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Rapid Life Cycle Assessment Software for Future Space Transportation Vehicles' Design - The Assessment and Comparison Tool

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Abstract

As opposed to performance, cost, safety, and programmatic metrics, impacts on Earth or on the space environment have not been drivers of space systems and mission designs until recently. This is changing thanks to a shift of mindset, growing risk related to space debris, and a need to anticipate regulations that are likely to be applied to the space industry.
The new Assessment and Comparison Tool (ACT) software is made to create configurations of space transportation vehicles (STV) and rapidly perform their life cycle assessment (LCA) based on user-known data and assumptions. Users can input high-level system values and select the relevant LCA datasets used to compute the environmental impacts of that system. This tool will be used in early design phases or other decision-making processes as support to identify key technology, life cycle steps, or components of future STV designs in order to adapt them to mitigate related environmental impacts while being aware of potential trade-offs and hotspot shifting. For now, ACT focuses on the launch segment, setting the system boundaries based on the dedicated ESA space LCA handbook [19]. ACT is being developed in the frame of a project with the ESA Future Launchers Preparatory Programme (FLPP) since 2022 by a consortium of Swiss entities: EPFL Space Center (eSpace), Paul Scherrer Institute (PSI), and Ateleris GmbH. The project follows previous research conducted at eSpace that focused on space logistics modelling and space sustainability.
Life Cycle Impact Assessment (LCIA) scores are derived from the Environmental Footprint v3.1 method. On top of such common LCA indicators, a space debris index score is used to assess impacts on the space environment, and preliminary estimations of the atmospheric emissions during the launch are computed as mass flows. Indeed, science gaps for the LCA of an STV have been identified, including the impacts of high-altitude emissions during the launch and the particles and gases generated during the re-entry. In this world of dynamic and fast-changing energy systems, industrial processes, and logistics, ACT enables its users to be proactive and adapts the background database to future scenarios. Therefore ACT helps to ensure that future STVs do minimise the environmental impacts like global warming or resources limitations, that are expected to be major drivers in the coming decades.
The tool is designed for evolution. It embeds a modular data structure which allows scope extensions and implementations of newer calculation methodologies as the scientific research progresses. Besides the science gaps, technology gaps can be highlighted from the computed impacts and the intention to mitigate part of them using ecodesign processes.
This paper presents the Assessment and Comparison Tool and details the ongoing and needed research to fill knowledge gaps in LCA for space systems. Test cases of imaginary future space transportation vehicles are assessed using ACT to introduce its functionalities and capabilities. Ideas for reusability, vehicles for new launch architectures, and new propellants or materials are discussed regarding environmental impacts before looking at the possible future development of the tool.

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1. Introduction

Our daily life relies on satellites orbiting around our planet. They are used to send information down to Earth for communication, observations (e.g., weather forecasting, science), or navigation. These satellites are placed in a specific orbit by a launch vehicle. The space launch services market shows a growing trend (not only to Earth orbit but to the Moon, Mars and beyond) which raises questions concerning the accumulated environmental impacts of an increasing volume of launchers.

Individual launchers or space missions have been subject to Life Cycle Assessments (LCA) in the past, mainly driven by the European Space Agency (ESA). Conventional LCA, as defined by the ISO standards 14040 [17] and 14044 [18], fails to capture the full range of impacts of space activities on the Earth's and orbital environments due to the specificities of the sector. These include low production volumes and long development cycles, extensive testing, specialized materials and processes, emissions to soil and atmospheric layers during launch and their impact on, e.g. climate change or stratospheric ozone depletion, and disposal of components in the ocean as well as in orbits [19].

ESA has enforced a "Green Agenda" with clear objectives on actions with regards to sustainability stated in the Agency's Agenda 2025[1]. This includes a yearly space debris environment report [21] as well as fostering LCA and eco-design studies in order to address the environmental impacts of ESA's activities combined with a holistic life cycle perspective.

The technical families of launchers include a variety of designs with manifold missions in terms of payload mass and orbit to reach. ESA Future Launchers Preparatory Program (FLPP) is anticipating the development of the next generations of launchers to fulfil future market and institutional needs. To scout, identify, and prepare the technologies in time, it is necessary to be able to quickly assess and compare the environmental impacts of different space transportation vehicles' (STVs) architectures and mission services. The tool Assessment and Comparison Tool (ACT), funded by ESA FLPP and set up by a consortium consisting of EPFL eSpace, Ateleris GmbH, and Paul Scherrer Institute (PSI), is the focus of this paper.

2. LCA in the Assessment and Comparison Tool

2.1 Life cycle assessment methodology and adaptations

Life Cycle Assessment (LCA) is a recognized method to capture the environmental impacts of a product or service in an iterative, multi-step and multi-criteria procedure, accounting for manifold environmental impact categories along the whole life cycle (figure 1). LCA allows for the identification of hotspots within the life cycle chain and enables the discovery of burden-shifting or trade-offs between impact categories.

The environmental assessment made with ACT applies common LCA principles but aims at providing rapid results, with simpler models in the foreground for easy use by engineers with little to no LCA knowledge. It will help engineers with early-stage decision-making before more in-depth analysis can be performed on a subset of selected STV architectures. Currently, the tool embeds the ESA space-specific and ecoinvent LCA databases to compute the environmental impact scores of a product or service based on user inputs. Further, prospective databases are integrated in ACT to explore future projections of the global industrial sectors depending on human actions for mitigating climate change (see the section 2.1.2 for more details and an LCA example in section 3.1).

Common LCA methodology has been extended to include space-specific aspects, namely space debris risk and estimate of atmospheric impacts from emissions occurring in all layers of the atmosphere (see sections 2.1.4 and 2.1.5).

2.1.1 Goal and scope

ACT is a tool to automatize a rapid quantitative analysis of the environmental impacts of different space transportation vehicles' (STVs) architectures based on the LCA methodology, and compare them.

An LCA study performed with ACT aims to assess the environmental impacts of user-defined configurations in an early design phase. Questions which can be answered with ACT include:

- Can the environmental impacts of a launcher be reduced by using another propellant?
- What are the environmental burden shifting and advantages when switching to a bio-based material or another supply chain/production technology ?
- What are the environmental impacts of activities related to a launch? Which are the environmental hotspots of a specific launch mission? How could they be reduced?

[1] https://www.esa.int/About_Us/Responsibility_Sustainability/ESA_Green_Agenda

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Figure 1: ESA infographic for life cycle assessment. https://blogs.esa.int/cleanspace

- Is it environmentally beneficial to introduce reusable components in the launcher?
- How will the environmental impacts potentially look for a launcher built and launched in 2030? 2040?

In order to allow comparisons, a common comparison basis needs to be introduced. The so-called functional unit (FU) used so far in ACT is: **To place X tons of payload into orbit Y** (X and Y are replaced with user inputs in ACT). Users of ACT will, for instance, compare a reference design to an alternative one (e.g. using other material types); assess various configurations such as expendable versus reusable launchers; or learn about how the environmental impacts might potentially evolve over time in the future (see e.g.section 2.1.2). Applicable systems boundaries are shown in figure 2.

ACT supports modelling of three types of scenario: expandable launch vehicles, (partially) reusable ones, and launchers that embed an active debris removal (ADR) capacity (i.e. a stage that is capable of capturing and deorbiting a debris), as seen in tables 1 to 3. Configurations from either scenarios can be compared with one another as long as they fulfill the same functional unit.

2.1.2 Life Cycle Inventory (LCI) - current and prospective data

LCA typically relies on foreground data collected as primary data, modelling the system under research, and background data modelling common products or processes such as steel or electricity production, or transportation modes. Primary data which needs to be collected by ACT users include amounts of materials and energy, transport modes and distances, direct emissions, and information on processing and assembly. The latter includes energy use as well as material losses.

The background databases used in ACT are (1) the ecoinvent database, version 3.9.1, system model "cut-off"; (2) the in-house ESA LCI database with datasets specifically created for the space sector, updated to rely on ecoinvent v3.9.1 data instead of v3.5; and (3) prospective databases.

Ecoinvent and the ESA LCI DB represent current and past technologies, energy mixes, efficiencies, in short: a model of the world economy as it is now. FLPP wants to investigate future launchers with ACT. With a changing world due to reactions on climate change, general environmental concerns, economic or socio-political reasons, the data used to model such future launchers need to be adapted. Integrated Assessment Models (IAM) are used by e.g. the IPCC to create scenarios on how the future world might look like in various sectors such as the energy sector, mobility, industry, or households. The open source premise python package links IAMs with LCI databases and is thus used to create future versions of both the ecoinvent database and the ESA LCI database [13]. Amongst other applications, such IAM scenarios are used by the Intergovernmental Panel on Climate Change (IPCC) to explore which societal and technical pathways might be linked to a specific global temperature rise compared to pre-industrial levels. For application in ACT, the following IAM and Shared Socio-Economic Pathways (SSPs) from the REMIND IAM [23] have been chosen: (i) National Policies Implemented (NIP) (+2.2°C); (ii) Paris Agreement Objectives more or less fulfilled (+1.7°C); (iii) Paris Agreement Objectives highly met (+1.3°C).

Especially in the launch industry, performing the LCA novel launchers which will be launched in several years or even decades time only, with data valid for today can potentially lead to wrong findings. ACT thus gives the possibility

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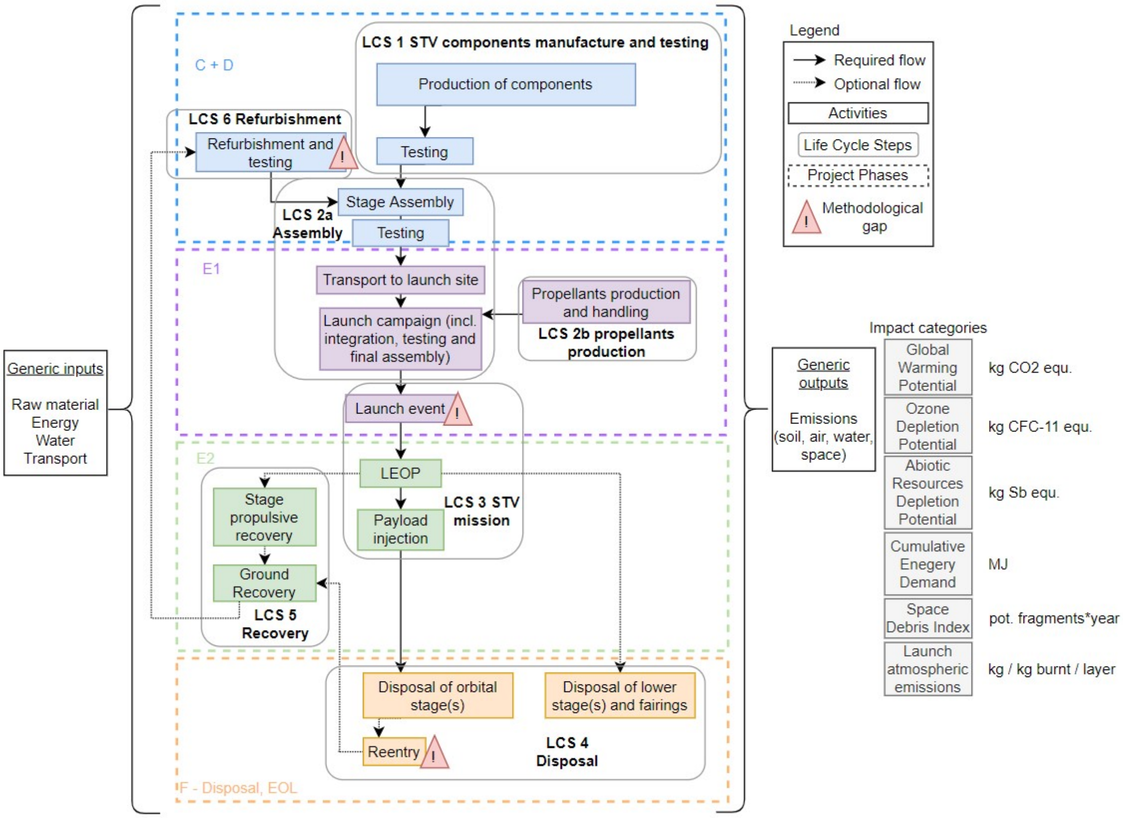

Figure 2: System boundaries defined for the LCA of space transportation vehicles using ACT.

to explore potential future states of the world. The latter are only as good as the state-of-the art IAM models are, which means that mostly the energy sector and industrial sectors heavily relying on energy are targeted by the changes as implemented in the model [5, 6]. Potential evolution of e.g. the chemical or the agricultural sector is not or to a lesser extend considered in the scenarios. However, the coupling of the LCA with such prospective scenarios and its integration in ACT is an important step towards extensive explorative LCA results representation in the future launchers sector.

For comparison of the results in ACT, users can select several configurations and one scenario (combination of a year and a socio-techno-economic pathway), or a single configuration assessed with different scenario databases.

2.1.3 Life Cycle Impact Assessment (LCIA)

LCIA methods translate the data inputs of the ACT user into environmental impacts. A selection of midpoint indicators from the Environmental Footprint method (EFv3.1) has been implemented in ACT following the list of indicators defined by ESA in 2016 [19], namely:

- Impacts on climate change: Global Warming Potential (GWP), kg $CO_2 - eq$.
- Abiotic resources depletion potential (ADP), kg $Sb - eq$.
- Stratospheric ozone depletion potential (ODP), kg $CFC - 11 - eq$.
- Non-renewable cumulative energy demand (CED), MJ

The space sector comes with a need for extended or even additional LCIA categories to cover the full scope of launch vehicles' missions. Two of them have been implemented in ACT, as described in the following two sections:

- Space Debris Index (SDI), potential fragments · year (see section 2.1.4)
- Layered atmospheric launch emissions, kg (see section 2.1.5)

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2.1.4 Space Debris Mitigation

The ESA handbook suggests using "mass left in space [kg]" as a simple metric and first measure of space debris. However, such a mass-flow accounting does not yet give exact information on the actual impacts related to the mass release. In order to quantify such impacts and support decision-making with ACT, accounting for the disposal strategy and, most importantly, differentiation of the impact depending on the orbit(s) of the mission was implemented via a novel Space Debris Mitigation (SDM) midpoint indicator.
Two options were considered: either ESA's mission index (MI) [9] or the space debris index (SDI) [14, 15]. The SDI was chosen to be implemented in ACT, as it had specifically been created to be a new LCIA indicator. Its unit is *[potential fragments generated · years in orbit]*, representing a certain risk measure. The characterization factors (CFs) used for the computation rely on the use of the MASTER database [14]. Each orbital cell, a circular orbit defined by increments of 50km between 200km and 2000km (LEO) in altitude and 2 degrees in inclinations, is assigned a CF. No characterisation factors have been defined for objects left in a graveyard orbit above 2000km or for those operating in the Geostationary Orbit (GEO) region, which means that they do not accumulate to the risks of this methodology.
In the script used for ACT, the scope of the SDI has been extended to cover risks of objects left on elliptical orbits, which is important for launch vehicles as some end up in highly elliptical orbits like GTO. The assessment also accounts for the post-mission disposal success rate (PMD, notedα). The computed risk is the weighted sum of the risk generated by the mission operation time, the end-of-life manoeuvre (EOLM), and the natural decay (more or less long depending on the success of the EOLM), as shown by equation 1. The approximation is usually valid for launch vehicles as α is close to 100%, and the operations and EOLM are short compared to the natural decay duration.

$$SDI_{LV} = SDI_{operation} + \alpha \cdot (SDI_{EOLM} + SDI_{decay,successful}) + (1-\alpha) \cdot SDI_{deay,unsuccessful} \cong SDI_{decay,successful} \quad (1)$$

In the case of a space transportation vehicle that includes an active debris removal (ADR) stage, the index risk of the removed debris is subtracted from the total SDI results:

$$SDI_{tot,ADR} = SDI_{LV} + SDI_{ADRcapture} + SDI_{ADRremoval} - SDI_{debris} \text{ [pot. frag· year]} \quad (2)$$

It must be noted that an updated paper on the SDI indicator has recently been published [16], so the script used in ACT will be adapted to this new information.

2.1.5 Atmospheric launch emissions

The two atmospheric impact categories as proposed by the ESA handbook [19], ozone depletion potential (ODP) and global warming potential (GWP), are not fully suited to cover environmental impacts caused during the launch event (LCS 3 - mission in the system boundaries, see 2). Common LCIA characterization factors (CFs) in these impact categories (translating environmental flows into impacts) are defined for emissions made at ground level or lower heights in the atmosphere layers. Some CFs exist or are being developed for the aviation industry, up to 24 km [3, 20], but launch vehicles are the only human-made objects to cross all layers of the atmosphere, with engines exhausting gases and particles directly into the ozone layer and above. Both the exact emission spectrum in all these layers and their physical impacts on the environment are unknown, and consequently, no CFs exist quantifying the environmental impacts of atmospheric launch emissions.
ACT undertakes a first step to fill this gap by using flow indicators computing the mass of 12 species emitted in the air during the launch event, including hydrogen chloride (HCl), and soot particles (often called "black carbon"). From the burnt propellant mass, the amount of emitted species [kg] is computed based on a table from [7].
The thrust curve is converted to a "mass flow curve" by using the equation 3 point by point. The tool interpolates the trajectory(ies) and mass flow curves provided as input to find a function for mapping the data points (see figures below). Then a method integrates the mass flow curves between ignition and cut-off using the extracted timestamps from the trajectory to find the mass of burnt propellant in different layers (figure 5).

$$F[N] = \dot{m} \cdot v_e = \dot{m} \cdot I_{sp} \cdot g_0 \text{ [kg/s·s·m/}s^2\text{]} \rightarrow \dot{m} = \frac{F}{I_{sp} \cdot g_0} \text{ [kg/s]} \quad (3)$$

The impact computation for GWP and ODP during the launch is closed as best as possible with current knowledge by translating the mass of some of the species as if they were emitted at ground level, namely for CO, CO_2, NO, OH, N_2, and Cl. Large variations of quantified GWP and ODP impacts are thus possible depending on the accounted species and the characterization factors applied, and an underestimation of the impacts is currently likely. For instance, soot and alumina particles might drastically increase the impacts of climate change and ozone depletion, respectively, even more so when emitted at high altitudes [7, 8, 25]. Once scientific knowledge is present, ACT can easily implement new

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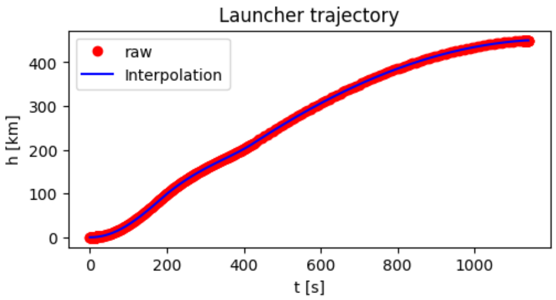

Figure 3: Example of extrapolated trajectory of an imaginary test case.

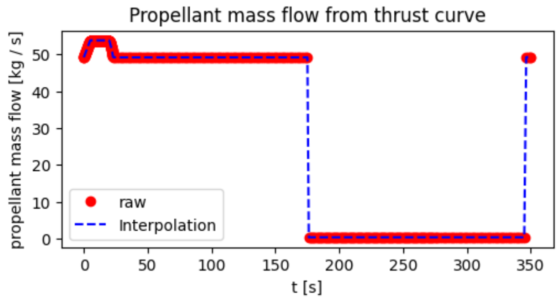

Figure 4: Example of extrapolated thrust curve of the hydrogen-based engine of an imaginary test case, converted in propellant mass flow curve.

Figure 5: Estimated emissions of 1 engine of an imaginary test case in the various atmospheric layers.

characterisation factors to give a more complete picture of the impacts on the environment from atmospheric launch emissions.

2.2 Current status and implementation of the software

The ACT tool is a web application utilising a React-based user interface (UI). React is an open-source JavaScript library for creating interactive and dynamic UIs. The UI communicates over secured application programming interfaces (APIs) with the .NET backend to access the precalculated LCA database, which is stored in a Microsoft SQL database. Except for the Microsoft SQL database, all technologies are open-source.
ACT has been made compatible with another tool developed at eSpace: the Technology and Combination Analysis Tool (TCAT) that can use an exported configuration from ACT to simulate a space logistics scenario and computes the space debris index score and atmospheric lanuch emissions with Python scripts.

2.2.1 Precalculated LCA database

ACT performs a simplified LCA, and, thus, not all LCA-related calculations are executed within the tool. Hence, an ACT user cannot follow the full supply chain of a material or component. Instead, the environmental impact scores of all input datasets used from different databases are calculated outside of the tool and then supplied to it as precalculated values. This calculation is done according to the usual matrix calculation that is the basis of LCA, as shown in figure 6, by defining which technosphere and biosphere flows are used (A and B matrices). Then the corresponding

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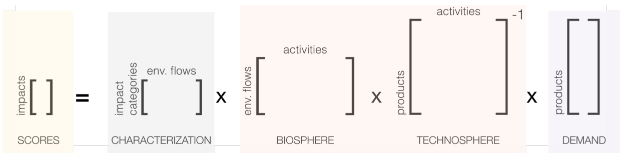
environmental impacts of each flow are calculated by multiplication with the characterisation matrix. ACT uses the resulting matrix by combining it with the demand vector (the user inputs) to calculate the final LCIA score of the provided functional unit. The demand vector is set by the user when choosing a specific material, process or emission and providing the required amount of it.
The database calculation procedure is as follows, using ecoinvent cut-off v3.9.1 as the backbone: (i) The ESA LCI database was originally built using ecoinvent v3.5 but has been linked to v3.9.1 for this project. (ii) All ecoinvent datasets which are used by the ESA LCI database and/or ACT are identified. (iii) Nine future ecoinvent databases are created via coupling of the described REMIND IAM scenarios with ecoinvent v3.9.1 at different timestamps (see 2.1.2). (iv) A version of the datasets defined in the ESA LCI database is created for each of these future databases. (iv) The precalculated matrix is created for the full set of datasets and databases and integrated in ACT.



$$h = C \times B \times A^{-1} \times f$$

h	Environmental impacts of final demand	e.g. climate change (kg CO_2eq/kg), particulate matter formation, ecotoxicity, land use, ionising radiation, water/resources depletion,...
C	Characterisation matrix	Impact factors
A	Technosphere (industrial economy) matrix	Processes vs. Processes
B	Biosphere matrix	Resource depletion/emissions vs. Processes
f	Final demand vector	Amount of product/service demanded

Figure 6: Matrices representation of the computation made in ACT. Based on a representation by Aleksandra Kim.

2.2.2 Reusability and allocation

When a launcher is modelled as expandable in the tool, the number of launches needed to fulfill the FU will multiply computed impacts in the production, assembly, mission and disposal phases (LCS 1 to 4).
When a configuration includes one or more reusable elements, the tool computes the number of *primary* launches and the number of reuse based on the total number of flights and the maximum number of reuse for the element (see equation 4 and 5). It follows that for each primary production, impacts in LCS 1 and 2a will be generated again, impacts in LCS 2b (propellant production) and 3 (mission) will happen anyway at every launch, and impacts for the recovery (LCS 5) and the refurbishment (LCS 6) will be multiplied by the number of reuse.

$$n_{primary} = ceil(\frac{n_{launches}}{n_{reusemax} + 1}) \tag{4}$$

$$n_{reuse} = n_{launches} - n_{primary} \tag{5}$$

2.2.3 User interface and user flow

After reading and understanding the LCA goal, scope, and system boundaries, an ACT user will follow four main steps to use the tool:

1. Create new parameterised building blocks (BB) (based on provided templates used in the default configurations) or import previously saved ones.
   Here the user selects the foreground data to model their system/product. Some inputs are values, Boolean (true or false), or LCA datasets to select from the precalculated database (see section 2.2.1), a trajectory and thrust curves are required in .csv format.

2. Define new ACT configurations with the parameterised building blocks (to fulfil a user-defined functional unit, see section 2.1.1), or import previously saved ones.
   The user selects the STV blocks and creates the relationship between some of the blocks (e.g., trajectories, propulsion, refurbishment strategies (optional) assigned to stages). They then define the ground logistics by setting travel distance and selecting a transportation mode (dataset).

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3. Generate the LCA results for the defined ACT configuration.
   The user can navigate between the different representations and analyse the LCIA results.

4. Compare several ACT configurations in the "comparison" screen and interpret the results.

Three default configurations are provided in ACT to cover different launcher use cases and act as starting point for ACT users: expendable space transportation vehicles; (partially) reusable space transportation vehicles; and space transportation vehicles with active debris removal (ADR) capacity. The required (minimal data input) and possible (maximal data input) building blocks to make a configuration of either type are shown in tables 1 to 3.

BB name	Min	Max
Fairings	1	1
Orbital stage	1	1
Lower stage (0 if SSTO)	0	∞
Propulsion – each assigned to a propelled related block	1	∞
EOL strategy – assigned to the orbital stage block if applicable	0	1
Trajectory info – each assigned to a propelled related block	1	∞
Sub-assembly	0	∞
Kick stage	0	∞

Table 1: Required (min) and possible (max) building blocks for an expendable STV.

BB name	Min	Max
Refurbishment strategy – each assigned to a reused related block	1	∞

Table 2: Additional required (min) and possible (max) building blocks for a (partially) reusable STV.

BB name	Min	Max
ADR stage	1	1
ADR strategy – assigned to a related ADR stage	1	1

Table 3: Additional required (min) and possible (max) building blocks for an STV with ADR capacity.

Test cases presented in section 3.2 can serve as examples for the LCA methodology and the ACT user steps.

2.3 Identified knowledge gaps of LCA in the launch segment

As explained above, one major current limitations to assessing the environmental impacts of launch vehicles is that exhaust emissions of engines still need to be measured and no scientific method allows for the precise characterisation of the impacts of these emissions in the higher layers of the atmosphere. This is true for both emissions happening during the ascent trajectory, during reentry from orbit, and when manoeuvring for a propulsive landing. Extrapolating with characterization factors gathered in [3], the difference in results for GWP could be of two orders of magnitude when including soot, alumina particles, and nitrogen oxides [25].
Similarly, the impacts due to stages, some with residual propellant, falling back down and sinking in the ocean waters are not understood yet. Casualty risks are often reduced below a threshold by performing a controlled reentry and targeting a fall within the South Pacific Ocean Uninhabited Area (SPOUA), or by improving the demisability of the objects with design for demise technologies (D4D) [24]. This is a typical example of trade-offs that engineers often face when mitigating environmental impacts, a design change can lead to burden shifting so deciding which system is better in terms of lower impacts is difficult and subjective. In this regard, an identified gap is a wide consensus over an LCA single score for space systems that would support decision-making with trade-offs in early design phases. Further gaps in prospective LCA can come from unknown unknowns: new disruptive technologies, future trends or regulations, that might affect the design and operation of future vehicles.
Identifying knowledge gaps is a continuous process, and for each one found, research projects should be started and approximations should be implemented while waiting for more robust knowledge.

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2.4 Identified limitations of ACT

Users of the tool will face data gaps in the available datasets and will need to select the best-matching ones as proxies to model their systems. For very specific materials or processes, it will be necessary to create new datasets by collecting data along the supply chain. It is needed to understand the exact energy mix and consumption, material use, facilities, etc. in the company and at their suppliers, and make sure that ACT incorporates them. This is a tedious process that should be facilitate with standardized data collection procedures. Once done, the creation of new datasets can greatly improve the modelling of current and future space transportation vehicles.
As per now, ACT does not support validation of user inputs, and the LCA results do not show any robustness rating or uncertainty ranges. Further, visualisation of the results will be improved in ACT updates.

These gaps underline the fact that LCA results for space systems, computed with ACT, should be handled with care.

3. Application example of the Assessment and Comparison Tool

3.1 Future Space Transportation Vehicles

The design of the future family of European launch vehicles has already started. ESA, national agencies, and the industrial space sector are planning for the development of technologies to improve Ariane 6 and Vega, and to produce and operate the next generation of systems [1, 10]. Concepts are being selected now with the objectives to lower costs, improve ground operations efficiency, and increase capabilities (in terms of payload mass but also to unlock human-rated technologies).
Technologies and systems development are anticipated many years before the first launch of a new vehicle. This is why it is important to assess and understand potential environmental impacts at an early stage of the design. It is still now that decisions are made, and changes can be done without costing too much. The field of ex-ante life cycle assessment [22] is still maturing but permits anticipation of hotspots, steering of ecodesign efforts, and trade-offs between performance and environmental risks before designs are frozen and mass production starts.
ACT has been developed with this vision, to be able to provide LCA results for systems that will be produced and operated years from now (see section 2.1.2). The following sections give an example of an application for the tool: to be able to trade off critical design choices early on.

3.2 Imaginary test cases

Test cases have been created for this paper to illustrate the features and possible use of the ACT tool, highlighting the capabilities of ACT and thus differences in environmental impacts due to design choices. They will demonstrate how engineers could use its outputs to compare solutions by adding criteria for environmental impacts in their trade-offs. These test cases do not model real launchers with high fidelity but rather are based on technologies and building blocks that exist or are in development, and for which some LCA-related data are publicly available. In general, access to primary data in the space sector is heavily limited because of confidentiality reasons.
The present case study focuses on the environmental aspects of the reusability of launchers. With the deployment of the first reusable stages (e.g., SpaceX), and the announcement of fully reusable launchers (e.g., Rocket Lab's Neutron[2]), it is understood reusability is economically viable and helps lower primary production rates. Reusability is often declared environmentally more sustainable, too. While it seems straightforward that some materials are saved because one does not need to re-produce a completely new stage for each launch, reusable launchers may generate more impacts in other impact categories or in different mission phases, an issue called burden shifting. It is then up to LCA practitioners and engineers to analyse if the shift generates an overall reduction of the impacts. For instance, some propellant is needed to land back down on the ground, lowering performance (see table 4). Refurbishment is not without impacts, and this is without mentioning the possible rebound effect: lower costs and impacts leading to more launches which ultimately increases the impacts [2].
Two test cases are defined here: a full hydrogen/oxygen (hydrolox) two stage to orbit (TSTO) launcher, expandable or with the option of reusing the lower stage. The recovery is "down range" (DR) as opposed to "return to launch site", because it brings less penalty to the performance. The created configurations of launcher have been modelled, getting inspiration and input values from public user manuals [11, 12], data sheets, and literature [4].

[2]https://www.rocketlabusa.com/launch/neutron/

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3.2.1 Functional unit of the test cases

The functional unit defined for this case study is to place a total payload mass of 280 tons into a target circular orbit at 450 km altitude, 6 degrees inclination (see section 2.1.1). This could happen with a manifest of 14, Ariane 6-like launches per year to LEO [10].
The performances and trajectories of the two imaginary test cases have been computed at ESA based on main parameters found in [4], using the tool Astos by Astos Solutions[3].

Configuration	Full hydrogen-based	
Reusability option	RLV (DR)	ELV
Dry mass (S1 + S2) [tons]	36; 8	34.2; 8
Loading (S1 + S2) [tons]	328; 71	328; 71
Unburnt propellant [tons]	15; 1	1.5; 1
Performance [tons]	27.4	31.7
Number of launches (computed by ACT to fulfil the FU)	11	9
DR distance [km]	1008	N/A

Table 4: Main mass parameters and performance computed for the two test cases.

3.2.2 Life Cycle Inventory

The life cycle inventory in terms of material and processes is not detailed since only limited data could be accessed from published sources. This is judged sufficient for this case study, which explicitly aims to showcase how LCA is done in ACT, but not to actually assess an LCA case study in detail with regards to technical and environmental implications. The elements of the launcher architectures are approximated with only a few LCA datasets including for instance aluminium alloy, stainless steel, honeycomb panels with CFRP skins, or some generic datasets for electronic systems or tanks, based on materials often found in present-day launch vehicles [11, 12]. Examples of an input trajectory and of an engine thrust curve are shown in figures 3 and 4. The point of those mock data is not to model nicely the architecture of a possible future launcher but to demonstrate the capability of the tools which account for precalculated LCA impacts as explained in section 2.

3.2.3 LCA results interpretation

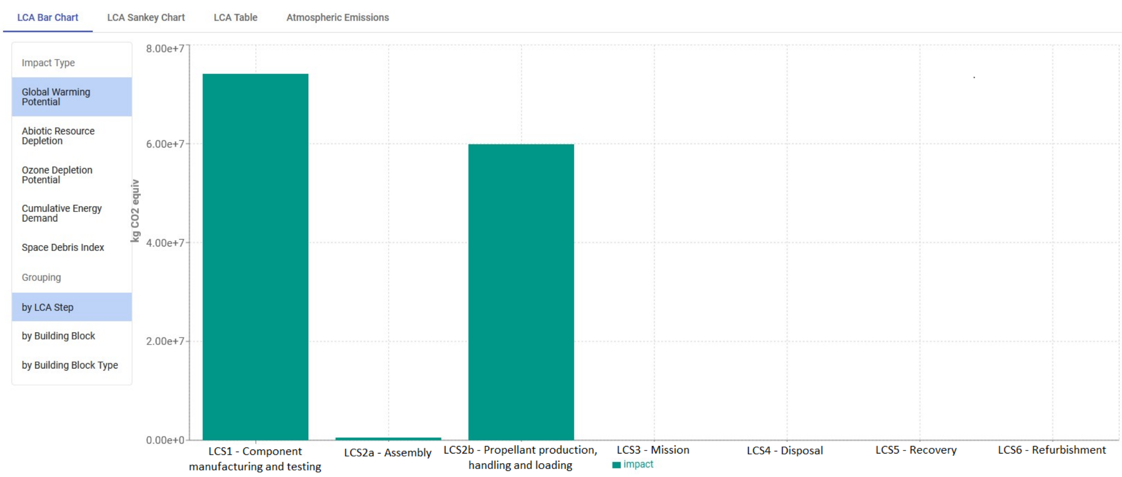

Figure 7: GWP results as bar chart grouped by life cycle steps for the expandable hydrogen-based configuration.

Figures 7 and 8 show the bar chart results grouped by LCS for the expandable and reusable test configurations respectively. The impact hotspot is shifted from LCS 1 to LCS 6 so from primary production to the refurbishment phase. This is expected since for the functional unit defined, there is 9 primary launches in the case of the expandable LV, while there is only 1 for the reusable one, with 10 refurbishment process before reuse (11 launches needed and a maximum

[3]`https://www.astos.de/`

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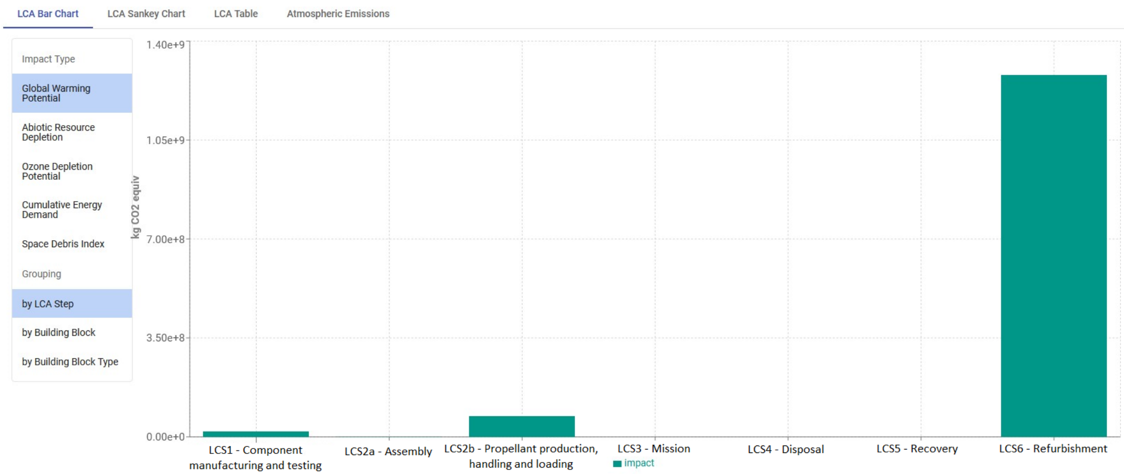

Figure 8: GWP results as bar chart grouped by life cycle steps for the reusable hydrogen-based configuration.

number of reuse of 15). Still the large difference in impacts between primary and refurbishment productions are probably due to an incomplete modelling in the inventory of the vehicle. Data quality is of the utmost importance when performing LCAs and will need to be assessed for real studies to understand the robustness of the analysis.
Comparatively, only a small impact score is computed for the recovery step. It has been modelled with a simple transport from a recovery point downrange back to the launch pad, using a barge. It is expected that creating a specific dataset for a recovery platform will yield more impacts due to the use of marine diesel and very heavy platform.
In both figures 7 and 8, the mission phase (LCS 3) seems to bare only very little impacts compared to other phases. This is thought to be largely underestimated because of lack of characterization and because some estimated species emitted with a hydrogen-based propulsion are not mapped to any impact scores as discussed in 2.1.5 and 2.3.

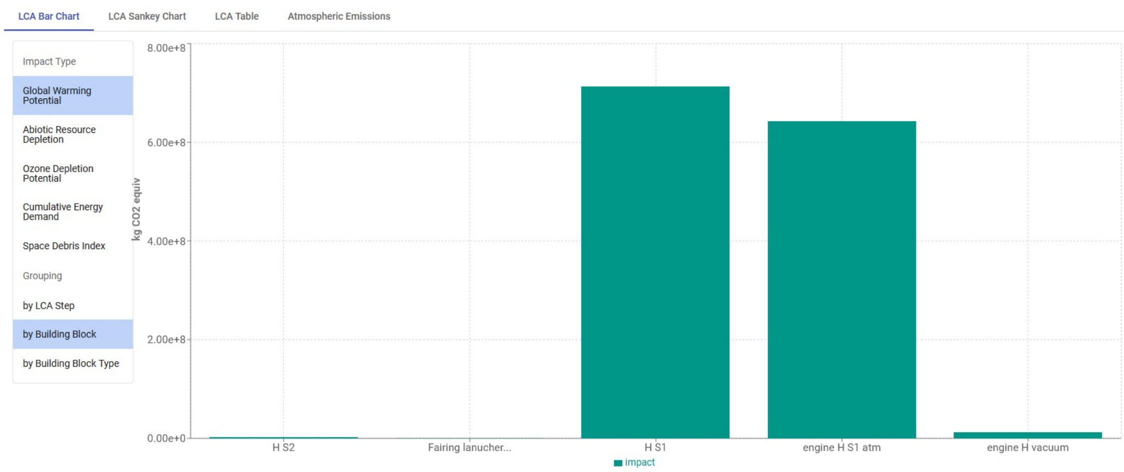

Figure 9: GWP results as bar chart grouped by building blocks for the reusable hydrogen-based configuration.

Results in the form of bar charts can also be grouped by building blocks (figure 9) and building block types (figure 10). This allow the users to explore the different sources of impacts and better understand where hotspots are located in the system nuder study. Figures shown in this report are only for the global warming potential indicator but users can select any of the four indicators described in 2.1.3.
With the materials and amounts assigned to the building blocks, it seems the lower stage and the propulsion systems (which include impacts of the propellant production) are the main contributors. Impacts due to emissions during the launch cannot be compared yet to the rest of the impacts.
After looking at the bar charts, users can have an overview of the impacts grouping by looking at the Sankey diagram (figure 11). The Sankey only goes down to the building block level, to keep global view of the system (but it might be more expandable in future). On the other hand, users cannot dive deeper in the impact sources and identify hotspots at equipment, components, or material level. For this, one must use the table view (figure 12) which lists all activities

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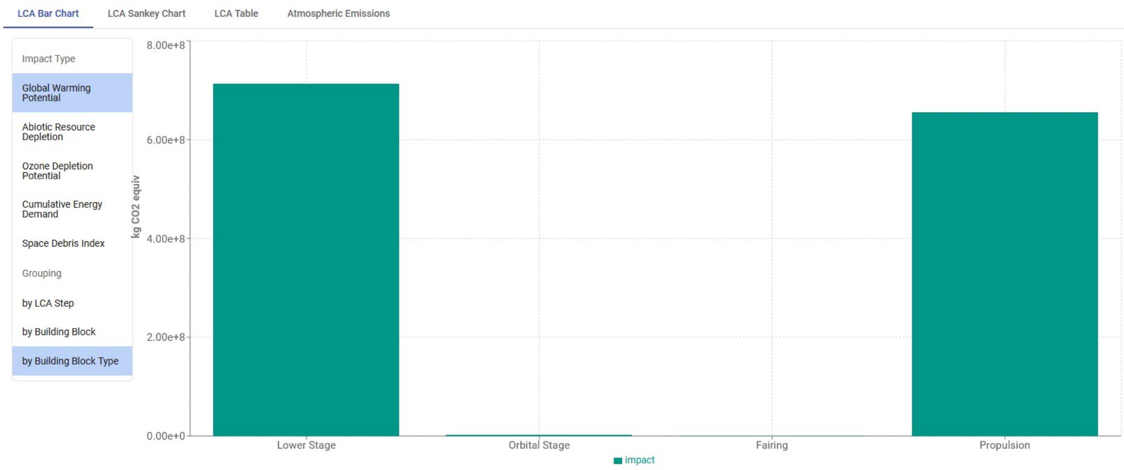

Figure 10: GWP results as bar chart grouped by building block types for the reusable hydrogen-based configuration.

provided in the inputs next to their calculated impacts in the four LCIA categories. It allows for detailed analysis of the importance of life cycle steps, building blocks, or materials in the various impact categories.

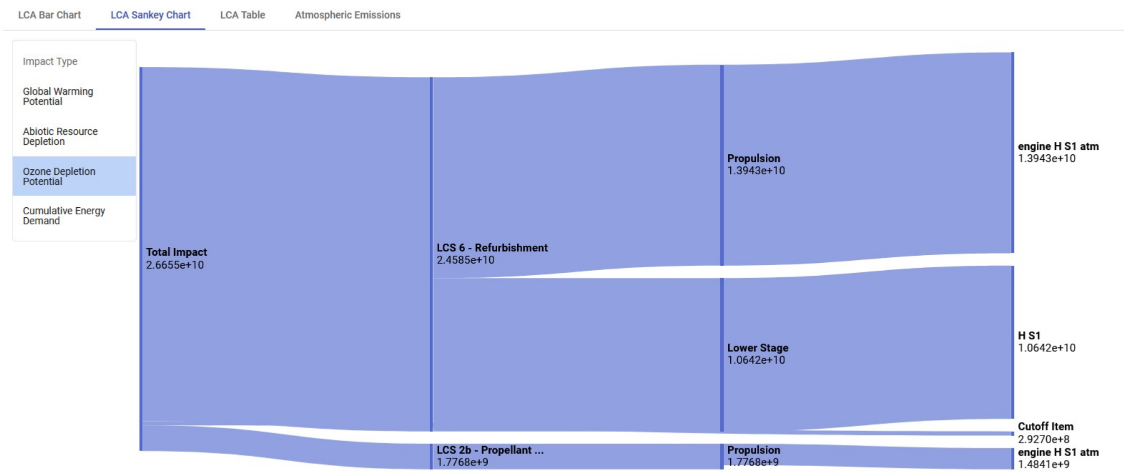

Figure 11: ODP results as Sankey diagram for the reusable hydrogen-based configuration.

The table can be exported by ACT as a .csv file or a PDF, to be used in further analysis or to disseminate results.

LCA Step	Building Block	Building Block	LCA Activity	LCA Activity Type	Amount	Unit	Emission	Emissior	Global Warming Potential (kg CO2 equiv)	Ozone Depletion Potential (kg CFC-11 equiv)	Abiotic Resource Depletion (kg Sb equiv)	Cumulative Energy Demand (MJ)
LCS 1 - STV com	Fairing	Fairing lanuch	AL 5052 Honeycomb with CFRP	Spacecraft equipment	2475	kg			397607.2342	7529232.858	2.170970526	0.663204558
LCS 1 - STV com	Lower Stage	H S1	Stainless steel 440b (X 90 CrMo\	Material, raw	1000	kg			18698.16754	375553.9801	1.192783922	0.000280767
LCS 1 - STV com	Lower Stage	H S1	Electronic component, average	Spacecraft equipment	1000	kg			11874346.93	183606495.5	14477.53112	25.29789029
LCS 1 - STV com	Lower Stage	H S1	Aluminium generic part AA 7075	Material, processed	17000	kg			1724791.027	22980618.02	29.16359169	0.022521041
LCS 1 - STV com	Lower Stage	H S1	Aluminium generic part AA 2219	Material, processed	17000	kg			1870954.925	29344361.84	66.81657654	0.025614156
LCS 1 - STV com	Propulsion	engine H S1 at	Cylindrical Tank, Titanium prima	Spacecraft equipment	100	kg			15158.98247	242818.8319	0.355052932	0.013176576
LCS 1 - STV com	Propulsion	engine H S1 at	Titanium, TiAl6V4 billet , RER	Material, raw	100	kg			18671.57107	367163.9039	0.114148496	0.001022209
LCS 1 - STV com	Propulsion	engine H S1 at	Electronit unit, high IC , RER	Spacecraft equipment	10	kg			2836.811425	46208.42166	1.818969356	0.000186511

Figure 12: First few rows of exported results in the form of a table, here for the reusable hydrogen-based configuration.

After looking at the impact scores of a configuration individually, users might be interested in comparing several configurations that fulfill the same functional unit. ACT allows comparison with the bar chart view, with impacts grouped by LCS or by building block types. Figure 13 shows the comparison between the two imaginary test cases.
Comparisons can also be made for a configuration assessed with different prospective databases (section 2.1.2). Defining a reference configuration, it can be compared against the same architecture, with the same materials, transport, processes, etc. datasets but the precalculated impacts of those are modified by the propagation of the integrated assessment models changes.

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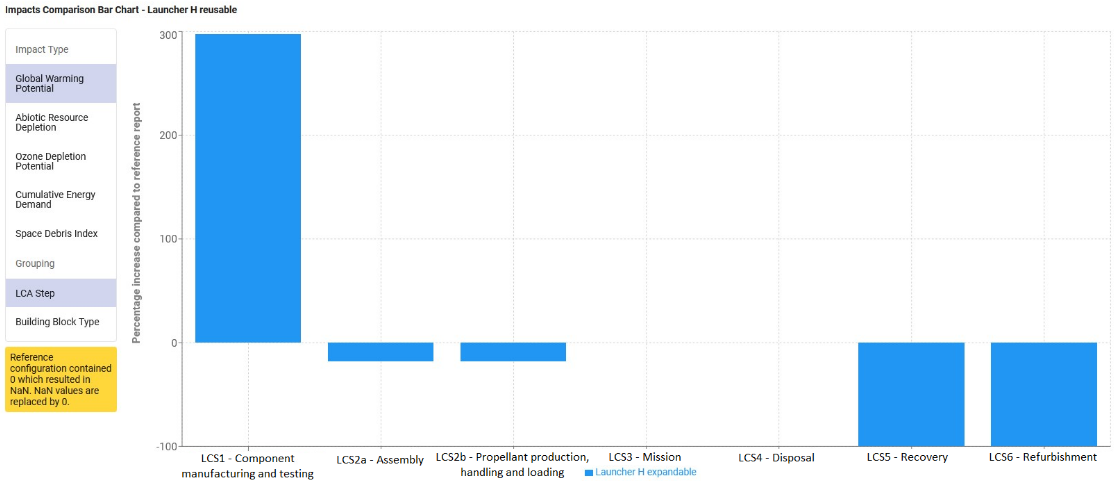

Figure 13: Comparison between the reusable hydrogen-based configuration (reference) and the expandable one, at similar functional unit.

4. Outlook

To cope with the above-mentioned knowledge gaps, the development will continue with extended scopes, boundaries of the systems assessed (incl. ground segment), and capabilities. For the latter, more environmental impact categories, and more diverse functional units will be added, and models and features of the tool will be improved.
To do so, the tool will be updated with relevant experience from other transportation systems (cars, aeroplanes, etc.) and include the latest research on the impact on the different layers of the atmosphere, which is the unique feature of STV. Moreover, the tool will be accommodated to be easily connected to existing software (e.g., atmospheric modelling). Further, ACT has been set up in a modular way and such that new interfaces with existing models or softwares can be added, for instance in order to facilitate application of ACT in the daily workflow of engineers.

5. Conclusion

By nature, LCA strives to provide a high-quality model of the system under research, which can be a very time-intensive task. This becomes even more challenging when dealing with systems under development or deployed in the future only. Hence, performing an LCA on future space transportation vehicle scenarios seemed *a priori* complicated due to the large number of assumptions involved. ACT now allows to easily combine technical space-specific inputs and primary data with current and future background data. It provides a state-of-the art way to investigate and understand environmental hotspots of launch vehicle architectures. The impact assessment of launcher configurations has been automatised. ACT has successfully demonstrated that novel end-to-end launcher scenarios can be quickly analysed from the environmental impact perspective. Due to its modular nature, it will allow for further extension, improvement, and implementation in design work.
In this paper, ACT has been described and visualised in a quick comparison of imaginary STVs. These two TSTO highlighted that from a simplified launcher vehicles architecture and ground logistics, key environmental impact parameters can be estimated. With that tool in hands, the user can compare various aspects of the STVs and focus a specific segment such as the propellant choice, production method, reusabilily, ground transportation, and so on.
Current knowledge and data gaps have been identified, which will need to be filled with future research projects to improve the robustness of LCAs in the space sector, in particular for launch vehicles.
Space transportation means and industry is on the edge of a fast transformation. A dynamic tool such as ACT is necessary to keep up with the constantly changing space transportation ecosystem, allowing integration and coupling of existing models and tools to enrich current design processes and life cycle assessments. Evolving propellant production method, transportation means and advanced scenarios of reusable launchers must be accounted to regularly identify end-to-end STV scenarios that minimise the environmental impact. The proof-of-concept of ACT is there, and its power will be expanded in future work in order to support sustainability aspects in the space sector.

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