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Impact of Life Cycle Assessment Considerations on Launch Vehicle Design

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Abstract

The continuous growth of the small launcher market and the emergence of many new concepts in the past years, combined with the growing need for sustainability in the space sector, raises the question of their environmental impact. The sustainability of space activities is becoming a significant constraint on future space applications. There is a need to integrate sustainability into the framework of micro launchers design at the preliminary phase. This work presents a novel methodology that considers the environmental impact of a launcher in its design phase, using Life Cycle Assessment (LCA) and Multi-disciplinary optimization tools (MDAO). Life cycle analysis studies the environmental impact throughout the launcher life cycle, from conception to disposal. This includes operations, but also development, manufacturing, testing of the launcher, logistics, construction and maintenance of ground facilities, as well as the recovery, refurbishment, and recycling if applicable. This paper focuses on greenhouse gas emissions and their influence on global warming. Multi-disciplinary analysis and optimization (MDAO) has been successfully applied to the design and optimization of space systems, including launcher vehicles. Launchers are usually optimized to fulfill a specific mission while minimizing the overall mass at take-off. The idea developed in the present work is to integrate outputs from the LCA of the launcher in the optimization process. First, the parameters needed to perform the LCA for a generic micro-launcher are identified, based on the dominant design from the many small launchers that are either operational or in development. Then the LCA is then integrated into the multidisciplinary framework to include ecodesign constraints in the optimization loop, using OpenMDAO. Finally, the results of the optimization of the launcher design using global greenhouse gas emissions as the main objectives are discussed, highlighting the current limitation of the model and possible developments of this methodology.

Keywords: Environment, Design, Launcher, LCA, MDAO, Optimization

Acronyms

GLOW Gross Lift-Off Weight

GWP Global Warming Potential

LAST Launcher Analysis and Sizing Tool

LCA Life Cycle Assessment

MDAO Multidisciplinary Design Analysis and Optimization

SSSD Strathclyde Space Systems Database

Symbols

$X_{eng} = [P_c, P_e, OF, TW]$ Design variables linked to the engine: chamber pressure, exhaust pressure,

fuel-oxidiser ratio, thrust-weight ratio

m_{pl} Payload mass

$X_{traj} = [t_{ascent}, t_{gt}, t_{meco}, t_{seco}, \dots]$ Design variables linked to the trajectory: initial ascent duration, gravity turn duration, first stage flight duration, second stage flight duration, ...

d_{stage} External diameter

$C_{eng} = [T, ISP, \dot{m}_f, \dot{m}_{ox}]$ Main engine characteristics: thrust, specific impulse, fuel and oxidiser mass flows

$M_{prop} = [m_{f,1}, m_{ox,1}, m_{f,2}, m_{ox,2}]$ Propellant masses: fuel and oxidiser mass for stages 1 and 2

$M_{dry} = [m_{fairing}, m_{tank,f,1}, m_{tank,ox,1}, \dots]$ Dry masses: fairing mass, fuel and oxidiser tanks mass,

...

$C_{geom} = [l_{stage,1}, l_{tank,f,1}, d_{tank,f,1}, \dots]$ Geometrical characteristics: first stage length, first stage fuel tank length and diameter, ...

C_x, C_z Drag and lift coefficients

N_{max} Maximum dynamic pressure

ΔV_{final} ΔV left in orbit (negative if orbit not reached)

1. Introduction

The concern for climate change and the ever-increasing human impact on Earth, combined with the continued growth of the space sector raises the question of its future impact on the environment, especially the Global Warming Potential (GWP) [1]. If the impact of commercial aviation has extensively been studied [2], the impact of the space sector has been ignored for decades and remains today difficult to correctly estimate [3]. This is partly the consequence of the lack of correct models for the high speed and high altitude emissions, as well as all the environmental impacts not linked to the launch event phase. In order to ensure the next generations of space launchers are compatible with the environmental limits of the Earth and the eventual legal constraints that may result from the increased awareness of these issues, environmental constraints will need to be integrated into the development process from the very early stages.

Previous studies have highlighted very large differences in atmospheric impacts during the launch event using different technologies [4], [5], such as hydrogen or hybrid rocket engines. However, those only assume the radiative forcing caused by the launch event itself and don't consider important factors such as the production of propellant or the launcher itself, and ignore the potential radiative forcing of H_2O or NO_x in the upper atmospheric layers. For example, a hydrogen-based launcher will only produce water vapor but as a result will have an enormous dry mass which could lead in a much higher overall environmental impact. Recent attempts of Life Cycle Assessment (LCA) especially carried out by ESA [6] and A. R. Wilson [7] highlight the importance of correctly analyzing the complete life cycle of the launcher, including design, manufacturing, disposal,

and reusability if applicable, while providing tools and databases to carry out such an assessment.

Multidisciplinary Design Analysis and Optimization (MDAO)[8] is a field of engineering that aims to model and optimize complex systems incorporating different disciplines whose couplings and modeling are critical for the overall design. Growing in the late 20th century with the increasingly available computational power, MDAO is now widely used in aerospace engineering, and many previous studies aiming to optimize micro launcher architectures have been conducted. However, MDAO often focuses on technical or economical objectives, not environmental ones.

This study proposes a new methodology to reduce the impact of newly developed micro launchers by using LCA as a key component and objective inside an MDAO architecture. Section 2 presents the detailed methodology and Section 3 presents the current environmental and technical model being developed. Section 4 presents early results, and Sections 5 and 6 present the current limitations, discussions, and possible developments for the project.

2. Methodology

The methodology developed to optimize the environmental impact is based on two key techniques: the LCA, to compute the relevant impacts, and MDAO, to implement an optimizer.

2.1 Life Cycle Assessment

LCA is a standardized method to evaluate the environmental consequences of a product or activity across its entire life. It's defined by a family of ISO norms [9], from ISO 14040 to ISO 14044, extended by the European ILCD [10]. The main characteristic of LCA is that it covers the entire life cycle of the launcher, including development, permanent facilities, logistics, etc..., and not only the launch event. Figure 1 shows the basic scheme of LCA scope for a launcher. In the present work we will only focus on one impact: the Global Warming Potential (GWP) as defined by IPCC[11]. To effectively compare different launchers, the functional unit used is the 1 kilogram of payload injected into a low earth orbit (LEO).

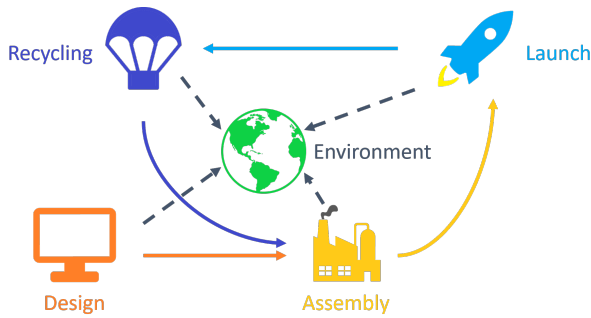


Figure 1: Generic LCA scope for a launcher

Specifically, the target orbit is a 700km altitude polar orbit.

2.2 MultiDisciplinary Analysis and Optimization

The MDAO problem can be described as an optimization problem, following the MDAO principles [12], [13]. The problem we define is the minimisation, under constraints, of the Gross Lift-Off Weight (GLOW) with respect to specific design variables:

Objective function : GLOW

Design variables : X_{eng} , m_{pl} , X_{traj} , d_{stage}

Constraints : $\Delta V_{final} \geq 0$

The model and variables are detailed in Section 3.

Aerospace engineering has many multi-disciplinary challenges, and always uses the latest development in MDAO techniques. MDAO for generic simple launchers has been the topic of multiple works [14], [15], and several review papers are available [16]–[19]. Of particular interest in the context of the present paper are recent published works on MDAO for small reusable launchers [20], and nano launchers [21], or reusable launchers with new propellants [22].

One of the major novelties of the present work is in the consideration of the output value for GWP from the LCA as the objective function f in an MDAO of the launcher. This will require to add another discipline in the MDAO code structure.

3. Modeling

The technical model for the launcher itself has to reflect the current developments of micro launchers, as highlighted by recent surveys of the industry [23], [24]. Several primary architectures are emerging from those developments, however the present work focuses on most popular one, already flying: a 2-stage RP-1 expendable launcher. The LCA of such a launcher also depends on parameters that are not directly related to the launcher design, for instance the location of the factories, the design phases, the location of the launch site, etc...

3.1 Technical Model

The technical MDAO model is called Launcher Analysis and Sizing Tool (LAST) and is a tool based on the open-source library *OpenMDAO* [25]. Some modules are derived from the software FELIN [26], developed at ONERA from previous work on MDAO for launchers [14]. The current rocket model for LAST is a classical 2-stage, expendable rocket, with a 500kg capacity to SSO. The same engine is used for both stages and uses RP-1 and LOX; the first stage has 9 engines and the second stage has 1. Figure 2 shows an example of the shape and components of the launcher simulated by LAST. The current LAST

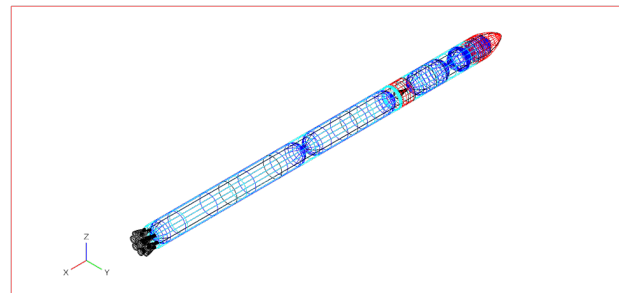


Figure 2: 3D model output of LAST

model has 15 design variables. One parameter is the payload mass m_{pl} ; one parameter is linked to the geometry, the diameter of the launcher d_{stage} . Four are linked to the engine and noted X_{eng} :

- the chamber pressure P_c ;
- the exhaust pressure P_e ;
- the fuel to oxidiser ratio OF ;
- the thrust to weight ratio at launch TW .

These parameters are shown in Figure 3.

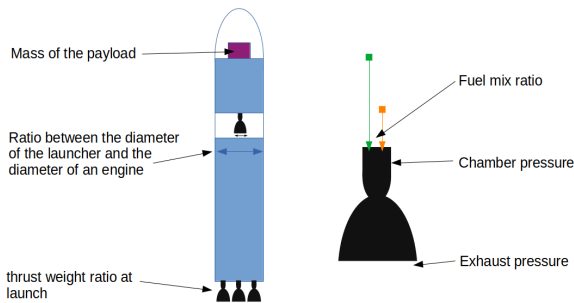


Figure 3: Current LAST design parameters

The other design parameters are linked to the trajectory and noted X_{traj} . Those include:

- flight duration of each phase, including the burn time of each stage noted with t_{mecc} and t_{seco} ;
- pitch over angle;
- parameters for the exo atmospheric command law.

As shown in Figure 4, LAST has currently 4 modules:

- **Propulsion:** models the engines.
- **Mass & Structure:** models the structure and computes the mass of the different parts.
- **Aerodynamics:** simulates the aerodynamic properties of the launcher.
- **Trajectory:** computes the trajectory of the launcher and validates if it can reach orbit.

The main objective is the GLOW; the MDA is solved using Gauss-Seidel fixed point iteration method, and the global optimizer algorithm is CMA-ES [27].

3.2 Environmental parameters

The LCA is based on the Strathclyde Space Systems Database (SSSD) [28], an environmental database built for space activities, and is itself based on Ecoinvent [29] and ELCD [10] background inventories. Further information on the SSSD can be found in the work of A. R. Wilson [7]. This is used to build environmental models for the following processes:

- Production and assembly of the launcher (2

stages and the fairing)

- Production of propellant
- Transportation of the launcher parts to the launch site
- Launch event
- Build and maintenance of the launch site, development, and design of the launcher.

The model assumes 100 launches in the program, dividing the fixed cost of the launch site and design. It also assumes an average distance between the factory on the launch site of 1000 km, and that all activities are carried out in Europe.

The environment model is built in LAST, as the fifth discipline module, outside of the MDA. The GWP is computed from the optimization result.

4. Preliminary results

Early optimisation results on the generic technical model specified in Section 3 gives a GWP impact of 194 kgCO₂eq per kg to orbit, or 96.8 tCO₂eq for a launch with a 500 kg payload. The LCA analysis gives the distribution of this impact among the main phases of each launch presented in Figure 5. We note that if the propellant is responsible for around 50% of the GWP impact, this is mainly due to its production, especially for liquid oxygen. Also, the manufacturing of the launcher, directly related to the properties of the dry parts of the launcher, has a non-negligible impact. This gives us an overview of the main contributors to the GWP, and thus the main focus points for the improvement in the model and where it's important to improve the accuracy of environmental models.

5. Limitations and discussions

The early results of this study are limited by many different factors, which limits the conclusion we can draw; however, it also highlights where the most potential improvement lies for the overall model accuracy and thus where the efforts at improving the models should be targeted.

5.1 Limitations of the model

The environmental model from SSSD and the technical model of LAST are based on publicly available

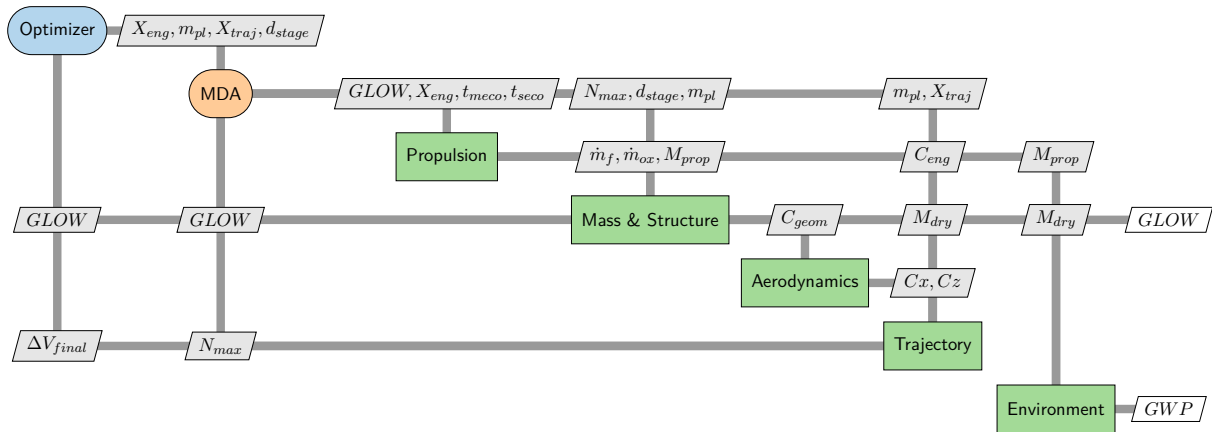


Figure 4: Current structure of LAST

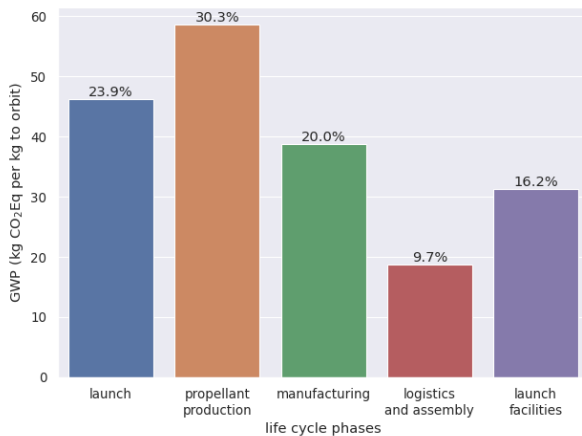


Figure 5: Share distribution of the different phases in the GWP

data, which may not correctly reflect the reality of modern launchers, as most of the design parameters, production techniques, and material characteristics remain confidential.

Some phases of the launcher life cycle directly impacting the GWP or other impacts are not strongly correlated to the launcher design itself, but to other social and geographical parameters like the location of the facilities or the development cycle. For example, two perfectly identical launchers would have different impacts if they were manufactured and launched from two separate locations in two different countries. The environmental databases such as SSSD or Ecoinvent also assume that the production technique used for materials, propellant, or energy

is the average of the geographic area specified; for example, it will assume H₂ is mostly produced from methane, whereas greener techniques exist.

Finally, some medium to high uncertainties remain on the exhaust effects of different species. The model assumes that everything, including black carbon [30], is burned, and the behavior of water vapor [31] is similar to the lower layers of the atmosphere. However, some studies speculate on the actual impacts of those chemicals without extensive experiment data being available.

5.2 Further developments

The current MDAO structure does not directly include the environment module inside an optimization loop, due to performance limitations. In the future, the different outputs of that module could be used directly as objectives for the main optimization loop, as shown on Figure 6 with the GWP.

Those early results only study one impact for one design but can be used as a base to explore and compare other designs. Adapting other architectures, like a three stages launcher, a launcher using different propellants such as hydrogen or methane, or even a completely different design like an airborne launcher or a fully reusable one, would allow for an in-depth comparison of their potential environmental sustainability.

This study focuses on GWP as the main impact, but the LCA methodology, the database used, and

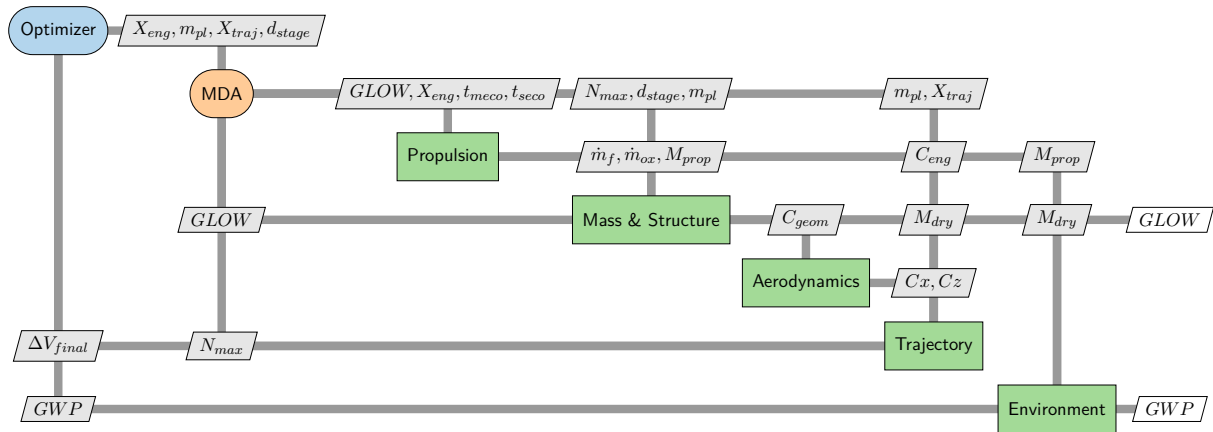


Figure 6: Extended structure of LAST

the compatibility of MDAO with different optimization algorithms could allow for the inclusion of other environmental impacts either as constraints, or other objectives. These include generic impacts like ozone depletion or more space-specific impacts including mass disposed in the ocean or left in orbit [6].

6. Conclusions

The combined usage of MDAO and LCA allows for the optimization of generic launcher design based not on any technical or economical value but on its impact on the environment, a parameter that may become significantly more important in a near future. This study highlights the importance of considering the entire life cycle of a launcher from a very early design stage in order to count all of the phases and activities that may contribute to the overall environmental impact, and subsequently optimize it. It also highlights the need for better environmental models, especially for high-altitude exhaust, to allow for better knowledge of these impacts and thus better reduce them.

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