Integrating sustainability in the design of space activities: development of eco-design tools for space projects

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1 ABSTRACT

The European Space Agency (ESA) has launched the Clean Space initiative with the objective of increasing attention to the environmental impacts of its activities, both on Earth and in space. In order to better understand the environmental impacts of the space sector, ESA successfully applied Life Cycle Assessment (LCA) to assess the environmental impacts of space projects over their whole life cycle, from resource extraction through manufacture and use to end-of-life, covering spacecraft and launcher-related activities as well as ground segment activities. ESA has adopted an eco-design approach to design future space missions in a more environmentally friendly way: eco-design is a preventive approach to mitigate the environmental impacts of a product (good or service) as early as possible in the design phase.
ESA wishes to disseminate life cycle thinking and eco-design by establishing a common framework that can also be used by other European space organisations when performing space mission design. This framework includes methodological and software tools as well as a database dedicated to space activities. The eco-design software tool is currently under development and testing at ESA's Concurrent Design Facility (CDF). It will be connected to CDF's design framework, i.e. the Open Concurrent Design Tool (OCDT). In order for system engineers to be able to consider environmental performance as a criterion in their design choices, the tool will provide the following results. Firstly, multicriteria results (i.e. different environmental indicators measuring the impact on climate change, non-renewable resource consumption, air pollution, water pollution, etc.) will allow identifying the "hotspots" in the analysed system: which activities in the life-cycle mostly contribute to the environmental impacts? Where is there mostly room for improvement? Secondly, the calculation of a single environmental score (aggregating the multicriteria results) will make the comparison of several design options easier. The eco-design tool relies on a database which contains environmental data on each individual activity in the life-cycle of a space project (material production, manufacturing processes, etc.). The robustness of the results provided by the eco-design tool greatly depends on the robustness of the database, and for that it is crucial that the database be as representative of the space sector as possible: it needs to depict as closely as possible the specificities of activities carried out in the space sector. A major challenge for this is the data availability for "space-specific" activities, for which the European space industry has a major role to play, in view of cleaner and more sustainable space activities.

2 LIFE CYCLE ASSESSMENT OF SPACE MISSIONS

2.1 Brief presentation of Life Cycle Assessment (LCA)

LCA is a powerful method, standardised at international level by ISO [1], to evaluate the environmental performance of products (i.e. either goods or services) in a comprehensive and objective manner: an LCA aims at assessing the quantifiable environmental impacts 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. In 2003, the European Integrated Product Policy [2] identified LCA as the "best framework for assessing the potential environmental impacts of products". Since then, LCA has been increasingly used both in policy development and business.

The methodology consists in carrying out exhaustive assessments of natural resources consumption, energy consumption and emissions into the environment (waste, emissions to air, water and ground), for each process involved in the life-cycle of a space mission.

Firstly, all incoming and outgoing flows (flows of materials and energy, both extracted from the environment and released into it) are inventoried for each life-cycle phase. Secondly, they are aggregated to quantify a set of environmental impact indicators.

LCA is a multicriteria approach as it looks at 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). 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. Consequently, LCA can be used in the context of a "design for the environment" approach, or as a support tool for decision making. Figure 1 illustrates the main principles and concepts of LCA.

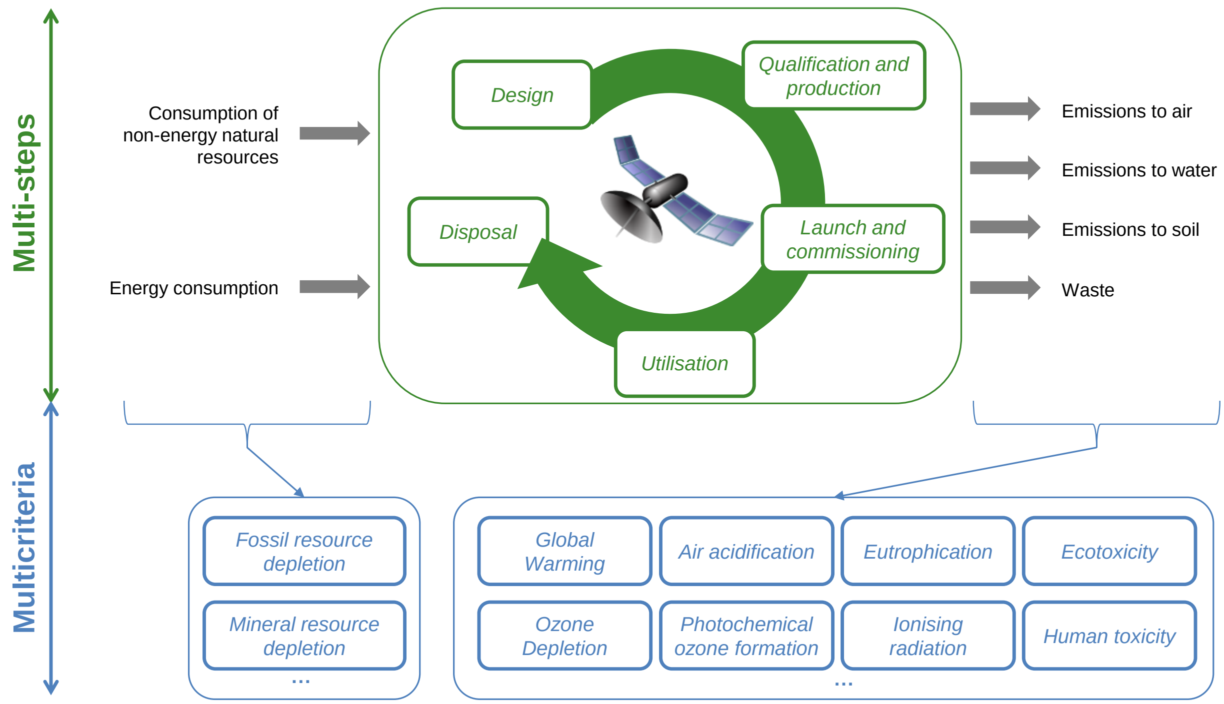

Figure 1: Illustration of the multi-step and multicriteria attributes of LCA

2.2 Overview of LCA use at ESA

ESA has successfully applied LCA to assess the environmental impacts of the European family of launchers over their whole life-cycle [3] [4], but also to study the environmental impacts of the entire life-cycle of space missions [5].

For what concerns space missions, pilot LCA studies were performed on a representative selection of space projects, including scientific, earth observation, meteorological and telecommunication missions. These pilot LCA studies provided detailed insight on the environmental profile of space missions: in particular, activities mainly contributing to the environmental impacts of a space mission, sources of these impacts, areas where improvements can be made, etc. were identified.

Furthermore, ESA continues its efforts with follow-on studies, based on these system level LCA studies, addressing the environmental impacts of space specific materials & processes and propellants and is also working on the development of methodological guidelines for the application of LCA to the space sector.

2.3 Objectives of the LCAs

The overall goal of the assessments was to quantify the environmental impacts related to typical space missions over their entire life-cycle, from R&D phase to the disposal of stages. The main objectives of these environmental assessments were:

- To better understand the environmental impacts of space missions and the sources of these impacts: results aimed to highlight the levers for improvement.
- To support the design of ESA's eco-design tool and to populate its life-cycle inventory database.
- To provide input for the definition of methodological guidelines for conducting LCA of space systems.

2.4 Scope definition

The whole life-cycle of space missions has been covered, as presented in Figure 2. This study also allowed ESA to build knowledge on the environmental impacts of materials, processes or activities which are specific to the space sector.

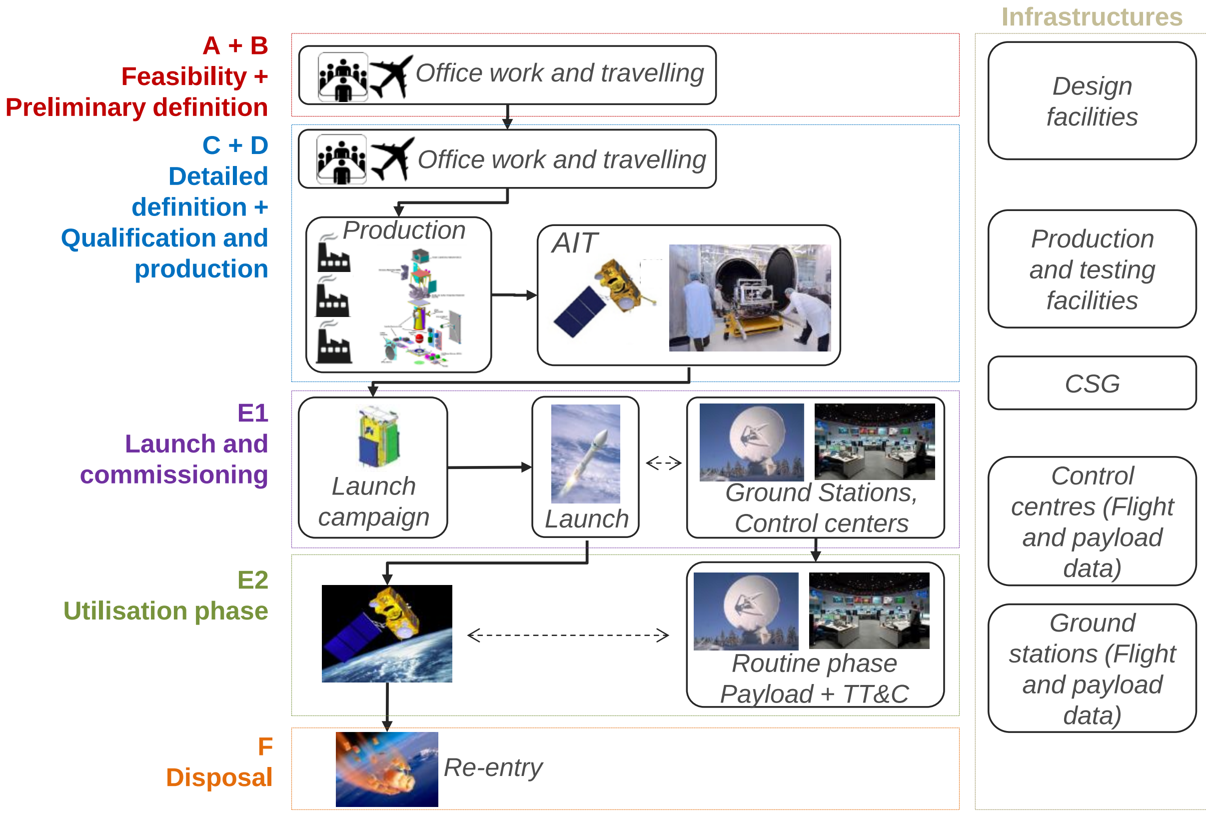

Figure 2: System boundary considered for the LCA of a space mission

2.5 Considered environmental impact categories and indicators

A comprehensive spectrum of environmental topics was addressed. They have been 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 taken amongst the most recognized impact characterisation methods, adapted to the specific case of space projects, and finally assessed.

Furthermore, in order to facilitate the decision making process, a single score was assessed in addition to the multicriteria results. The single score calculation method is a first proposal, which should be improved in the future.

2.6 Data collection and data quality

An important data collection process allowed establishing environmental data over the whole life cycle of space missions:

- 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 launcher's and 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.

2.7 Uncertainty analysis

The uncertainty of the environmental impact assessment was assessed using a Monte-Carlo simulation. The uncertainty range varies greatly from one indicator to another. Most accurate indicators include global warming and fossil fuel depletion, while uncertainty is particularly high for ozone depletion, toxicity indicators and ionising radiation.

2.8 Key findings of the LCA

Launcher-related activities (including production of the launch vehicle) are the main contributor to most potential environmental impacts of a space mission. However, other space mission life-cycle steps also have a significant contribution to the environmental impacts:

- The 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.
- Also, the utilisation phase (phase E2), which includes ground segment activities during the routine phase, is the main contributor on freshwater eutrophication potential, due to the electricity consumption of either control centres (case of earth-observation missions) or ground stations for broadcast (case of communication missions).

3 ECO-DESIGN OF SPACE MISSIONS

3.1 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, ESA is currently establishing a common framework that can be used by any European stakeholder wishing to consider the environmental criterion when performing the design of a space project or to assess its environmental performance. This framework will include methodological and software tools, as well as an environmental database dedicated to space activities.
Similarly to cost assessment, the environmental performance of systems is highly driven by design elements which are defined at an early stage in the design process [6]. Consequently, the eco-design approach should be initiated as early as possible in the design process (pre-phase A), when main design choices are still open, so as to maximize the potential for improvement of the environmental performance. However, as illustrated in Figure 3, environmental performance will also provide useful results throughout the mission's design process, as it will guide the design towards more environmentally friendly technological/design alternatives at each step of the design process.

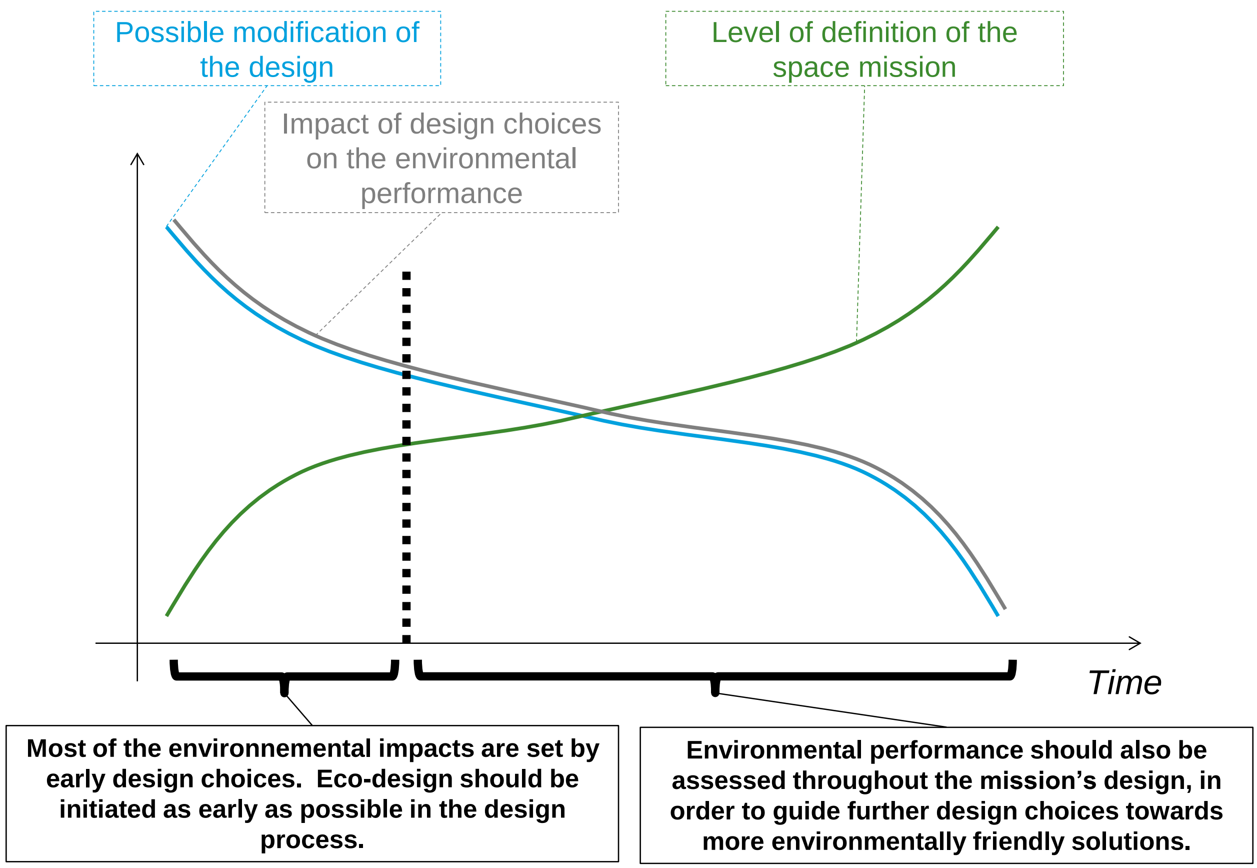

Figure 3: Eco-design in space missions' design process

3.2 Integrating environmental performance as a new design criterion for concurrent design

ESA will integrate environmental performance of space missions at an early design stage, i.e. "pre-phase A". ESA and BIO by Deloitte are developing a dedicated eco-design software tool that will allow assessing the environmental impacts of a space mission design within the concurrent design approach.
By means of this tool, the environmental performance of a space project will be 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 4.
The eco-design tool comprises a calculation tool and a dedicated database which contains environmental information on typical materials, processes and activities involved in the life-cycle of a space mission.

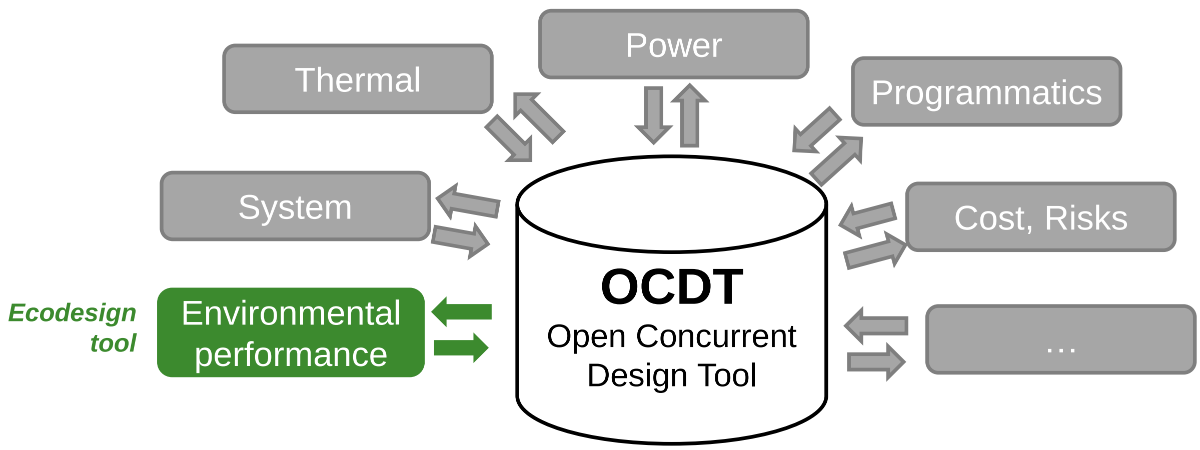

Figure 4: Integration of environmental performance as a new area of expertise at CDF

3.3 Inputs of the eco-design tool

The inputs of the eco-design tool will consist in mission-specific design data that describe the mission under study. Examples of the main types of design data that are typically used as input data for the eco-design tool are:

- Man.hours dedicated to the design of the mission,
- Bill of materials (type and mass of equipment or material),
- Model philosophy (number of full or partial models that are built),
- Type, number and duration of tests (thermal vacuum, acoustic or vibration tests, as well as the use of electrical ground support equipment),
- Type of launcher (Ariane 5, Vega, or Soyuz),
- Operation of ground stations and control centres (duration of utilisation phases, location of facilities and size of dedicated teams).

3.4 Outputs of the eco-design tool

Multicriteria results

The main output of the eco-design tool will consist 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. In addition to the quantified results for the whole mission, a breakdown of the contribution of each life-cycle step will facilitate the eco-design process by highlighting the main sources of environmental impact, as illustrated in Figure 5. This type of breakdown can be done at each level of the life-cycle, i.e. at mission level, or for one main life-cycle step or any activity.

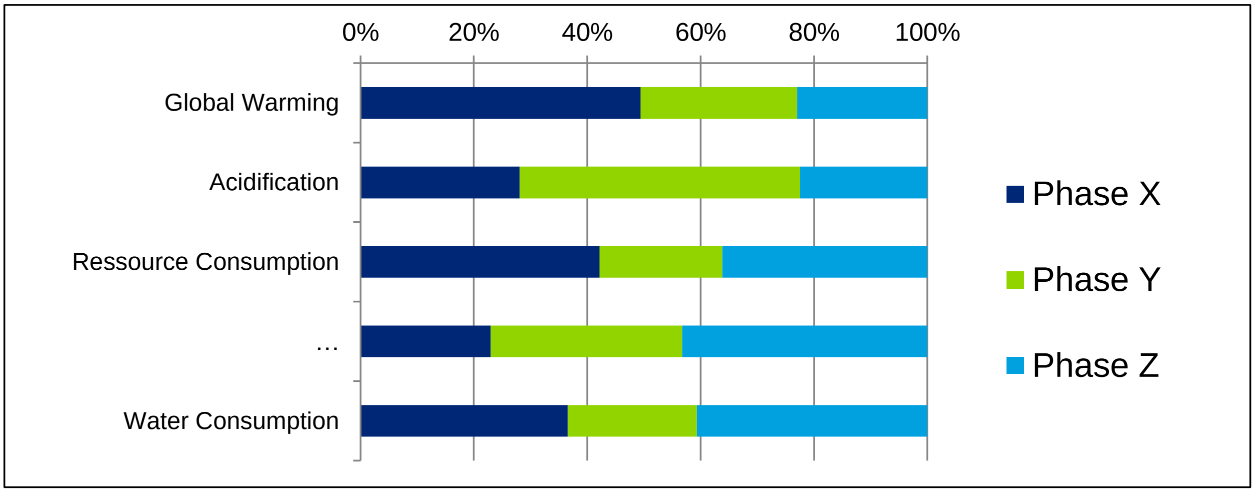

Figure 5: Breakdown of the impacts per life cycle steps (illustrative example)

Single score calculation

As previously mentioned, the multicriteria nature of LCA is essential in order to avoid transferring impacts from one environmental issue to another. At the same time, it can hinder the introduction of environmental performance as a design criterion, since when comparing two design alternatives, one alternative can perform better than the other on some environmental indicators while performing worse on others.

To overcome this difficulty, it is necessary to give priority to the most important environmental issues, i.e. to rank all environmental impacts according to their relative importance. In practice, this can be achieved e.g. by giving environmental impacts a weight depending on their priority level and then aggregating in one single environmental score or by giving a monetary value to the generated impacts. This enables an easy comparison and choice between two or more design alternatives.

Several methods exist to derive such weights/priority levels. It is important to point out that most of them are based on panel methods or expert judgements (assigning weights depending on the "importance" or urgency to address one specific environmental concern), which means that in such cases, weighting introduces subjectivity in the assessment, which is a limitation of the method.

Figure 6 illustrates how the single score allows a clear ranking between two scenarios and thus simplifies the design choices based on the environmental performance compared to multicriteria results.

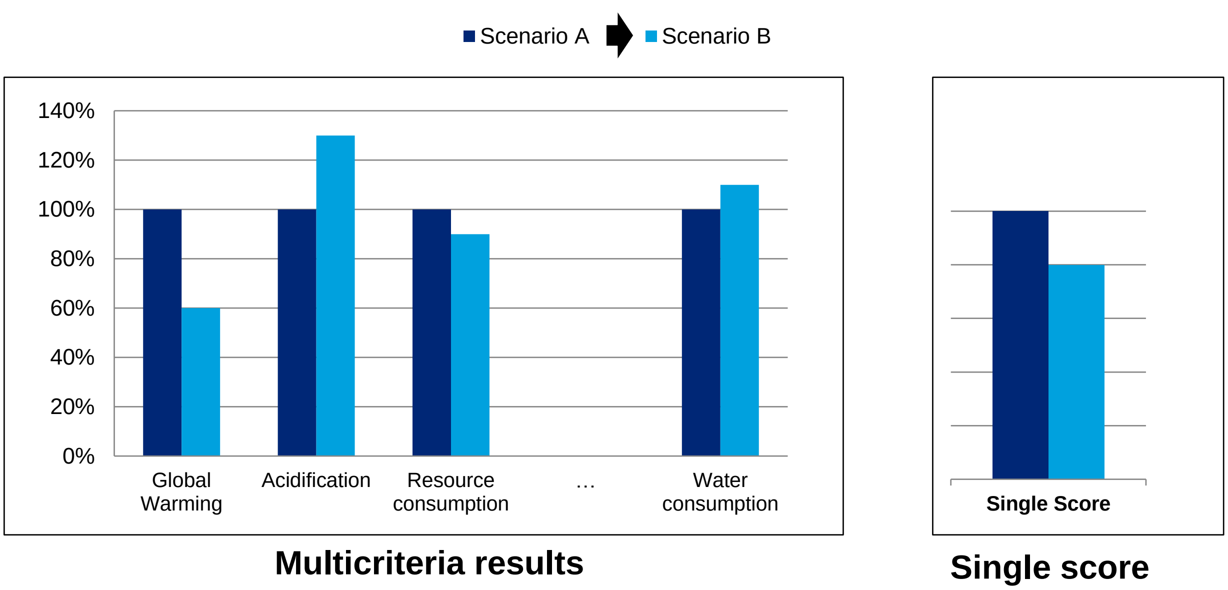

Figure 6: Trade-off between design alternatives using a single environmental score (illustrative example)

4 MAIN CHALLGENGES

The pilot LCAs were the first LCAs covering the entire life-cycle of space missions. As a consequence, there was no prior knowledge of the environmental hotspots. This required an in-depth investigation of the life-cycle of space missions. Furthermore, in order to optimise the overall process and given the complexity of the studied systems, an iterative approach was used to overcome this challenge.

Besides, data representative of the space sector is scarce (materials & processes that are specific to the space sector are not covered by common LCA databases). In order to overcome this challenge, an extensive data collection process was carried out, involving industry and ESA experts, complemented by an intensive literature review.
Furthermore, the space sector has a very specific production chain: there is very little recurrent production compared to consumer goods. As a consequence, LCA assumptions that are commonly applied when considering consumer goods (e.g. exclusion of development phase and infrastructures) were challenged.

Finally, given the wide variety of space missions and used technologies, the main challenges of the tool development consists in:

- Populating the database with data with sufficient coverage and representativeness. In order to cover as many activities as possible, a collaboration with numerous domain experts was initiated: experts provided data, validated first assumptions and helped define a "technical mapping" of possible technologies (i.e. identification of existing design alternatives at each life-cycle step and subsystem of the spacecraft).
- Ensuring that the tool is flexible enough in order to take into account a wide range of configurations for space missions (e.g. multiple spacecraft, different equipment types) while avoiding that the user of the eco-design tool has to reconfigure the space mission from scratch.

5 CONCLUSIONS

The project initiated by ESA proved that Life Cycle Assessment was a relevant and efficient method for assessing the environmental performance of space activities, that it was applicable to the whole life-cycle of a space mission and that it could be performed in a cost-effective way.
The pilot LCAs allowed to identify the environmental hotspots of space missions and to develop a first version of a database containing environmental data on materials, processes, equipment and activities specific to the space sector. This database has been developed in order to be used within the eco-design tool which is currently being developed with the aim to be used during early design stages (pre-phase A).
The integration of eco-design in ESA's concurrent design process raises specific challenges that need to be addressed: methodology, database, presentation of simple and easily understandable results. ESA is currently developing the methodological and IT tools for the eco-design of space missions, and will test their implementation at CDF in the coming months.
The eco-design tool will help raise awareness on major environmental hotspots of space projects and help designers understand how their design choices influence their environmental performance.
In parallel to the development of the eco-design tool, ESA has initiated projects that aim at improving and extending the environmental database, in order to cover as many space-specific activities as possible with the highest level of data quality possible. This will increase the quality of the LCA results obtained and, more generally, the robustness of the eco-design approach.

6 REFERENCES

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