect to risk of using a new technology). Following these steps to prepare a roadmap, to develop new materials, new components, and subsystems that can be alternatives to existing ones, with reduced environmental impacts. This exercise is ongoing at European level, as the lack of design alternatives and supply choice have been identified as a challenge to implement ecodesign. And before eco-designing, or eco-innovating, the environmental hotspots - *in* and *for* space - need to be better understood.

#### 4.1 Literature review and known projects

From known research projects done at the EPFL Space Center and some presented at conferences, key take-aways about the inclusion of (space) sustainability assessment and criteria in system design can be highlighted.

### 4.1.1 Sustainability *for* space

Life cycle assessment (LCA) has been tentatively connected to systems engineering (SE) processes several times. Since the first full LCA studies conducted by ESA (2011 for launchers, 2013 for satellites [13]) until about 10 years later, LCA studies were mainly performed on existing space systems (Ariane 5, Proba 2, etc.) that were produced and in use at the time of the study [13]. A first test to integrate ecodesign in a concurrent engineering study was made already in 2009 with ECOSAT study [19]. Another notable tentative was done in 2015 by Chanoine et al. [8] by developing an ecodesign tool for space systems design (OPERA). In parallel, methodologies to apply LCA to emerging technologies and systems still in design, to be produced and used in the future, started to be developed and used in other sectors [5], [10], [36], [38].

Later, sector-wide efforts to adapt these methodologies and use them in space systems have been concentrated at ESA CleanSpace office, in the ESA-led ecodesign workforce, and in the LCA Stuttgart workshops (2022-2024) [23]–[25]. The ongoing development of the Product Environmental Footprint Category Rule (PEFCR) for the space sector will directly affect LCA for reporting purposes [18] which indirectly will also influence LCA performed in early stages. Indeed, compatibility of methodology and reusability of data to improve the assessment through iterations until the final reporting will be interesting to lower the burdens.

The development of the Assessment and Comparison Tool (ACT) by the EPFL Space Center and its partners for ESA FLPP [43], [44], started in 2022, targets the need for a simplified, space-specific, prospective life cycle assessment (LCA) tool for the space sector. Simplified LCA here means both for the methodology, only screening the environmental hotspots to enable comparisons between two versions of the same system, and for the process, simplifying and guiding the standard steps of the LCA for non-experts. Prospective LCA is especially relevant for products that are complex and have long development times and lifecycles.

Along the R&D efforts, different versions of the tool have been tested with industrial partners to understand how this way fits in the existing design processes of different space companies, and sometimes to accompany their first tries with implementing LCA or space sustainability in their processes.

Project VOLARE was conducted in 2023 by a consortium led by ArianeGroup, with EPFL Space Center bringing their expertise about LCA of space systems, and the Assessment and Comparison Tool. The prospective LCA iterations of a family of future reusable European launch vehicle were required by the customer: ESA Space Transportation Systems (STS). A team of ecodesign engineers is working at ArianeGroup, one of them was the main point of contact for the collaboration on sustainability during the project. The LCA was done on two different but complementary tools: ACT and SimaPro [33]. Figure 2 shows the iterative process, with updated technical data compiled by systems engineers, used to update the LCA results, which in turn were forwarded to the systems engineers. because no direct interface existed between the LCA and design teams, it is unclear how LCA results were used to drive key decisions. The most direct ecodesign question was about the choice of the propellant and its production technology [33], and was considered next to other performance indicators.

In 2023, The Exploration Company (TEC), developing a cargo capsule and demonstrators, hosted and co-supervised an intern with the EPFL Space Center, to lay the foundation of life cycle assessment in their design process. The project focused on the Nyx capsule, and prepared the foundation for future iterations of the system. Later, a dedicated "sustainability and ecodesign engineer" was hired in the company to continue this work [6]. A proof of concept version of ACT was used by the student and initial feedback on the tool could be collected.

Finishing in 2025, a master thesis project in industry was co-supervised by EPFL Space Center at Latitude, a French startup developing a microlauncher, with the goal to perform the first LCA of their launch vehicle Zephyr and anticipate future requirements for their next systems. The analyses were made using two software: OpenLCA and EPFL's ACT, with the student's position in the global team, which enabled him to interact with all the subsystems. After this project, a full position was created in the company to continue managing the aspects of LCA compliance.

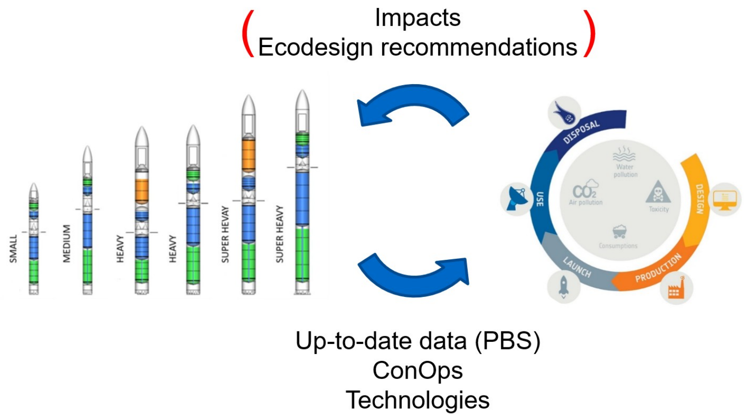


**Figure 2:** Planned iteration process during the VOLARE project [33].

LCA and other space sustainability aspects are getting infused in the requirements of some space projects (see also survey results in Section 4.2. This is the case with the ESA call for proposal "European Launcher Challenges", with two specific requirements:

- "[...] shall perform a life cycle assessment (LCA) of the systems and subsystems used for the upgraded launch service capacity".
- "[...] shall be compliant with the ESA Space Debris Mitigation Requirements".

The former does not set quantified objectives for impact reduction yet. But ESA has pledged to reduce their climate change impact with the Green Agenda [20], so one can expect specific requirements on impact thresholds in the future. The latter is referencing an ESA document that goes on many points beyond the ISO 24113 [17] standard.

Imposing requirements on projects is one way to drive the implementation of LCA and later ecodesign for space systems. The issue with this approach is that industries might see it as only additional constraints in an already complex type of projects. Highlighting the co-benefits of performing those studies - including for safety, resilience, risk reduction - should also motivate companies to anticipate regulations and perform space sustainability studies voluntarily. This is the case of several companies already as discuss below.

Many other projects presented during the CleanSpace (Industry) Days have integrated LCA in early design stage (see contributions in CSID2016, CSID2017, CSID2018, CSID2021, CSID2022, CSID2023, CSD2024).

ESA is operating a concurrent design facility (CDF) for early stage projects. There exist other CDF across Europe in academic or industrial settings. Each integrate their set of expertise and specificities but at minima are made of: a team of experts, a centralized data/model tool, a process, some supporting software / hardware.

Infusing (space) sustainability already during feasibility / concurrent studies in a CDF has been tried in the past [7], [47]. This would show the benefit of adapting the design choices to reduce the expected environmental impacts most efficiently and at low cost since the design freedom is still high. On the other hand, the available data and its quality might not be sufficient to perform deep analysis at this stage. More recently, a test was performed at EPFL and is presented in Section 5 below.

The CDF is also used on specific components or technologies to enable ecodesigned systems and missions that integrated space sustainability mitigations (e.g. technologies to deorbit space objects [19]).

#### 4.1.2 Sustainability *in* space

Not only LCA is integrated in the design process, some companies especially focus on the aspect of sustainability *in* space and space debris risks and mitigations since the early design stage [2].

The adoption of this is emphasized by the growing number of signatories of the Zero Debris Charter [22] and the industry's development of the Zero Debris Technical Booklet [49]. Whilst non-binding, the charter provides aspirational goals that signatories set themselves in the field of Zero Debris. The Booklet is a translation of these goals into technical solutions and into the definition of enablers that still may need to be researched. With over 170 signatories to the Charter and a large community working on the development and maintenance of the Booklet, sustainability *in* space is clearly taken into consideration by the space community.

There are expected projects on the design of electronic components and antennas to better understand and reduce their unintended emissions during operations. Those unintended emissions are not regulated by the International Telecommunication Union (ITU) and their effects are not (yet) considered during the design of new satellites [26].

On another topic, a wider view on sustainability is also mentioned in some corporate social responsibility / sustainability reports of larger companies (e.g. ArianeGroup which included sustainability commitments at the corporate level [1]) which will imply requirements and efforts in the technical projects.

### 4.2 Survey to practitioners in the space industry

A survey was circulated around contacts of the authors to reach experienced profiles in space system design, systems engineering, and / or space sustainability. Twelve answers were collected and analysed below. Most interviewees are familiar or have expert knowledge about LCA, systems engineering, and project management. The topics with the least expertise in the panel are space situational awareness, and concurrent engineering. More participants identify their field of work in the space segment, some in the launch segment, and few in the ground segment.

About which space sustainability topics are most understood and which are still lacking in industry, the participants agree that the discussions about space debris risks and mitigations are the most widely understood ones. LCA is understood by more and more actors, especially its limitations (e.g. launch and reentry emissions, end-of-life impacts), but not all impacts are at the same level of maturity and engineers still requires training to implement ecodesign.

Regarding flow-down of environmental requirements, the survey results highlight that the main drivers of sustainability requirements are the final customers, be it a space agency, a government, or an armed force, and regulations. This is not surprising as industries will not impose additional constraints on themselves if not required, although it discards the potential co-benefits mentioned in Section 4.1 above.

It is mentioned that some of the requirements are directly for collecting data for life cycle assessment, others are more specific (e.g. approximating reentry impacts with materials and shapes) or more high level (e.g. reporting of Corporate Social Responsibility policy). This also means reviewers shall be aware of the risk that some industries will perform the minimum analysis to comply with the requirements, without effectively infusing space sustainability as a clear objective in the design process.

An identified pain point for the application of LCA and other comprehensive methodologies in the early phases of the design process is the lack of data. Both foreground data about system (knowledge of the product under study) and background data (information on the suppliers, energy production mix, etc). The former can be compensated with heritage from previous missions and as much as possible with documentation available early in the design. The latter requires making assumptions which are sometimes adapted by using prospective LCA [36], [43]. Interviewees were asked which documents are available to get foreground data, at which stage of the process. This exercise has also been done at the ESA-led ecodesign taskforce and consolidation is required.

| Earlier stage ( phases 0/A/B1) | Later stage ( phases B2 and after) |
|---|---|
| • Very limited to none according to some interviewees.<br>• Heritage missions and environmental studies, to help make assumptions.<br>• Preliminary mass and other technical budgets.<br>• Declared Materials List (DML), Declared Processes List (DPL) are relevant system level documents, but not intended to help for LCA.<br>• AIT plan, procurement plan, etc.<br>• Guidance on assumptions for data gaps and scaling laws to fill them in. | • Similar documents as on the left, with improved data but still with some limitations, unless contracts (from customers and to suppliers) specifically require the data collection.<br>• Contractor and production details on mass, dimension, material of subsystems, consumables.<br>• Data from the supply chain, from contracts.<br>• More details about masses (buy-to-fly ratio), selected materials, production methods, cleanrooms, etc. |

**Table 1:** Data availability - relevant deliverables / documents / data available in different design stage. Summarized from survey answers.

Impacts on climate change and ozone depletion are quite known in the space industries but other types of impacts less so. A question about the seven recommended design guidelines proposed by Desing et al. [12] to reduce the resource pressure of products (any, not necessarily in the space sector) was added to see if they were known and applied in the space sector too (Figure 3).

Reducing the mass is clearly an interesting co-benefit for several objectives: environmental impacts reduction, improved performance, and reduced cost of space systems. It was expected to appear already in the applied design guidelines.

To increase the lifetime of parts and components to serve on long-term mission also appears clearly in the results. With a larger panel and including more engineers from the *new space* would maybe show a different results as for the new space, the strategy tends more towards short-lived satellites that deorbit rapidly from LEO to be replaced with a high launch rate. Therefore they do not need parts and components with long lifetime.

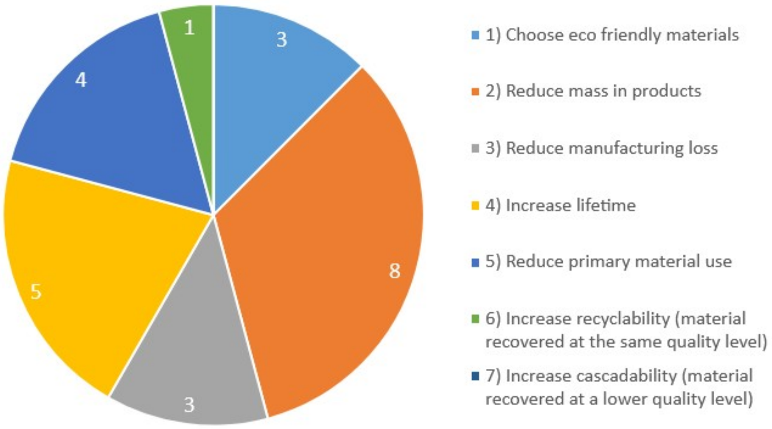


**Figure 3:** Results of question 12, in survey 1. Interviewees could select several guidelines.

Four interviewees ticked the guideline to reduce the primary material use. This can work in synergy with increased recyclability of the product, with the use of cascaded material (probably not in space application as the materials used are of the highest quality), or thanks to topological optimisation to reduce the mass of the part. The latter again shows a co-benefit between system performance and environmental impact mitigation.

To recycle and cascade materials (guidelines 6 and 7), one needs first to recover the materials. This is not the case for most space systems apart from reusable launch vehicle stages. There are concepts of recoverable space systems also in Europe (e.g. SUSIE, SpaceRider, Nyx capsule coming back on ground), which can be reused and at some point recycled or cascaded after a certain amount of reuse. There are also some concepts to recycle or cascade materials in orbit [3] or even on the Moon after end-of-life of a mission.

Finally, it seems the concept of *cascading* [12] is not understood (or less known than recycling) although it's probably a more realistic option when recovering space-grade materials. Since space technologies usually integrate top quality materials, they could still be used in other sectors even after degradation of their properties (e.g. from thermodynamic loads during reentry).

### 4.3 Comparisons and recommendations

From the different projects presented above in Section 4.1, and the survey in Section 4.2, some key take-ways, similarities or differences in ways of implementing (space) sustainability in the design process, can be extracted:

Similarities across known projects

- Projects often focus on space debris OR using LCA, only few projects include both approaches.
- The challenges to collect data in early design stages, even internally.
- The added value of being guided (ESA handbook, zero debris approach) with harmonised methodology rules for robustness and comparability.
- The same knowledge gaps (especially atmospheric impacts of launch and reentry) across studies.

Differences between known projects

- The position of the sustainability engineers (sometimes working at the interface with systems engineers and other domains of expertise, versus only in touch with the SE team).
- The tools used and some LCA methodological choices.
- The moment at which the first analysis are performed, between very early stage to later design stages.

Recommendations to space industries

- The LCA / sustainability team should work closely with the design team(s) and other members of the project. This in order to set hypotheses; improve the inventory; and coordinate and influence the design iterations [33].
- Early LCA studies should be improved and iterated upon after each design milestone. When reviews are passed, it unlocks the release of newer and more up-to-date data that can be used as inputs.
- In very early stage, "common-sense" guidelines that have synergies with other performance objectives (e.g. reducing the mass) should be followed and encouraged.
- Thorough environmental assessment of the mission in later project phases (e.i. after launch) should still be performed, not only for reporting purposes but also to support and improve future environmental studies.
- Lessons learnt from application of early stage environmental assessment should be shared amongst practitioners.

## 5. Sustainability in the CDF - a practical case study during EPFL course on concurrent engineering

Concurrent engineering consists in grouping experts from different relevant domains in one "room" to concurrently design a mission or system. The experts supposedly carry the knowledge of the State-of-the-Art in their relevant fields and directly face constraints from other parties to reach a compromise that is the most suited for the goals of the mission. To this date, active efforts to integrate sustainability as a role in the CDF were made [47] [7], but further advancements are required to enable a concrete application as part of an actual space mission design. This section aims at integrating it and defining how sustainability can transition from an assessment purpose to design, and how it interacts with other roles. A test conducted at EPFL's concurrent design facility over the course of a 7-week timespan, and the different elements were refined and improved based on the lessons learned from these design sessions.

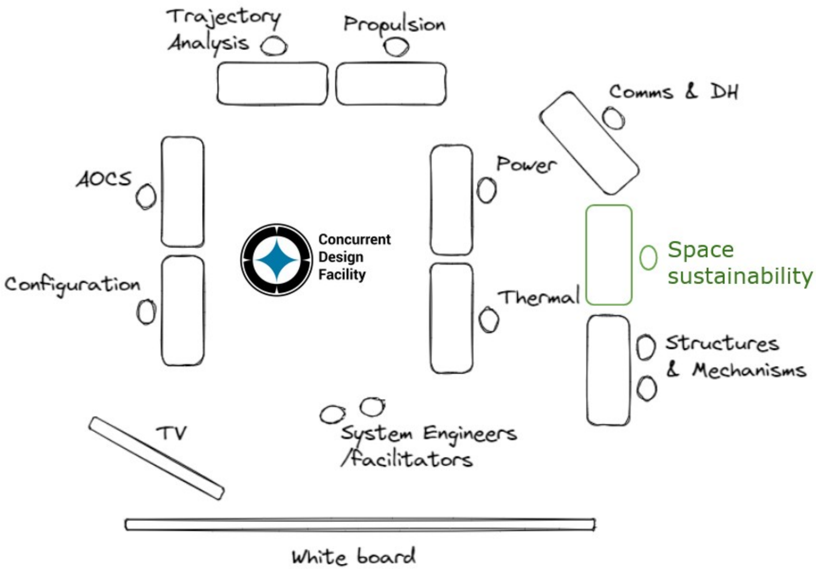


**Figure 4:** Set up of the EPFL CDF, with the space sustainability domain of expertise.

#### 5.1 High-Level Design Processes for Sustainability in the CDF

The role of sustainability in concurrent engineering follows the direction dictated by the previously defined objectives (See equation 2, p.3). To this end, four main processes ensure a comprehensive approach to the design of the mission: Launcher selection, End-of-Life strategy, high-level Life Cycle Assessment, and a mission sustainability score (itself integrating resilience and safety assessments).

### 5.1.1 Launcher Selection

The atmospheric impact of the launcher on the atmosphere is a topic that is quite unknown [45]. Some tools attempt to assess quantitatively these effects, but they require too much information to be used and to be relevant at this level. It is known from Sirieys et al. [39] that the most impactful parameter for the atmospheric impact of a launcher is its propellant.

It is also known that the main negative impacts of each propellant occur through three different phenomena. These phenomena are ozone depletion and radiative forcing in the Stratosphere, as well as cloud formation in the Mesosphere. The figure 5 provides the foundation for the selection of a launcher in the CDF, with an integrated qualitative sustainability rating based on whether each propellant impacts those phenomena, and on their mass proportions.

### 5.1.2 End-of-Life Strategy

The traditional method for selecting the end-of-life strategy is to simply perform a trade-off between the different alternatives, select one, and compute the required Delta velocity ($\Delta v$). This method becomes less and less robust with time because some uncertainties are more impactful. For instance, increasing debris population or future regulations are more and more important for the mission design. These uncertainties cannot be ignored if the long-term operability of the space environment needs to be ensured.

Recognising these uncertainties is especially crucial in the selection of the end-of-life strategy because it is planned for the end of the mission, usually being after at least 5 years of operations, without accounting the time between mission planning and commissioning.

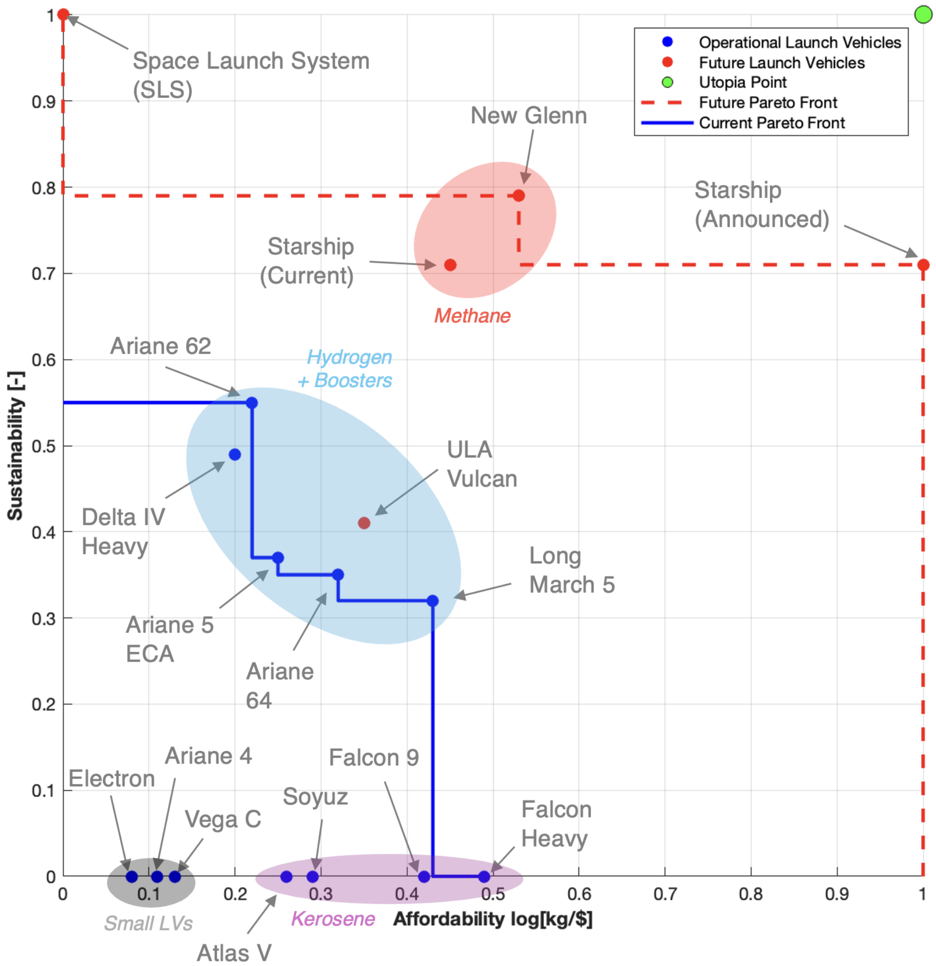


**Figure 5:** Trade-off analysis for launch vehicle selection. Sustainability index based on negative atmospheric impacts of propellants described by Sirieys et al. [39]. Sustainability defined as atmospheric impact suring burn time, evaluated with qualitative index based on propellant proportions. Clusters found through k-means clustering with $k = 4$ (SLS and Announced Starship identified as outliers). All results normalized by MinMax. Data collected from Wikipedia pages of individual launch vehicles.

Real-Options Analysis (ROA) [32] offers a solution to this matter by introducing flexibility in systems to make them more robust to inevitable uncertainty. The ultimate goal of such an analysis is reduce risks, but also to take profit of opportunities. Due to the constraints of the CDF, this analysis is limited to being qualitative but sets the foundation to recognising uncertainties, and planning options for potential case. These options then allow to refine the computations of the propellant margins for instance. The merit of this strategy is improved by the addition of the ROA, and is then qualitatively evaluated, based on a predefined rationale.

### 5.1.3 High-Level Life Cycle Assessment

LCA is a method used to evaluate the environmental impact of a system from the extraction of materials to the disposal. It is mostly used to evaluate systems that are already designed and manufactured, as a reference for future improvements. In the present case, one wants to determine if it is feasible to integrate this method as a design tool, especially in very early design of space missions.

To evaluate the feasibility of such a task, one needs to identify the unknown parameters at the stage of the CDF, and assess the sensitivity of the outcomes to these parameters. In the CDF, trade-offs are performed for the selection of technologies, hence the suppliers and the detailed components of each technology is unknown. The figure 6 shows the parts of the carbon footprint, specifically for aluminum production, that are dependent on the direct emissions of the production processes and the indirect emissions due to their energy consumption. One can immediately observe the very high impact of this second parameter. Therefore, having it as an unknown is a major issue, and one can directly draw the conclusion that it is unfeasible to reliably assess the carbon footprint at such a high-level.

One can also observe that the carbon footprint due to the process itself is constant across locations, showing a standardisation of the process. So the variation is due to the impact of the energy source and that the required energy for production is stable across locations. Moreover, for the second unknown parameter, the components being defined by the architecture has to be stable for a technology, given that it is a mature one, which is the case for space systems. Therefore, it is determined that the carbon footprint

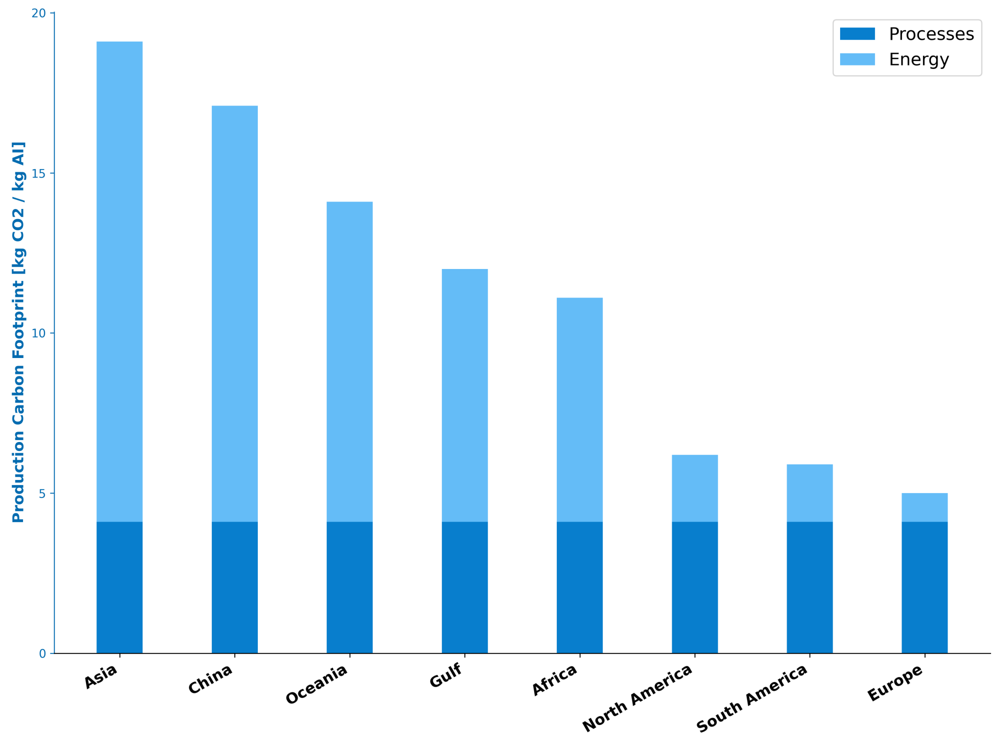


**Figure 6:** Carbon footprint and production cost of aluminum, by region and on average. Data for carbon footprint from Saevarsdottir et al. [37].

is unfeasible to evaluate in the CDF (See olive factor in equation 3), but by removing the uncertainty source (namely the supplier's environmental impact, see red factor in equation 3), one obtains a stable metric, which is defined by the required energy to produce a technology (See blue factor in equation 3).

$$\left[\frac{kg.CO_2.eq}{kg}\right]_{\text{Production}} = \left[\frac{kg.CO_2.eq}{kWh} \cdot \frac{kWh}{kg}\right]_{\text{Energy}} + \left[\frac{kg.CO_2.eq}{kg}\right]_{\substack{\text{Process}\\ \text{(constant)}}} \tag{3}$$

For an integration in the CDF, the metric of the required energy for production is used as reference for the environmental impact of a technology, and traditional trade-off analysis methods can be applied. It can be accounted in the exact same way as cost and performance are, and provided to relevant subsystems.

### 5.1.4 Mission Sustainability Score

One now wants to compute a sustainability score that accounts for all the aspects of the mission and is provided to systems engineers to enable the integration of sustainability in mission level trade-offs. A score for the sustainability of the launcher was previously defined, the LCA also returns a score from the required energy for production (relative to other technology alternatives, normalised), and the End-of-Life strategy is accompanied by a rationale that enables a scoring of the outcome.

To integrate resilience and safety (See equation 2, p.3), the scores are added based on two additional assessments. Both of these assessment result in qualitative scoring, based on predefined rationale. One can therefore integrate all of these previous processes in the overall score.

The first analysis aims at assessing the resilience of the mission, through an external forces analysis. Resilience is defined as the capacity of a system to provide value under unexpected conditions. These conditions are defined by external forces, which themselves constitute the main sources of uncertainty for any system. Hence, one wants to characterise a realistic case of degraded conditions and evaluate the merit of the system under these circumstances. The difference of provided value between the expected scenario and the degraded scenario will characterise how resilient the system is.

The second analysis aims at assessing the safety of the mission. Safety is defined by the capacity of a system to protect from hazards. Hazards are defined in this case by all undesirable events that occur from within the system boundaries, like the failure of a subsystem. One wants to identify all the parts that may fail or behave in a way that was not intended. Then one wants to analyse the behaviour of the system that is caused by such an issue, especially how failure propagates.

For the final score, a survey was conducted with engineers and managers from the industry. A goal of this survey was to determine the weights of the different objectives, and the following results were obtained: Environmental impact 22%, Long-term operability 26%, Safety 26%, and Resilience 26%. To compute the score, a weighted sum of the different input scores is applied.

All of these scores are required to be normalised and comprised between 0 and 1, so to get a percentage of sustainability for the mission as an outcome.

**5.2 Integration in the Concurrent Engineering Process**

The content of the process that are integrated in the role of a sustainability expert is important, but the most crucial aspect of concurrent engineering is communication, and therefore the interfaces with others. This part will elaborate on the integration within the concurrent engineering process, and specify the interfaces both for inputs and outputs.

### 5.2.1 Interfaces with Other Roles

The figure 7 defines the conceptual model of the role and emphasizes four interfaces, namely the Systems engineers, Structure engineers, Power engineers, and Propulsion engineers.

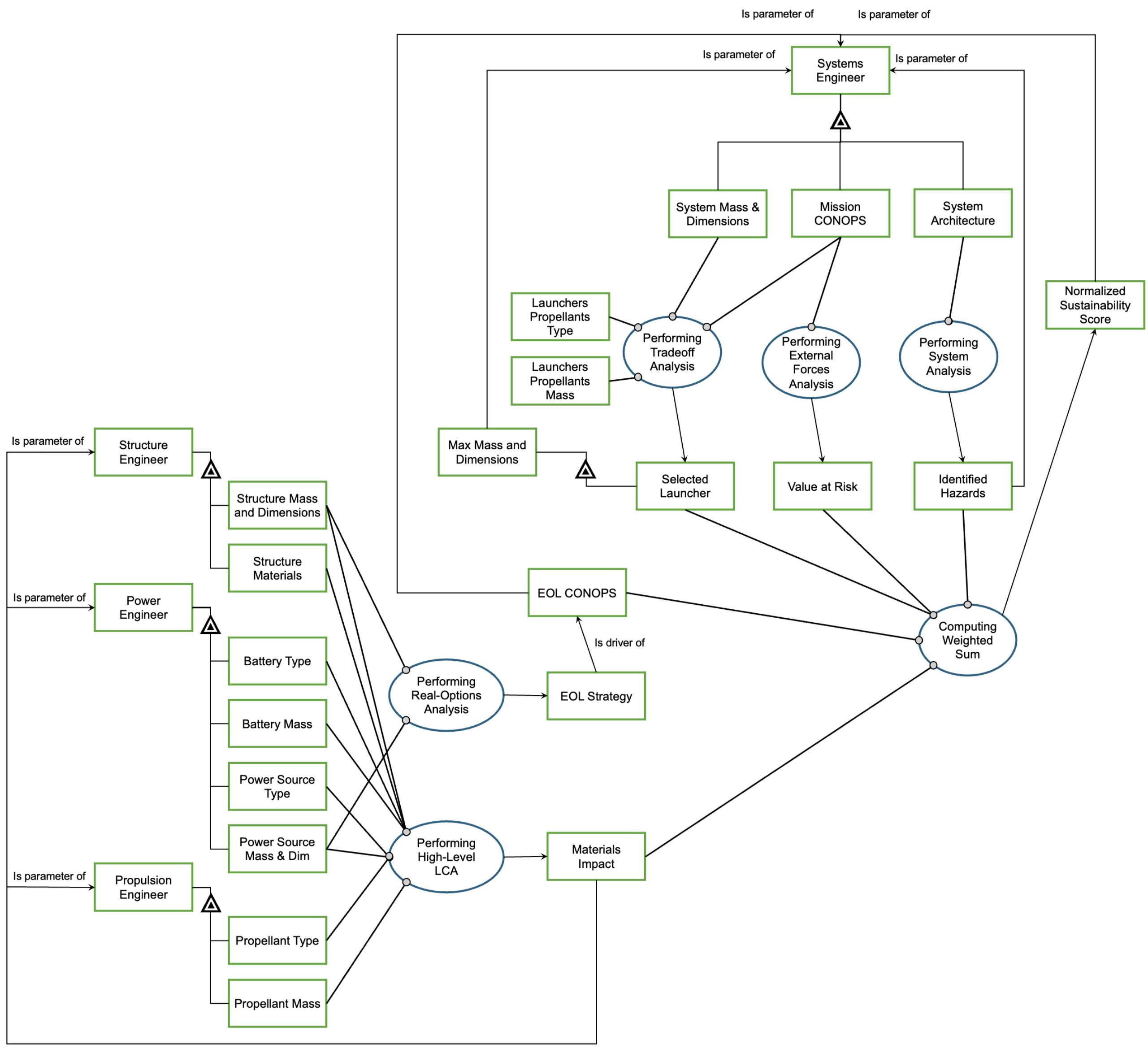


**Figure 7:** Object Process Model of the role of a sustainability expert within a CDF environment.

### 5.2.2 Integration Test at EPFL

The previously defined system was experimented at EPFL in the course "Concurrent Engineering of Space Missions", where its integration was successful. The interfaces with other experts were clear and respected. Another important aspect that was noted is that the role did not only have an assessment role, but exhibited an active impact on the mission and clearly oriented the different choices. To see more about the results of the feasibility study in the course, check the study report [31]. This system could now be tested in larger scale concurrent design sessions and refined for more rigorous applications, with a proven architecture.

### 5.3 Identified Research Gaps and Conclusions

In terms of integration in the concurrent engineering process, the role that was specified was a success and a positive impact was noticeable. On the side of the pure content of the role, multiple research gaps were identified during the specification of the processes. These gaps are not only specific to concurrent engineering, but belong to any case of sustainability in space systems engineering. Indeed, processes such as a traditional LCA were found unfeasible, and research directions are proposed for future projects:

- LCA projects for the definition of a database for the selection of technologies, based on the required energy for the production of different technologies ($\frac{kWh}{kg}$).
- Definition of policies or guidelines for the integration of sustainability in the supplier selection process (in addition to cost).
- Projects in collaboration with launch vehicle operators to measure the atmospheric impact of launches in the different layers of the atmosphere [45].
- Projects to evaluate the atmospheric impact of reentry and trade-off between demising and non-demising strategies [45].

## 6. Need for education about space sustainability

To correctly implement sustainability criteria in the design of future space systems as discussed in section 4, a trained workforce is necessary. This is true for future engineers and managers that will soon graduate, and for current decision-makers.

The growing need for education regarding space sustainability is not yet matched with enough offer, but some new programmes are created to fill this gap, at university and for continuous education.

This section gives an overview of existing courses and trainings on the topic and analyse data from a survey sent to students and alumni about space sustainability education.

### 6.1 Review of existing space sustainability education programmes

There exists an educational offer on space sustainability, with courses and trainings, for university students and as continuous education for professionals. A preliminary list was compiled in Table 2.

One can clearly see in Table 2 that sustainability *in* space is the most covered pillar in existing educational programmes. The topics of space debris and space law are included in most of them, apart from the more specialised ones. Sustainability *from* space is less present, while LCA and ecodesign (sustainability *for* space) are covered also by specific trainings. Finally, one can see that few options cover all topics, but it is the case of the space fresco, an awareness-raising workshop built on the same format as the climate fresk. The survey also mentioned guest lectures and presentations, by ESA or external experts. Those were not included in Table 2.

### 6.2 Surveying alumni about space sustainability skills

A second survey was disseminated to alumni and students of different universities and of professional courses with space sustainability content. 24 answers were received and analysed in this section. Most responses come from alumni who graduated at bachelor or master level in the past two years. There might be a bias coming from the way the survey was disseminated (mainly through university professors), but some answers are from professionals active in the sector for more than a decade. About half of the interviewees followed at least 1 course that included some aspects of space sustainability during their education.

A first question was asked to capture the definition of space sustainability that interviewees had in mind when participating in the survey. Many use words such as "limit", "reduce", "minimize", "protect", "preserve", "regulate", "design" which are preventive approaches, but also "remove", "mitigate", "keep (clean)", which are more in reaction to an existing situation. The topic of "space debris" and sustainability in space is most often cited overall (19/24). While aspects of sustainability from space are only hinted by 8/24 participants. Some mention some lesser known / covered topics like "RF spectrum" (DQS), nuclear use, or the protection of other celestial bodies.

Figure 8 shows which **domains**, from a predefined list, have been most encountered by interviewees who followed courses with space sustainability topics. As expected, space debris is one of the mostly cited one. The topic has been making headlines in the past years and has been a concern since several decades, with the now famous Kessler syndrome which was coined in 1978 already [30]. Space law and regulations were also often cited, probably since the few existing treaties serve as a basic introduction to the current context of the space environment. It is confirmed by the mapping shown in Table 2 where most of the existing courses at least partially cover the topic of space law.

In the least cited domains, one can find the topic of dark and quiet skies (DQS) with the management of the frequency spectrum, although it is currently very relevant for astronomers [4], [26]. Space traffic management is a subdomain of debris risk

**Table 2:** Space sustainability education programs, provided by various entities with different target audience. The topics within each pillar of space sustainability is shown through a greyscale: dark grey = covered; light grey = partially covered; white = not covered (based on publicly available information).

| | | | Sustainability for space | | Sustainability from space | Sustainability in space | | | |
|---|---|---|---|---|---|---|---|---|---|
| **Institution / entity** | **Course name** | **Target audience** | LCA | Ecodesign | Space 4 SDG | Zero debris | Space law | Space weather | Dark & Quiet Skies |
| EPFL | Space Sustainability (EE-587) | Masters students | | | | | | | |
| | Space Sustainability Course for professionals | Professionals | | | | | | | |
| | Space mission design and operations (EE-585) | Master students | | | | | | | |
| Georgia Tech | Space Sustainability | University students | | | | | | | |
| | Space Policy | University students | | | | | | | |
| Helsinki Uni | Sustainable Space MOOC | Open | | | | | | | |
| Uni Stuttgart | Orbital Mechanics in Low Earth Orbits | Master students | | | | | | | |
| TU Braunschweig | Raumfahrtrückstände | University students | | | | | | | |
| TU Darmstadt | Space Debris - Risks, Surveillance and Mitigation | Master students | | | | | | | |
| PoliTo, ISAE, Leicester | SpacE Exploration and Development Systems | Master students | | | | | | | |
| ESA Academy | Space Debris Training Course | University students | | | | | | | |
| | Clean Space Training Course | University students | | | | | | | |
| ESA & Deloitte | Environmental Life-Cycle Assessment and Ecodesign of Space Systems (<2022) | Professionals | | | | | | | |
| International Space University | Space Studies Program (SSP) | Professionals | | | | | | | |
| UN online | Introduction to The LTS Guidelines | Open | | | | | | | |
| Azurite & AeroDecarbo | Space Fresco (fresque du spatial) | Workshop on demand | | | | | | | |

and is apparently not the main focus compared to other mitigation measures. Societal benefits of space data (sustainability from space) is also mostly untouched.

When asked to comment on the missing domains in the courses they experienced, interviewees mentioned they would complement the programme with the remaining domains that were proposed in the initial list, especially SSA, STM, LCA, DQS, and regulations. Some stated that even when the topics are mentioned, the depth of details should be increased.

New domains that were not in the list but proposed to consolidate it are "space-related economics", "systems engineering", "cultural implications of space travel". Earth Planetary Boundaries, and degrowth are also mentioned. These ideas show how broad the topic of (space) sustainability can be. Some of them could be briefly covered in existing programmes while other would need more dedicated research to get to a maturity level at which they can be introduced to students. Also, some of these ideas are targeting different specialisations, while the offer list in Table 2 is mostly targeting engineering students and professionals.

Regarding necessary **skills** that are taught within existing space sustainability courses (see Figure 9), a majority of interviewees that followed one selected "understanding of specific methodology(ies)" from a predefined list of options. The least covered skills are transversal ones (communicating and reporting). Although they are not specific to space sustainability, they are nonetheless important for a successful implementation, and later knowledge retention and dissemination, of space sustainability efforts. Transversal skills should be trained through group projects on the topic.

Most answers about which domains or skills are currently missing mentioned some from the proposed options that are not covered by all courses yet. Several interviewees also underline the important for all to be aware of at least the basics of space

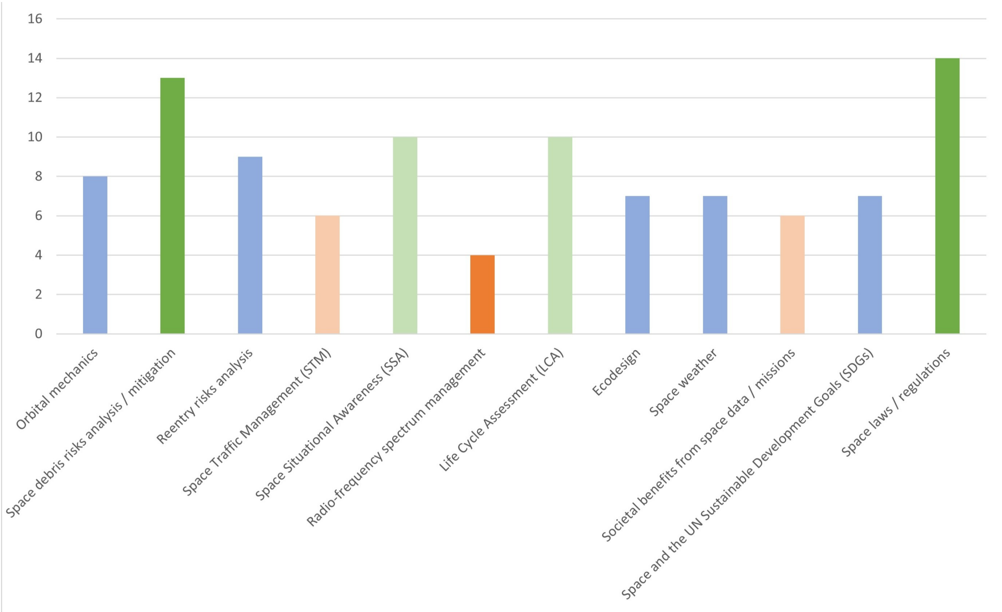


**Figure 8:** Count of domains selected by interviewees that followed courses with space sustainability topics (12). Colours only to support the interpretation.

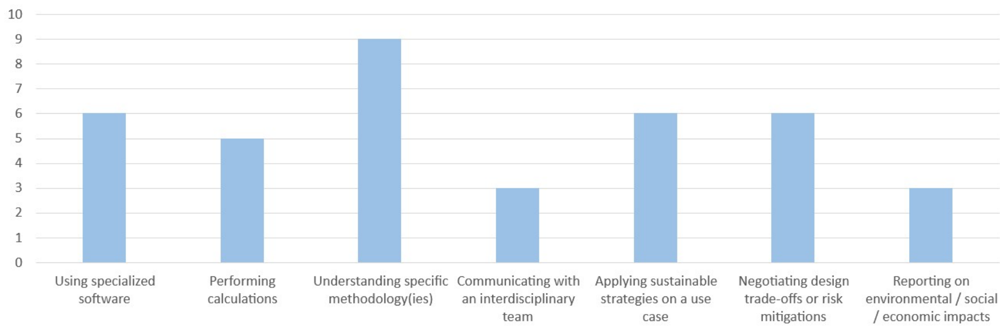


**Figure 9:** Count of skills selected by interviewees that followed courses with space sustainability topics (12).

sustainability, to bring the knowledge into their specialised field. Some also mentioned systems engineering, the capacity to trade-off alternatives, and ethics, to keep a broad overview and be able to make the right decisions at a system level.

In summary, space sustainability is a broad topic, touching upon several domains, sometimes very different from one another, and requiring a complete set of skills. The existing education offer covers domains unequally and prepares the workforce with the necessary skills to at least be aware of the subject.

## 7. Discussion

Some of the limitations of the research done for this paper would need to be addressed to consolidate the main findings:

- By collecting more answers to the two surveys, and updating them regularly to understand evolving trends regarding the implementation of sustainability in the design and systems engineering processes.
- By validating the methodology of the CDF use case presented in Section 5. It was developed this semester in parallel to the design sessions of an EPFL master course, and it should now be applied since the beginning during a concurrent study with professionals from industry, and at the next course for master students.
- By expanding the search of courses and trainings that include space sustainability domains, for instance via university networks. The analysis of existing education programmes (Table 2) might have been biased by collecting information in priority on those already known by the authors.

Working on those limitations might also highlight the needs for new features and interfaces between engineering and design tools, and sustainability assessment tools like the Assessment and Comparison Tool [46].

## 8. Conclusion

Space sustainability is increasingly integrated in the early design process of space systems, incentivised by stronger stakeholder expectations. This is in part accelerated by the prospect of new regulations and guidelines in Europe and by industry-led initiatives. Regarding sustainability *for* space, one can note the PEFCR4space rules expected to enter in effect by 2027 [18] and the integration of new requirements about LCA by ESA. On sustainability *in* space, the Zero Debris Charter and Technical Booklet also form a pioneering driver for change, along with requirements set out by ESA and other agencies.

To support this change of perspective in the industry, an effort to harmonise methodologies and standardise tools is underway, particularly in Europe. Examples include ESA's LCA guidelines, the ACT tool developed at EPFL, and the zero debris technical booklet and charter. An initial use of some of these tools in early projects and a CDF study at EPFL demonstrated that sustainability can be included earlier in the design phase, with more positive effects. It remains to be seen in the near future if the industry will indeed systematically apply sustainability with new tools and data during those earliest design phases of space systems.

Education programmes on a wide variety of topics within space sustainability are being developed and have already been put in practice over a number of years. This paper has shown that they particularly cover topics around sustainability *in* space (e.g. space debris, space law), whilst sustainability *for* space and *from* space are discussed to a lesser extent. The needs for these programmes have clearly been highlighted by the interviewees, and it is found that certain domains and skills need to be strengthen. Indeed, the survey sent to alumni and students underscores the importance of preparing the workforce (current and future) about space sustainability challenges for the sector.

Overall, this paper sheds light on the current transitional period of the space industry, where sustainability is increasingly being integrated within design processes. This is supported by the overview of past projects in the field of space sustainability, the discussion of a CDF experiment done at EPFL and the summary of various education programs needed in the workforce. As such, the space industry might be on its way to meaningfully address its increasing effects on the sustainability *in* and *for* space.

The EPFL Space Center will continue researching the topics of space sustainability infused in systems engineering process as well as methodologies for specific domains of space sustainability, including for dark and quiet skies, life cycle assessment, and space debris risk analysis.

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