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ABSTRACT:

This document is the executive summary of the study named “environmental impact assessment analysis”, which aimed to understand the environmental profile of space missions and to develop an eco-design tool for use at pre-phase A to design more environmentally friendly space missions.

First, this report provides an overview of the impacts of two analysed missions, i.e. a typical Earth observation mission and a telecommunication mission. Then, a focus is made on the tool that was developed for use at CDF, detailing its main purpose, interest and functional principles.

The final section of the report provides recommendations for future work, both in terms of scientific and technical work (either to be done at/by ESA or to be performed by other stakeholders of the space sector) and possible activities to push the eco-design strategy forward, and engage the whole industry.

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Environmental impact assessment analysis

Technical Note D8: Executive summary

Final version v2

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Introduction

➔ Context

Public awareness of the urgent need for mitigating the environmental impacts of human activities is ever growing. This results in a more and more stringent public environmental legislation and an increasing public pressure. In this context, the European Space Agency (ESA), as a public sector intergovernmental organisation, wants to put the environmental concern as a priority in all its activities, as expressed in its Framework Policy on Sustainable Development. The first step in this direction is a deeper analysis and understanding of the environmental impacts of space programmes, to provide ESA with the necessary know-how to take a pro-active role regarding legislation on this topic and to drive technical and scientific innovation in the European space industry. In order to have a better knowledge of the environmental impacts of its activities and to be able to integrate environmental aspects during early design phases of space missions, ESA launched the project "*Environmental impact assessment analysis*", in the frame of the Clean Space initiative. Deloitte Sustainability (formerly BIO Intelligence Service [1]) was awarded the contract for this GSP study.

➔ Objective of the project

The overall objective of the project was to provide ESA with the necessary methodological and software tools to design future space missions in a more environmentally friendly way.

➔ Main methodology used: Life Cycle Assessment

Within this project, we used Life Cycle Assessment (LCA) and adapted it to the space context. LCA is a powerful method, standardised at international level by ISO standards ISO14040 and ISO14044, to evaluate the environmental performance of products (i.e. either goods or services) in a comprehensive and science-based manner.

LCA aims to assess the environmental footprint of a product **throughout its whole life-cycle**, from the extraction of the materials required to the treatment of these materials at the end-of-life stage, i.e. from cradle to grave: it is a multistep approach. LCA is also a **multicriteria approach** as all quantifiable environmental issues related to either resource consumption (e.g. energy consumption, mineral resource depletion, water consumption), air pollution (e.g. climate change, acidification, ozone depletion), or soil or water pollution (e.g. eutrophication, toxicity towards the ecosystems) are assessed.

As a multistep and multicriteria approach, LCA makes it possible to compare different situations and to identify pollution transfers from one type of environmental impact to another, or from one life-cycle step to another, between two different scenarios of the same system, or between two different systems. Figure 1 illustrates its main principles.

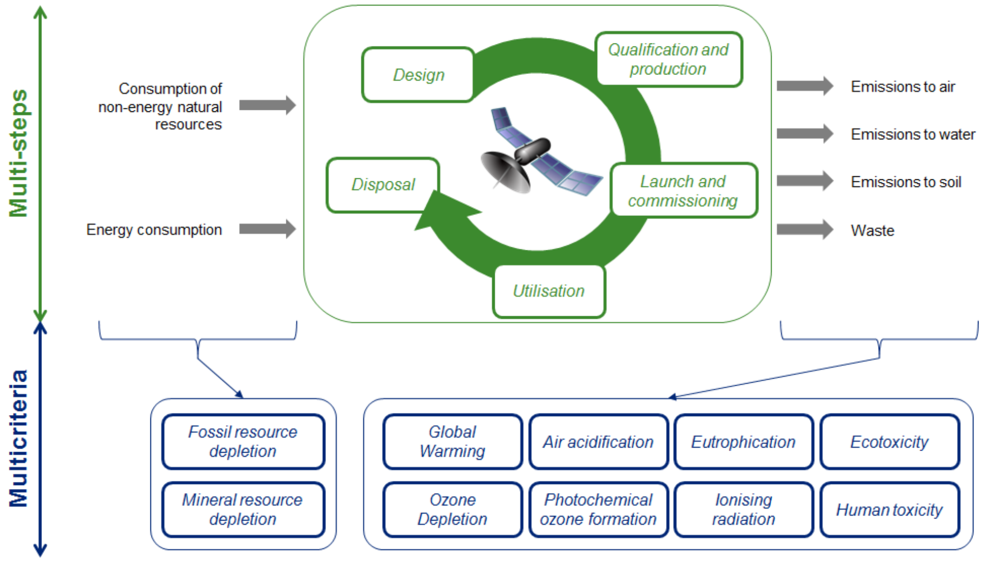

Figure 1 - Illustration of the multi-step and multicriteria attributes of LCA

[1] Deloitte Sustainability was the result of the acquisition by Deloitte France, in 2013, of BIO Intelligence Service, one of Europe's leading consulting firms in the field of sustainable development. After the later acquisition (in 2015) by Deloitte France of Synergence, a major player in the sustainable engineering and communication sector, the resulting team is now Deloitte Sustainability. Deloitte SA is part of the global Deloitte Touche and Tohmatsu network. To know more about the legal structure of Deloitte Touche Tohmatsu and its member firms, please visit http://www.deloitte.com/about. To know more about Deloitte Sustainability, please visit http://www2.deloitte.com/fr/fr/services/developpement-durable.html

Environmental impacts of space missions

➔ Overview

Two pilot Life Cycle Assessments were carried out on two space missions: one Earth observation (EO) mission and one communication mission. The two pilot LCAs were conducted in an iterative way: environmental hotspots and data quality analysis carried out at each of the four iterations allowed prioritising the need for additional data collection and further refinement of the LCA model. An important data collection process allowed establishing environmental data over the whole life cycle of space missions.

➔ Goal definition

By quantifying the environmental impacts related to typical space missions over their entire life-cycle, from R&D phase to the disposal of stages, these environmental assessments aimed:

- To **better understand the environmental impacts of space missions** and the sources of these impacts: results aimed to highlight the ecological weak points, i.e. life-cycle phases that generate the greatest impacts, but also their origin.
- To support the design of ESA's eco-design tool and to populate its life-cycle inventory database.
- To provide inputs for the **definition of methodological guidelines for conducting LCA of space systems**.

However, it should be noted that these pilot LCAs neither aimed to compare space missions between one another nor aimed to support comparative assertions intended to be disclosed to the public.

➔ Scope definition

The following chart shows the activities considered in the pilot LCAs and illustrates how they were broken down per main life-cycle step.

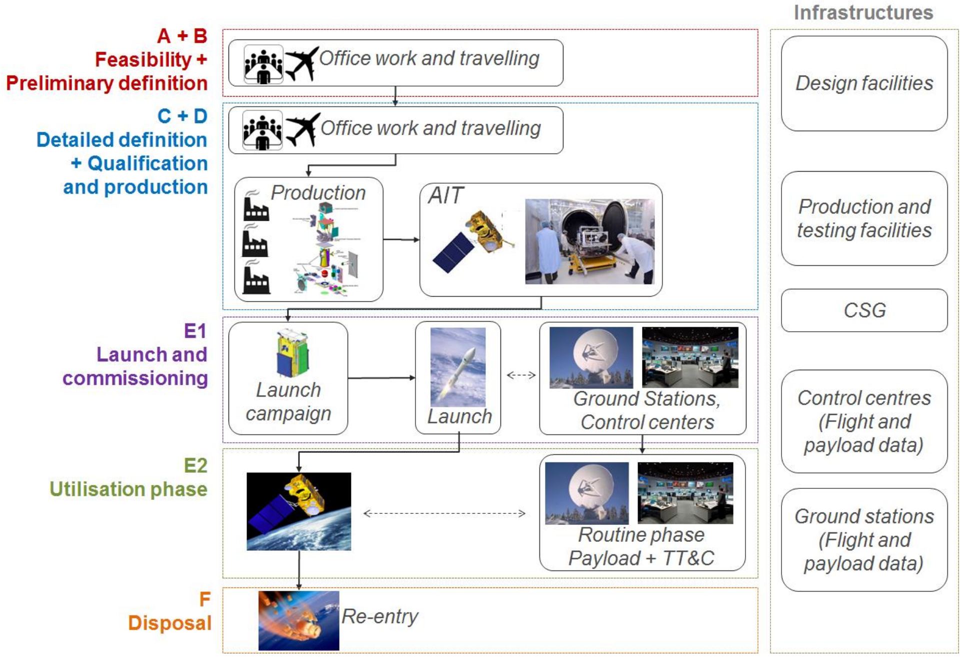

Figure 2 – Scope (system boundary) considered for the LCA of space missions

➔ Considered environmental impact categories and indicators

A comprehensive spectrum of environmental topics was addressed. They were selected in order to cover all impacts related to the 3 so-called "areas of protection": human health, natural environment and natural resources. In total, twelve impact indicators and 4 flow indicators were assessed.

Furthermore, in order to facilitate the decision making process, a single score was assessed in addition to the multicriteria results. A first methodology to assess this single score was proposed but needs to be adapted to ESA's specific context.

➔ Functional Unit

In LCA, the functional unit corresponds to the quantity of service provided by the studied system. It sets a reference against which all impacts are scaled and enables the comparison of environmental impacts of different systems providing the same service. In this project, we considered the following functional unit:

"To fulfil the requirements of the specification of mission *X*"

It is reminded that the purpose of the project was mainly to define a suitable model for the LCA and to identify the hotspots of the environmental impacts of a mission, and not to perform comparisons between different space missions. Therefore, the detailed function of the product was not included in the definition of the functional unit, as a more detailed definition of the Functional Unit is crucial in case of comparison only.

➔ Data collection and data quality

Environmental data was established over the whole life cycle of space missions thanks to an important data collection process:

- Knowledge on space missions and how they are designed were gathered, e.g. by attending a CDF design session in order to get insight on space mission design process.
- An intensive data collection process was performed with spacecraft's manufacturers.
- More than 10 experts were interviewed in the frame of the data collection process, on such aspects as communication subsystem, thermal subsystem, solar arrays, batteries, chemical propulsion, electric propulsion, Electronics, ground segment, testing activities…
- More than 40 environmental Life Cycle Inventory datasets (or Life Cycle Inventories - LCIs) representative of space activities were developed in the frame of the project.

The two pilot LCAs were conducted in an iterative way: environmental hotspots and data quality analysis carried out at each iteration allowed prioritising the need for additional data collection and further refinement of the LCA model.

The quality of the data collected was assessed based on a series of criteria. One such criterion is the type of source from which each piece of data was drawn from: in practice, data were collected partly from spacecraft and launcher manufacturers and for other elements for which no specific data could be collected, a generic data collection process (mainly performed through a desk-based research) was performed, and complemented by interviews with experts from ESA to make the generic data more specific.

➔ Uncertainty analysis

To better understand the level of robustness of the provided results, their uncertainty was assessed using Monte-Carlo simulation.

➔ Key findings of the environmental impact assessments

Note: Except mentioned otherwise, key findings are valid for both missions.

❖ Key finding #1 (from multicriteria assessment):

Launcher-related activities (phase E1b) are the **main contributor to most potential environmental impacts**. This step includes notably material extraction, dry-mass and propellant production, launch campaign and launch event.

However, other life-cycle steps also have significant contributions to the environmental impacts:

- Definition, qualification and production of the spacecraft (phase C+D) is the main contributor on mineral resource depletion, due to the use of scarce materials. Office work is also an important contributor within this phase, due to the energy consumption of design buildings.
- The utilisation phase (phase E2), which covers ground segment activities performed during the routine phase, is the main contributor on freshwater eutrophication potential, due to the electricity consumption of either control centres (case of the EO mission) or ground stations for broadcast (case of the communication mission). This stage also carries significant impacts for toxicity indicators for both missions, due to the fossil share of electricity consumption for the functioning of control centres and antennas.

❖ Key finding #2 (from multicriteria assessment):

Overall, **four life cycle steps appear as significant contributors** to the environmental impacts of a space mission:

- **Phase A+B[2]: Feasibility + Preliminary definition** (office work and business travels);
- **Phase C+D: Detailed definition + Qualification and production** (office work and business travels, raw material extraction, production, testing and transport of S/C models);
- **Phase E1b : Launch and commissioning** (launcher-related activities, including production of the launch vehicle: material extraction, dry-mass and propellant production, launch campaign, launch event);
- **Phase E2: Utilisation** (use of ground facilities during the routine phase: ground stations, control centres and payload data handling stations).

❖ Key finding #3 (from data quality assessment and uncertainty analysis):

Most of the data comes from experts' inputs, which was scaled using mission-specific parameters (mass budget, mission duration etc.).

Results uncertainty varies significantly from one indicator to another. **Most accurate indicators include Global Warming and Fossil fuel depletion**. On the contrary, the uncertainty is particularly high for ozone depletion, toxicity indicators and ionising radiation.

➔ Limitations and options for improving the robustness of the LCA

❖ There is still room for improvement on some environmental datasets developed in the frame of the project

- Data refinement on payload instruments is needed.
- Data refinement on dedicated staff for ground segment during routine phase is needed.
- Data refinement on man power and plane travels during design phases (A+B and C+D), especially for suppliers, is needed.
- Regarding telecommunication missions: the LCA model used for ground stations is specific to ESA stations (Kiruna, Redu, and Cebreros). They are well suited for ESA-operated missions but may not be completely representative of stations used for telecommunication missions. The same limitations apply to the LCA models of control centres.

❖ The following limitations on impact indicators can be underlined:

- Mineral resource depletion results are highly dependent on the characterization method (the characterization method used in this study is the one recommended by the JRC of the European Commission). A way to deal with this would be to perform sensitivity analyses with alternative characterisation methods; it would reinforce the level of confidence in the results related to resource consumption.
- Toxicity indicators bear a high level of uncertainty. ESA should follow the developments that will be made by the LCA research community in the years to come to stay updated, especially given that toxicity is a priority for ESA.

❖ The single score calculation methodology can be further improved:

- The scope of normalisation factors was found to be incomplete on some specific aspects (e.g. impacts from space-specific activities like the exhaust of ozone depleting substances from launchers); further work can be done to complement the "intervention profile" and the resulting normalisation factors.
- Also, normalisation factors are based on data of extractions and emissions occurring on the European territory (perspective referred to as "production-based", as opposed to the perspective referred to as "consumption-based" which includes all embedded impacts of imported materials). Consequently, the extraction of natural resources in particular is not taken into account in an exhaustive way in the normalisation factors and the underlying comparison which is implicitly done between the considered product's LCA results and the reference values when normalising the LCA results is not fully consistent in terms of scope. However, the proposed approach is consistent to the latest guidelines provided by JRC in the frame of the PEF-OEF initiative of the European Commission.
- Weighting factors could be adapted to space activities and to the specific context of ESA, e.g. based on its defined environmental priorities and targets.

[2] Only for the EO mission investigated

Use of Life Cycle Assessment for eco-design

Integrated within a concurrent design process, LCA will provide a new and innovative view on the design of space missions.

➔ Integrating environmental performance in the design of space missions

As a next step in the deployment of life cycle thinking for space applications and in order to foster the eco-design approach for space missions, a common framework was developed. This framework includes a methodological framework and an eco-design software tool, as well as an environmental database dedicated to space activities.

The eco-design tool was developed with the objective of integrating environmental performance of space missions at an early design stage, i.e. “pre-phase A”. By means of the eco-design tool, the environmental performance of a space project is accessible for domain experts and system engineers as a supplementary decision-support element in the design process, next to technical performance, cost, planning aspects, risks etc.

As a first step, the eco-design software is currently being implemented at ESA’s Concurrent Design Facility (CDF), where it will be connected to CDF’s design framework, i.e. the Open Concurrent Design Tool (OCDT), as illustrated in Figure 3.

The eco-design tool comprises a calculation tool and a dedicated database which contains environmental information on materials, processes and activities involved in the life-cycle of a space mission.

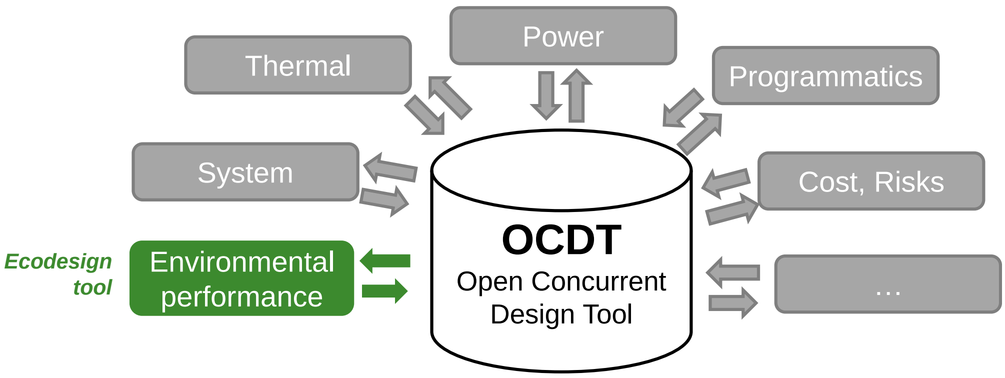

Figure 3 – Environmental performance as an additional field of expertise within OCDT

➔ Overview of the eco-design tool

The eco-design tool consists in the following parts:

- A LCA calculation engine that computes the environmental impacts of a space project based on mission-specific data, according to the calculation rules defined in the Methodological Framework (D5 Part 1).
- A database which contains LCIs representative of space-specific activities, developed according to the Methodological Framework (D5 Part 2).
- A user interface that allows users to edit input data as well as visualise assessment results and export them back to OCDT.

➔ Outputs of the eco-design tool

The eco-design provides two main types of results:

- **Multicriteria results**: The main output of the eco-design tool consists in the environmental performance of the studied mission, for a given design iteration. The environmental performance is presented as a set of environmental indicators, each one quantifying one specific environmental issue for the entire life-cycle but also for any described activity within the life-cycle. This type of breakdown can be done at each level of the life-cycle, i.e. at mission level, for one main life-cycle step or for any activity.
- **Environmental single score**: the single score provides a clear ranking between two scenarios and thus simplifies decision-making based on the environmental performance.

Figure 4 below illustrates these two types of results in the case of a comparison between two design alternatives.

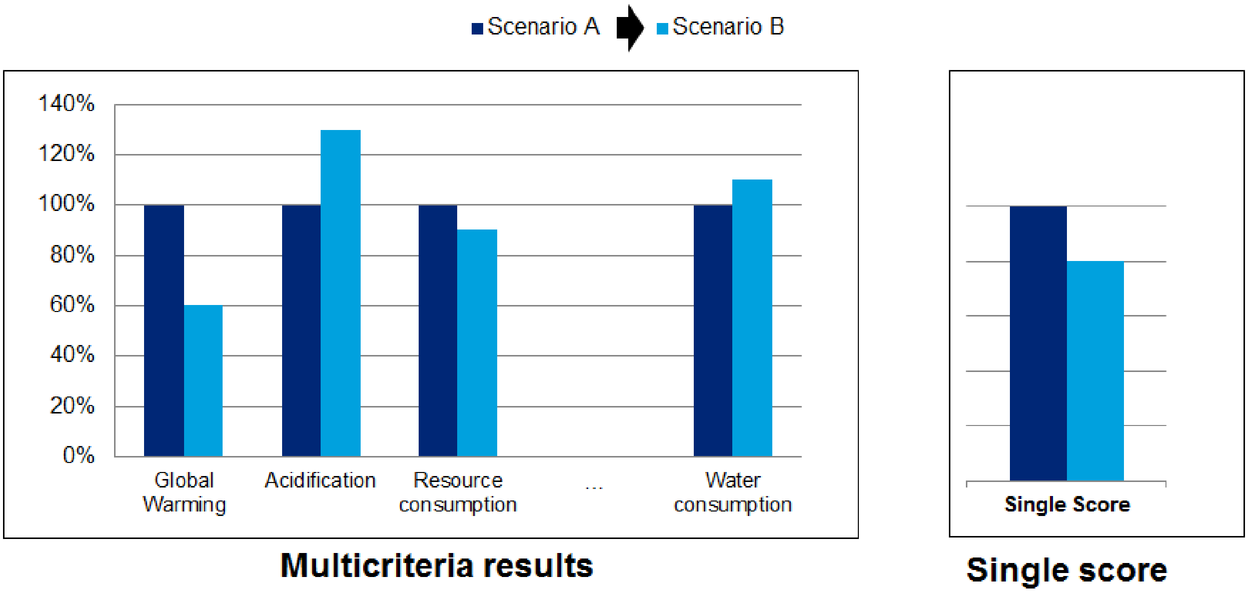

Figure 4 - Typical results of the eco-design tool – multicriteria results *(left)* and single environmental score *(right)* *(illustrative example)*

Recommendations for future work

This project allowed ESA to make a significant step forward in the integration of the environmental performance as a decision criterion in the design of space missions, placing the European space industry at the forefront of sustainability in the space sector worldwide. More importantly, this project is considered as an initial step towards a more sustainable and competitive European space industry. The following recommendations can be considered as further ideas to strengthen the leading position that ESA has taken and make it a long-lasting leadership.

➔ Applying environmental impact mitigation measures to the design of space missions

The following recommendations are given to improve the environmental impacts of a space mission.

When looking for possible ways to mitigate the impacts of any system, three distinct elements have to be considered:

- First, **what are the main environmental hotspots?**
- Second, **where are the levers for action**, or what magnitude of change is to expect by the considered mitigation measures?
- Third, **what is the expected feasibility** of the considered mitigation measures?

While the answer to the second question is inherently dependent on each mitigation measure, first thoughts are provided for the first and third questions below.

The main environmental hotspots of the space mission were found to be launcher-related activities in Phase E1a, Phase C+D (in particular the production of solar cells for the power system of the spacecraft) and finally, within Phase E2, the electricity consumption of the control centre during the routine phase.

As regards the feasibility of mitigation measures, in the aerospace sector, an important criterion to be considered is **whether the component** of the life-cycle that would be changed by a specific mitigation / eco-design measure **is subject to strict qualification rules**. This of course makes it more difficult to apply mitigation measures; at least to apply such mitigation measures will take more time. Of course, launcher and spacecraft systems are more subject to stringent qualification rules and procedures than systems that stay on Earth.

The following figure shows how the main phases and elements of a space mission's life-cycle are placed with regards to environmental importance and expected feasibility, considering qualification procedures expected to be applied to each considered element as one of the main criteria to judge the expected feasibility of possible mitigation or eco-design measures. It also provides some first ideas for improving the performance of each phase or element.

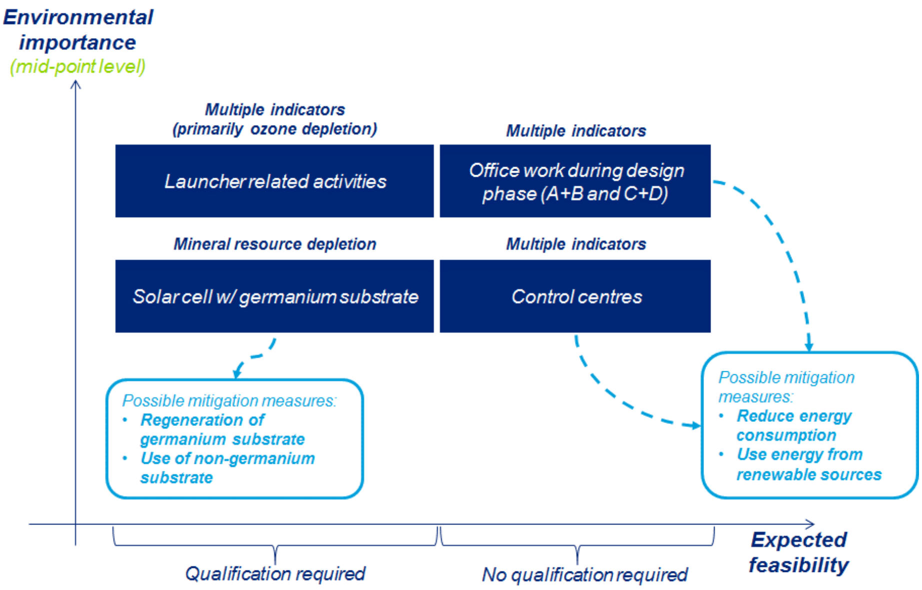

Figure 5 - Environmental mitigation of space missions

➔ Following new developments in LCA

Tools (e.g. databases, characterisation methods) and initiatives to make these tools more operational in business are evolving at a fast pace in the field of environmental assessment and life-cycle approaches. Thus, we would suggest ESA's **LCA task force** to follow the following topics, projects and initiatives:

- **The PEF/OEF experimentation and possible follow-ups.** The Product and Organisation Environmental Footprint experimentation has been conducted by the European Commission (EC) for now three years, and aims to define harmonised LCA methodological rules at the European level. The space sector is not isolated from other industrial sectors, and most companies in the space industry are also players of other sectors (e.g. battery manufacturers, producers of electronic equipment). It would be difficult for these companies to comply with a first set of rules for their activities in the space sector and with other, distinct rules for other sectors "affected" by PEF-OEF and potential regulatory follow-ups. Hence, ESA would benefit from following the methodological developments of PEF/OEF and trying to include, where possible, elements of this work in its own framework (e.g. Space system Life Cycle Assessment (LCA) guidelines).

- **Initiatives to operationalise recent research findings in the field of life-cycle thinking**. Examples are the LCM annual conference (Life Cycle Management) or the operational LCA studies of the French industrial association SCORELCA.
- **New developments concerning weighting methods.** As mentioned before, another way to go further regarding this point would be for ESA to develop its own single score method. Yet, other weighting methods are also making their way and would be worth looking into, such as **monetary valuation** and **planetary boundaries**.
- **Consequential LCA and assessment of macro-level decisions.** A single decision taken in the space sector can have greater consequences than in other industrial sectors. Consequential LCA would be well suited e.g. for the assessment of the environmental consequences of the likely increase of spaceflights in the next decades.

➔ Harmonising the framework of LCA methodology and tools

We see two different use modes of the LCA methodology and associated tools:

- **One mode for decision making during the design process of space projects**, based on an approach suitable for preliminary design phases. This mode should enable ESA's design team to obtain quick answers and simple guidance to choose between different technological or design options during the design of a space project.
- **One mode allowing for more extensive LCAs** which could give more precise environmental results at a later stage in the product / technology life-cycle. This would be typically used for environmental communication.

In terms of tools and databases, the upstream eco-design tool is SPACE OPERA, and the extensive LCA tool is SimaPro. More generally, the following figure shows how the different elements (or building blocks) of the LCA framework developed by ESA could be linked with one another and could work together.

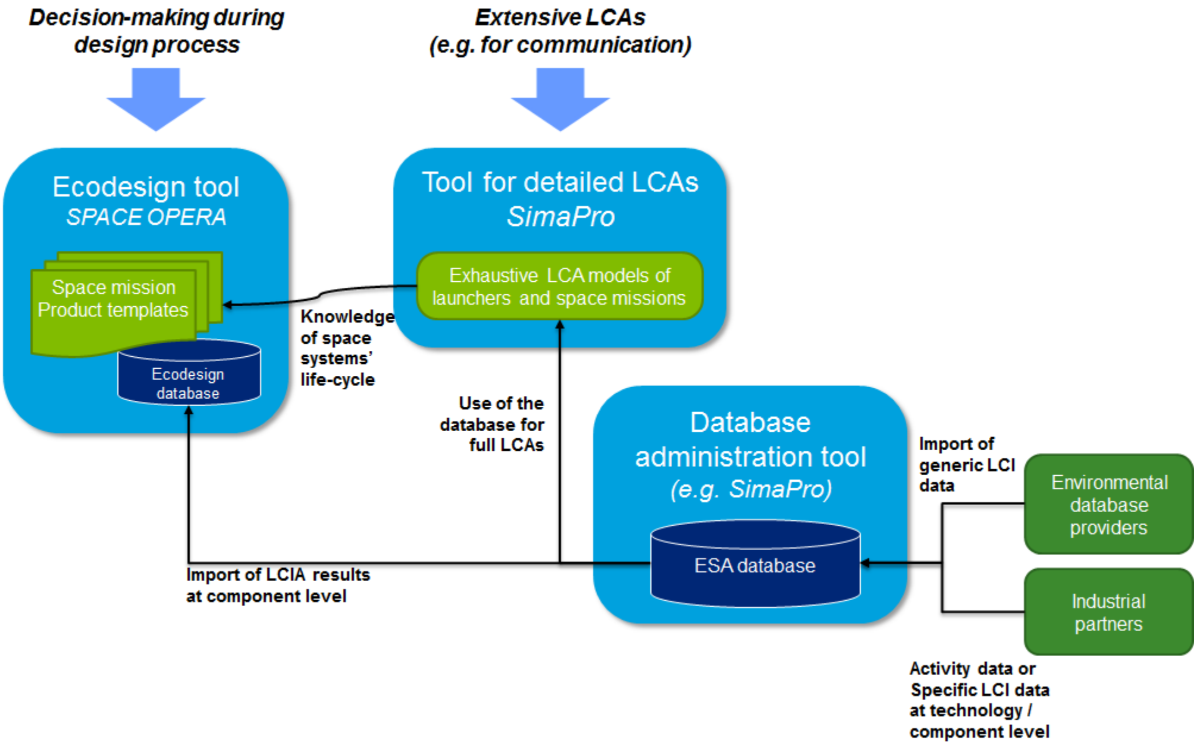

Figure 6 - Articulation between ESA's LCA tools, models and databases

A link is to be found between the extensive LCA tool (SimaPro), the data administration tool (which can also be SimaPro), the eco-design tool (SPACE OPERA), and ESA's partners.

To go further, and as can be seen in more and more European-funded research projects, we think **developments of new technologies or environmental subjects should always be accompanied by an environmental analysis**, using the LCA handbook currently under development at ESA.

➔ Improving the eco-design tool

❖ Industrialising the environmental assessment of space missions

The development of the tool and the implementation of the LCA model was made on the basis of the two pilot LCAs. However, **significant efforts were made to go beyond a "one-shot" LCA tool** and to make it as much scalable as possible. Actions were undertaken and features were implemented, such as:

- The development of the OCDT was seen as an opportunity to facilitate the co-evolution of the eco-design tool with the current software used by ESA and its partners for the concurrent design of space missions. Therefore it was decided to develop the interface between SPACE OPERA and OCDT, instead of the (Excel based) tool IDM currently used at CDF.
- Life cycle inventories of spacecraft components were adapted according to their geographical scope.
- Multiple-choice questions were implemented for main components (launchers, type of batteries, antennas, etc.).
- Options (e.g. electrical vs. chemical propulsion) can be compared in one single import/iteration with the tool;
- A distinction was made between mandatory and optional parameters, with default values implemented for the latter.

❖ Bringing new features to the eco-design tool

Regarding the usability of the eco-design tool, **the following improvements are suggested**:

- A visual representation of uncertainties could be provided so as to help the user understand the magnitude of the uncertainties.
- Solutions to improve the ergonomics of the model philosophy page in the tool could be considered.
- The database includes already characterized impact factors. Implementing non-characterised LCI datasets could allow the analysis of contributing flows, in case a more precise interpretation is required (e.g. on resource depletion).

➔ Developing a methodological framework for the practice of LCA in the space industry

❖ Involving other entities in the eco-design process

As the eco-design principles should be disseminated as much as possible in the European space industry, **the use of the eco-design tool could be extended to partners and members of ESA**: national space agencies and prime suppliers to begin with.

❖ Clearing the path for future developments through the Handbook

ESA is currently developing a Handbook to establish guidelines on how to evaluate the environmental performance of space systems. It is partly based on the LCAs performed in the frame of this project. This will provide ESA and its partners a competitive advantage over their competitors in the field of sustainability.

Moreover, the Handbook may be integrated in the frame of the work of the European Cooperation for Space Standardization (ECSS), notably by involving ESA's partners.

ESA could then adopt a progressive approach for the integration of quantitative environmental criteria in its activities:

1. As a first step, technology development **projects performed internally at ESA** could assess and optimize, as much as possible, the **environmental performance** of the developed technologies.
2. Then, ESA could **extend the requirement to projects funded by ESA**, including the performance of an LCA as a requirement for each project. For instance, Ariane 6 on-going development includes the performance of a LCA, in order to provide an information about the environmental footprint of the new launcher. This example illustrates well the proposed approach.
3. In the long term, one can foresee **the integration of a requirement to provide quantitative environmental assessment results in all ESA's calls for tenders**.
4. In a longer term, **suppliers / contractors could be compared on the basis of the environmental performance** of their technologies or services (green procurement).

While in the first three steps ESA would require the provision of environmental information, in the fourth step the requirement would be on the environmental performance of systems.

The process proposed above is a step-by-step approach. However, if this approach is deemed relevant by ESA and fits with its overall sustainable strategy, these aspects should be thought at the earliest stages, beginning within the elaboration of the Handbook. Of course, getting industry engaged in this process is quite a challenge, as ESA has already experienced. However, engaging industry might be made easier with the ongoing developments, in particular the elaboration of a designindicator for space debris, and the integration of REACh and CRM respective obsolescence risks into ecodesign as well as through holding workshops on ecodesign.

❖ Dealing with the methodological issues of recycling and reuse

Reusable space launchers have been discussed quite intensively in the media recently, in particular the progress made by SpaceX on the subject. However, we saw during the communication study that SpaceX or its partners had not brought forward the environmental benefits of this innovation.

Whether reusable launchers / boosters are beneficial for the environment should not be assumed a priori. Indeed, to do such an assessment, one should look not only **at the avoided production of a new launcher, but also at the additional quantity of propellant needed, the refurbishment step, etc**. Therefore, reuse requires a specific investigation. In LCA, this comes with specific methodological challenges related to the assessment of management systems at end-of-life.

All in all, **the environmental aspect of reuse is likely to surge in the future**. ESA may prepare for potential questions from stakeholders and environmental claims from competitors.

❖ Comparing with other sectors / services

A notable comparison that would be of interest for ESA is satellite communication vs. terrestrial communication. Compared to the launchers study, the present project has made this comparison possible, although there are some elements still missing (definition of a common scope and functional unit for comparison, data gaps to fulfil). Such a comparison could be made following the same approach as the one developed for the current project or for the launchers study, by making a pilot LCA for one or several case studies.

Based on our knowledge and recent experience working on the environmental performance of ICT activities, ICT's sector's maturity on sustainability has still to be further improved. Nonetheless, this is a fast growing topic, also within the ICT sector, so the subject may emerge in the coming years.

❖ Conciliating the three pillars of sustainable development

With this project, ESA has integrated the environment as an additional criterion in the design of space missions.

To adopt a fully sustainable approach and to be strong on all three pillars of sustainable development, ESA may look closer at the social impacts and benefits of European space activities.

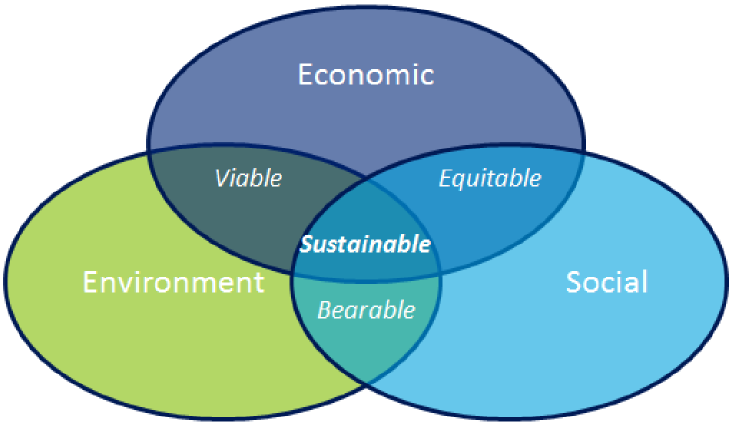

Figure 7 - The three pillars of sustainable development