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RLV applications: challenges and benefits of novel technologies for sustainable main stages

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Abstract

Within the scope of the European Green Deal, the aerospace industry is currently staking on sustainability. To fulfil the objectives and in order to ensure Europe's independent and cost-effective space access capabilities, the ASCenSIon (Advancing Space Access Capabilities - Reusability and Multiple Satellite Injection) project, funded by H2020, is connecting fifteen Early-Stage Researchers (ESRs) and twenty-four partner organizations all across Europe. The pillar concept within the project is to adopt a Concurrent Research Network (CRN) methodology. Accordingly, different host institutions, each one with its main research program and vision, are connected to develop the design under a new perspective. This approach emphasises the cooperation between the fifteen ESRs, thus covering the design of a Reusable Launch Vehicle (RLV) in its overall complexity, facing the new challenges deriving from the required sustainability in a more efficient manner.

Corresponding to work package two (WP2) of ASCenSIon, this paper focuses on main stages for RLVs, and how the goal of sustainability affects their design. Therefore, many different interconnected disciplines, such as propulsion system, structural design, fatigue-life analysis and Health Monitoring (HM) have to be taken into consideration. These different domains are represented by the individual research projects of the ESRs, supported by a collaborative environment which promotes the foreseen interactions. At first, this contribution gives a general State-Of-The-Art overview of the mentioned topics. A preliminary trade-off on RLV architectures is established through multi-disciplinary design analysis and optimization methods based on propulsion modelling, optimal staging and structural sizing. These use performance and cost design metrics as objective functions, accounting for operability and maintainability factors. This investigation is then used to discuss the different Advanced Nozzle Concepts (ANCs) tailored on the system requirements and mission constraints. At this point, a one-dimensional performance analysis addresses the performance gain deriving from altitude-compensation properties of ANCs. Subsequently, the identification of a suitable green propellant will give the needed/accurate/required inputs to conduct a trade-off between engine cycles w.r.t. the fatigue-life of their most critical components. Consequently, fatigue-life analysis contributes to HM and sensing requirements for RLV systems. As a common approach between the ESRs, the data collection is organized in various Databases accessible within the network, which encourages their interconnections and collaborative research.

This paper provides a preliminary analysis of the above discussed topics and their interconnections within the framework of ASCenSIon, aiming to develop novel technologies for future sustainable main stages.

Keywords: **Reusable Launch Vehicles, Advanced Nozzle Concepts, Health Monitoring, Fatigue Life Analysis, Multidisciplinary Analysis & Control, Liquid Propellant Rocket Engines, Environmental impact of propellants operations, ASCenSion**

I. INTRODUCTION

The reusability of launch vehicles is a major keystone for the development of a fully sustainable space access sector. This has been pursued since the advent of the space era, and most notably since the Presidents Science Advisory Committee (PSAC) released a report in 1967 on the post-Apollo space flight future with recommendations to reuse major elements of space launch systems to lower the costs of launching humans into space [1], eventually leading to development of the partially reusable Space Transportation System. Recently, the attempts are on the way to develop fully reusable stages – as with Starship and Super Heavy Booster by SpaceX. Also in Europe various concepts are being developed [2]. In the context of the increasingly growing interest in advancement and evolution of a fully reusable main stages, the ASCenSIon consortium developed a programme that focuses on several specific areas of cutting-edge space access research, with particular focus on propulsion technologies and their reusability, but accounting also for the aero-thermo-dynamics of re-entry and safe disposal. More than providing design concepts, the network aims to identify and advance critical technologies, to prove the feasibility of these concepts. The development of the liquid propellant rocket engines (LPREs), suitable for reusability, is the key aspect here. In order to create a sustainable system with reusability capacity of minimum 10 missions [7], the multidisciplinary approach must be undertaken already at the early phase of the engine's mission lifecycle design and assessment. The main technical challenges, which shall be tackled when designing such a system, include:

- efficient engine maintenance – to avoid loss of performance, efficient engine maintenance has to be executed over a short period of time while incorporating multiple system control entry [8];
- implementation of the HM sensing and processing system for fault diagnosis or prognosis;
- introduction of the well-structured methods for evaluation of the crucial sub-components' remaining useful life – especially on the account of degradation due to e.g. turbine blades erosion, combustion chamber thermal ratcheting effects or thrust chamber plastic deformation in the course of repeated operations [9] [10];

The amelioration of the above-mentioned elements for improved main stages, suitable for reusable launch vehicles (RLV) application, will benefit not only from more economically favorable model for the future liquid rocket engines (21-40% expected savings from current prices based on the reusability model of Falcon 9 [29]), but will also result in the consolidation of the "green" approach towards rocketry design through: "longer lasting products that can be repaired, recycled and re-used", "cleaner energy and cutting-edge clean technological innovation", as well as "fresh air, clean water and biodiversity" (in accordance with European Green Deal postulates) [11].

Within this paper, we present the analysis of the principal challenges and benefits of the sustainable main stages for RLV applications, focusing on aspects such as:

(Section A) Impact of reusability on system requirements. In this section the impact of reusability on system requirements is presented. Moreover, a detailed overview on requirements for the propulsion system, with particular attention to the engine and the fatigue life of its components are discussed.

(Section B) RLV concepts addressing the Advanced Nozzle Concepts (ANCs) tailored to system requirements and mission constrains. Starting with the Plug nozzle, a general discussion of these ANCs is presented, based on literature studies and previous work conducted by Sapienza University. The main focus is put to comparatives between different nozzle architectures and the governing operative modes w.r.t. efficiency. On the basis of this investigation, main system requirements can be derived. Subsequently, one-dimensional performance analysis addressing the performance gain due to altitude compensation properties of ANCs is presented.

(Section C) The fatigue life analysis with health monitoring (HM) and sensing requirements for RLV systems. Firstly, the concept of fatigue life analysis, looking at the requirements introduced by this discipline is demonstrated. Subsequently the Health Monitoring is presented and a discussion leading to the definition of which can be the best architectural and methodological solution for accomplishing fatigue life analysis task is promoted. Accordingly, a brief overview about architectural sensing requirements is presented.

(Section D) Environmental impact of propellants choice on RLV lifecycle and the launchers main Ground Operations and Working Operations Aspects are discussed from a sustainability point of view.

The paper is structured in the following way: after introducing the RLV architecture in the context of system design and cost (point II), we present more detailed RLV concepts as a part of various subsystems (point III) and explanation of the main requirements (section A to D). The conclusions and future outreach are presented in point IV.

II. RLV ARCHITECTURE – SYSTEM DESIGN OVERVIEW

The launch vehicle market of today is becoming increasingly competitive with recent newcomers developing novel reusable launchers (e.g. SpaceX and Rocket Labs). Such competitiveness is redefining the foundations of the launch sector. Specifically, SpaceX has demonstrated the capabilities of ballistic reusable launchers with vertical take-off and vertical landing capabilities with the successful development and launch of Falcon 9. Although the launcher has demonstrated a high degree of reusability, there are other architecture options which could further decrease costs for access to space and increase its sustainability. This ranges from the use of different recovery strategies [12], methalox and hydrolox propulsion, and developing winged and air-breathing concepts. The established launch providers are responding with evolutionary redesigns of current expendable launch fleets to remain competitive, but eventually, innovation dynamics may lead to technological breakthroughs taking over [13]. To succeed with new ballistic reusable vehicles and other novel concepts, it is important to consider the functioning of early design phases, where the aerospace vehicle concept is being synthesised and several major design options are available. The challenge here is to further increase the level of knowledge available, while increasing the design freedom at later design phases, as seen in Figure 1.

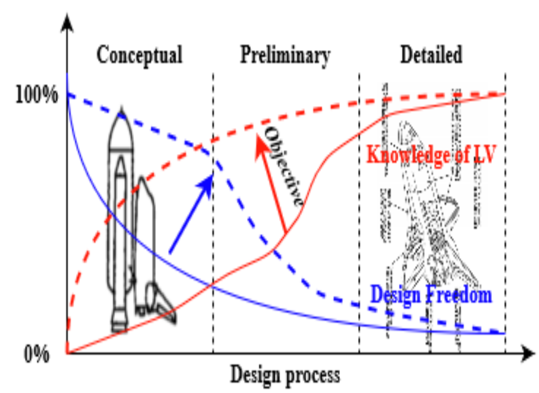


Figure 1 Progression of knowledge and design freedom on launch vehicle design and flexibility during a typical development phase and its challenges. The continuous lines indicate the current state of art in conceptual design, with knowledge on the system capabilities increasing as design progresses at the expense of design freedom. The dashed lines indicate the objective of increasing knowledge at early design stages while also increasing design flexibility. Adapted from [14]

Several strategies and options exist to achieve these, from the use of concurrent engineering approaches, developing a philosophy to "design faster, better and cheaper", managing the risk variable directly, testing as early as possible in the design phase as possible, and automating and optimizing the design process. In early design, this later aspect may include parametric approaches and advanced Multi-disciplinary Design Analysis and Optimization (MDAO), which could also include uncertainty quantification. Different tools have been developed to achieve this [15], progressing from the early monolithic approaches as the Space Shuttle Synthesis Program (SSSP) [16], to increasingly modular and expandable approaches leveraging on MDAO and multi-fidelity techniques.

MDAO in RLV system studies

RLV early design system studies assess full launcher concepts considering various engineering disciplines as aerodynamics and structures. These can be assessed based on various metrics, from its payload performance to orbit to reliability or even cost effectiveness.

MDAO approaches can leverage on the various architectures and optimization strategies to design vehicles optimally, while automating the design process and accounting for the disciplinary trade-offs. The approach is key, given the emergence of highly integrated systems as blended winged body configurations, scramjets, spaceplanes and winged reusable launchers. This has been applied for the design of reusable launchers [17]- [20] and has shown that it can use high level of disciplinary fidelity for early design of expendable launchers [21] [22], while obtaining optimal solutions in acceptable computational time. A typical eXtended Design Structure Matrix (XDSM) [23] for a reusable launcher including major disciplines for the early preliminary design phases can be seen in Figure 2.

Within ASCenSIon, several challenges of MDAO are addressed and activities are being pursued to increase its state of knowledge, including:

- application of relatively high fidelity early preliminary design engineering methods within a MDAO framework, particularly advanced structural design methods based on shin thell theory for structural mass estimation;
- adaptation and integration of legacy tools and methods;
- comparisons between various monolithic and multilevel MDAO architectures with gradient based and global optimization techniques;
- inclusion of uncertainty in the design process;
- integration of additional design metrics for early design, such as reliability and sustainability-based considerations.

The first aspect was addressed for expendable launchers by F. Castellini et al [22], showing that high optimality could be attained while including advanced engineering methods as beam theory approximations for structural design and range safety considerations.

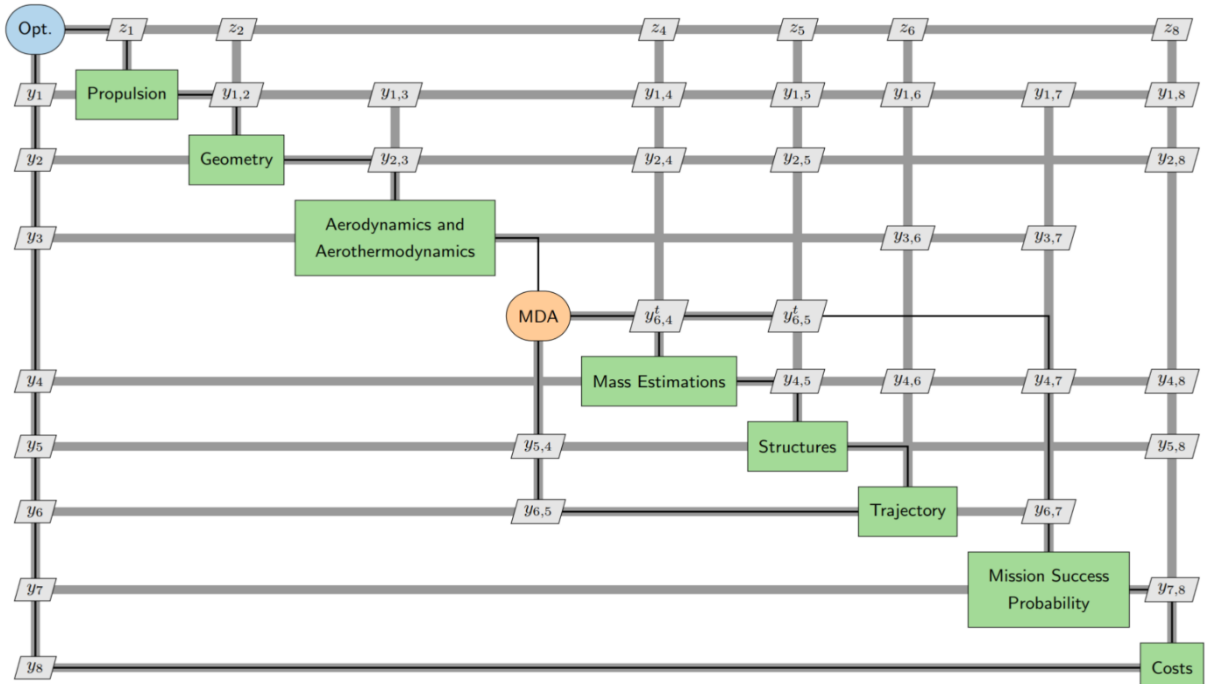


Figure 2 MDAO eXtended Design Structure Matrix for a reusable launcher design process

Within ASCenSIon, this is being studied within the context of reusable launchers. Particularly, advanced fast methods for structural design traditionally applied for expendable launchers [24] [25] and aircraft [26] are being expanded for reusable launchers and MDAO applicability.

The second aspect addresses the potential of monolithic optimization strategies leveraging on gradient based optimization for reusable launch vehicles. In addition, techniques to include uncertainty in the design process are also being reviewed. These allow to obtain robust and reliable configurations considering various sources of epistemic and aleatory uncertainty [27] [28]

Uncertainty based optimization has been applied to MDAO of reusable launchers [20], but challenges remain with the integration with legacy engineering tools and methods, and in the application of multi-fidelity strategies. The latest aspect considers additional design metrics for early design of reusable launchers which can allow for design for cost [29] [30], reliability [31] or even sustainability considerations considering its life cycle [32] and atmospheric impact [33], as done in the aircraft design community [34] [35]. These can support larger trade studies while enabling optimal early designs [36]. In F. Castellini et al [22], reliability and mission success considerations were included in the early design phase of expendable launchers and in [37] for the design of a SSTO hypersonic airbreathing vehicle.

III. PRESENTATION OF THE RLV ARCHITECTURE

Section A Impact of Reusability on Propulsion System requirements

The reusability concept comes with additional system requirements, depending on vehicle mission profile (recovery and re-start modes). In case of a boost-back (or toss-back), they should overcome all the challenges that come from the supersonic re-entry and landing manoeuvres, sustained by retro-propulsion. Some of these technical challenges are [57]:

- management of deceleration and landing;
- stage re-orientation manoeuvres;
- variation of acceleration and module;
- thermal management (propellant tanks, propulsion aft bay, engines, etc.);
- higher operation cycles;
- safety and reliability (flights and ground phases);
- ground operations (costs, efficiency, safety, refurbishment);

These scenarios translate into additional necessities for the propulsive system, and more specifically for the engine [57] (see Table 1). All of these requirements set up high standards from the early phases of the design process. The overall performance (in particular, in off-design) should maximise the payload by overcoming the reusability mass budget. During deep-throttling (down to 20-30% of nominal thrust), sufficient pressure drops at the injectors and flame stability should always

Table 1 - Additional system requirements for RLV engine, derived from SOTA.

Technical Property	Requirement
Deep throttling	30-110% range for a soft landing
Multiple re-ignition	2-3 additional burns for re-entry
Reusability	> 70 times
Steerability	high span, rate and precision [55]

be ensured, together with a precise throttling control that slows down the vehicle during the landing manoeuvres. The engines have to be re-ignitable multiple times, also while facing supersonic and transonic counter-flows. The high thrust capabilities should also ensure redundancy in case of an engine-loss during re-entry (i.e., in case of a failed reignition). Additionally, the requirements imposed on the fracture critical structures such as in combustion chamber or turbomachinery, especially in case of the reusable units, must account for potential failures. As there are no official standards available on how to address the reusability aspects of the modern sustainable LPRE w.r.t. fatigue life analysis and other aspects such as design or components examination, the undertaken approach is to use primarily the standards with the highest sets of requirements to identify the most critical components. For that reason, the human rated space flight mission standardization is predominately employed, where the requirements are of the highest level e.g. NASA-STD-5019, STD-5012B or STD-6016. In addition, the requirements connected with total mission duration and expected number of cycles are implemented to the analysis – that includes e.g.: acceptance test (acceptance hot-fire test before the actual flight), ascent phase, retro propulsion manoeuvre studies. This allows for components suitability evaluation for the specified number of missions with implementation of the predefined operational conditions for a given mission number (e.g. 10 missions).

The requirements for the critical components such as: thrust chamber incl. main combustion chambers subcomponents as well as turbomachines elements, must be identified with respect to Low Cycle Fatigue (LCF) and High Cycle Fatigue (HCF) utilizing various verification methods and through an implementation of the Fatigue Analysis Factor (FAF). Furthermore, a Service Life Factor with demonstration of minimum calculated life of 4x service life for LCF and 10x service life for HCF, as well as stress concentration to account for alternating and mean stress/strain to encompass for the impact of the stress concentration factor must be shown [58] [59] [60]. Although the above mentioned requirements may be demanding, it is the Responsible Fracture Control Board (RFCB) which assures the technical compliance with given requirements as well as- in case of the not attainable requirements- it is RFCB responsibility to review the specific case with Fracture Control Plan (FCP) as well as "…develop, interpret, and approve fracture control requirements and the responsibility for overseeing and approving the technical adequacy of all fracture control activities at the Center." [58].

Another important aspect to be considered for reusable system is the high demand on requirements for TVC, such as rapid response (deg/s rates), higher degree span and precision level, always come with a Ground, Navigation & Control (GN&C) system of excellence, able to correct re-entry trajectories in real-time and to reach safely the landing site with a high precision level (order of meters). More in general, the additional requirements also extend to the overall propulsive system (incl. feed-line and propeller tanks) [57] [61]:

- propellant cinematic and anti-sloshing control (critical in boost-back manoeuvres);
- propellant pressure control (thermodynamics);
- tanks (cryogenic) thermal insulation;
- engine, fluid equipment and feed lines protection (aerothermal flux, pressure field);
- propulsion system control after landing (pressure, leakage) & durability of the components;
- operational and refurbishment costs, safety measures during ground phases;
- maintainability & Inspectability;

The general idea that one could get from the previous lists of high-level requirements is how deeply reusability impacts at design level since the early phases. It is common in space industry to adopt design models derived from existing stages and propulsion technologies, in order to rely on established technologies, reduce costs and convince sponsors more easily. Nevertheless, the approach pursued by SpaceX and Blue Origin nowadays is to tailor the design to recovery/reuse requirements from the early phases of design process. In this perspective, it is considered a necessity to design, build and fly European RLV demonstrators so to gather solid knowledge of VTVL technologies [62] [63] and to favour an agile approach [64] [65] for design and development, in order to iterate the upcoming version after each flight. This approach needs the rocket and its subparts to be predisposed for rapid access, so to ease detailed inspections, maintainability and for safety purposes. Furthermore, the recover requirements should not impact the propulsion/vehicle design process only, but also include a higher demand on operation engineering for safety during the ground phases following the recovery. In this perspective, automation offers alternative solutions that could support the human operations.

Section B Advanced Nozzle Concepts (ANCs) – System Requirements and Mission Constraints

Advanced Nozzle Concepts (ANCs) [38] are a category of solutions for the propulsion systems that aim to increase the overall performance through the adoption of novel architectures for the nozzle extension, alternative to conventional bell nozzles. The concepts addressed here for reusable main stage applications are Dual Bell (DB) nozzles and Aerospike Engines (AEs). Despite of major achievements for ANCs in the past decades (in particular for aerospike nozzles [39]) towards their application to launch vehicles main stages, nowadays they still do not find applications due to their low Technology Readiness Level (TRL) [40]. This is even more true for reusable main stage applications, neither in space agency programmes or commercial space projects. Most of the information about State-Of-The-Art (SOTA) [39] - [41] rely on previous campaigns on concepts, mostly by space agencies, academic projects and demonstrators.

AEs, already achieved considerable mass savings w.r.t. a comparable conventional engine (up to 20% for a spike truncated to 25% of its theoretical length) [42]. A linear aerospike demonstrator, by NASA, reached up to 429 s of I_{sp} and about 1 MN of thrust [43] [44], while in more recent years, complex geometries for combustion chamber, spike and cooling channels were achieved through Additive Manufacturing (AM) techniques [45] [46] - [47]. Moreover, AE offer the possibility to avoid gimballing and achieve Thrust Vectoring Control (TVC) through differential throttling or secondary fluid jet injection [48] - [49]. The first one involves clustered chambers on the spike that can be throttled down in order to achieve TVC, the latter adopts secondary fluids injection in specific points on the spike, in order to modify the momentum distribution in the expansion flow-field and generate side-forces for TVC. In case of annular AEs, a single annular chamber maximizes the performance, weighs less and the effort for regeneratively cooling the continuous throat gap is equivalent to a cluster of up to 16-chambers [42]. Nevertheless, clustered chambers are still considered an option, even though increasing the number of chambers limits the altitude performance gain due to losses for non-optimal expansion on the spike and adds complexity to the propulsion system and to the regenerative cooling [39]. In conclusion, the continuous altitude adaptation behaviour and the engine-on/off steerability makes AE good candidate for reusable main stages sustained by retro-propulsion, even though the research on this application is very limited.

The DB nozzles, as well, could offer performance gains thanks to their step-wise altitude adaptation. Recent studies investigated methods to control the transition phase between the operative modes [50], increase the predictability on its behaviour and limit the hysteresis phenomena. Other studies addressed the main difficulties deriving from design optimization (parametric investigations on inflection point and contouring) [51], as well as aspiration drag and side-load generation [52] in supersonic co-flow testing. Even if DB nozzles inherited certain inefficiencies (aspiration drag above all), they still offer performance advantages for a relatively lower mechanical complexity, difficulty in cooling and cost w.r.t. aerospike engines. This combination of performance, simplicity, low weight and ease of cooling supports further investigations on DB nozzles also for RLV applications.

Another ANC is the Expansion-Deflection Nozzle (ED) that was also initially considered for Main Stage applications. Even though altitude adaptation up to the geometrical expansion ratio is possible, as in case of the Plug Nozzle it is inferior leading to a comparatively limited sea level performance [116]. According to [53], [54], [38], the main reasons are aspiration and overexpansion losses. In addition, high performance can only be achieved by small throat gaps leading to cooling difficulties. This forced compromise in connection with complex design [53] led to comparatively little interest since the 60s. However, studies by former EADS Space Transportation GmbH showed that a possible ED nozzle substitute for the Vinci engine that was originally planned for the Ariane 5 upper stage would result in a better thrust to weight ratio compared to conventional configurations, due to shorter nozzle lengths. This promises a possible payload gain and is therefore the main reason why ED nozzles are finding again more interest connected to upper stage applications. Hence, they will not be further considered in this publication.

Recently, ANCs got back in interest for commercial space projects [55]- [56] and military applications. On the other hand, this makes reliable data less and less attainable. This lack of information encourages the research to investigate their applicability for reusable main stages in-depth, which is one of the purposes of this paper. In Section A the impact of reusability on propulsion system requirements coming from SOTA, and more specifically from vertical landing sustained by retro-propulsion, was addressed. This offers a starting point for tailoring ANC's to the novel mission profiles and to put in evidence foreseeable advantages that come from the adoption of ANCs on reusable main stages.

As already mentioned, the Plug and Dual Bell nozzles are possible concepts for Main Stage Applications. The primary expansion area of Plug nozzles can be designed with a continuous gap but also with a cluster of modules exhausting onto the plug surface. Primary nozzle partitioning enables lower thermal loads, higher thrust vector capabilities by differential throttling of modules as well as easier manufacturing and cooling. These advantages contrast with losses due to three-dimensional flow inside the modules and interactions of jets exhausting from adjacent modules. Geron et al. [69] investigated different shapes of the internal expansion modules and concluded that care should be devoted to the design of module shape since it is a critical element for the nozzle performance. Numerical 3D simulations have been performed for modules with squared exit planes since this yield the lowest module thrust loss among all possible rectangular shapes. The supersonic jets were charged over a single linear plug surface, designed by the Method of Characteristics (MoC). The results show that the change from vertical wall nozzles to round to square nozzles reduces the thrust coefficient by round 1.3%. By adding a gap between the modules, with a width as big as one module, a possible module failure can be simulated. Simulations show that, in this case independently of the investigated module shapes, an efficiency reduction in terms of the thrust coefficient CF of around 3% would result [69].

Within plug nozzles, a distinction can be made between linear and circular/ axisymmetric plug nozzles. According to [38] both types show similar performance behaviour and flow field development as a function of the ambient pressure. However, this will change if the nozzle is considered in full length or truncated [38]. Only truncated plug nozzles have real practical interest due to less length and structural weight and the fact that the performance is not dramatically changed by the truncation [70] [71]. Therefore, only they will be discussed in this paragraph. Like in conventional nozzles, there are different operational modes also for plug nozzles, significantly affecting the performance. For low pressure ratios P_c/P_{amb} (see Fig. 3-1, low altitudes) the nozzle is operating in the Open-Wake regime leading to a small thrust loss since the wake pressure is due to the aspiration effect a bit lower than the actual ambient pressure [70] [38]. The aspiration effect finally triggers that the change from Open to Closed-Wake mode happens below the actual design pressure ratio (see Fig. 3-2) leading to a performance loss [38]. Analysis showed that shorter plug bodies (higher truncation) result in an even earlier change in wake flow and therefore to an even bigger thrust loss [38]. However, former experiments have shown that asmall amount of bleed gas, i.e. 1% of the total mass flow rate, expanded to the base area, slightly increases the base pressure during open wake conditions and thus has a positive influence on the plug performance efficiency [70].

For pressure ratios higher than that of the transition point (see Fig. 3-3, increasing altitude) the altitude capability stops and the closed wake pressure remains constant while the ambient pressure further decreases.

Hence, at some point, a positive thrust contribution of the base region is expectable when the base pressure overcomes the ambient pressure. In case of linear plug

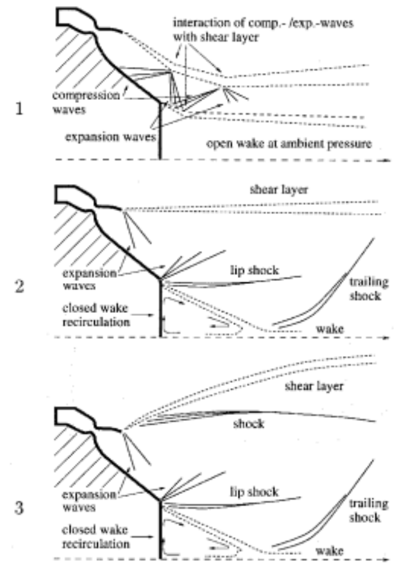


Figure 3 - Flow Phenomena of a Plug Nozzle with Truncated Central Body at different pressure ratios, off-design (top, bottom) and design (center) [38]

nozzles, special attention must be paid to the influence of both sides where a flow expansion is triggered normal to the flow direction. The resulting performance loss can be reduced by end plates like in the X33 demonstrator vehicle [38]. However, due to clustering and truncation, the plug nozzle provides worse performance than conventional bell nozzles for the same area ratio [38]. The external flow surrounding the truncated plug nozzle during its flight operation may also noticeably affect its performance, because of local changes of the ambient properties. Driving mechanism is that with increasing external velocity the shroud base pressure decreases and is lower than the actual ambient pressure [70]. Thus, the base pressure of the plug is affected by these lower pressure values what causes the open/ closed wake transition point to move towards lower pressure ratios reducing the overall performance [70].

In case of Dual Bell nozzles, which are characterized by the absence of any movable parts and therefore its high reliability the primary or base nozzle typically features classical bell shapes or a truncated ideal contour (TIC) [69] [71]. In contrast to parabolic nozzles, the latter guarantees a smoother flow in the core and avoid the occurrence of the internal shocks typical of parabolic nozzles. The second bell starts with a slope angle higher than the first bell ends. In the under-expanded regime the flow is fully attached in the primary nozzle and separates symmetrically at a precise location, the inflection point by generating only small side loads. In this case, the nozzle performance is penalized by the drag of the recirculating flow region in the second bell referred to as aspiration drag [72]. For Dual Bell nozzles in sea-level operation, this is less than 3 % and decreases linearly with

increasing altitude [69]. As the ambient pressure decreases, the operation mode changes to fully attached flow in the second bell, improving the vacuum performance/specific impulse compared to classical bell nozzles [71]. Like for the truncated plug nozzles, the aspiration effect also triggers a flow transition before the optimum crossover point, which leads to further thrust loss as compared to an ideal switchover [69]. The flow transition behavior depends on the contour type i.e. wall pressure gradient of the nozzle extension. As described by a negative wall pressure gradient like in conventional nozzles will lead to best performance but higher risk of side loads in the transition phase. A positive wall pressure gradient leads to a fast and safe transition in terms of side loads, but a lower performance, caused by higher pressure values located at the nozzle end. Hence, a second bell with a wall pressure gradient of zero is the best trade-off between performance and side loads [69] [71] [72].
In case of external flow over the vehicle in flight, the vehicle base pressure is reduced in the region where the engines are installed. Analogously to the plug nozzles, an earlier flow transition is triggered, decreasing slightly the efficiency of the Dual Bell nozzle operating along the trajectory. However, Dual Bell nozzles provide a significant net impulse gain over the entire trajectory as compared to conventional Bell nozzles [69].

<u>1-D Performance Analysis for ANCs adopted in RLVs</u>

In order to have a comparison on performance and payload gains between different nozzle concepts, a 1-D performance analysis comes as a good starting point.

The main goal is to establish the impact of altitude compensation and its efficiency on the overall performance, as well as on the achievable payload gain, for a selected propulsion system and trajectory. The technique adopted in this early phase of development is based one-dimensional nozzle models under ideal assumptions on the working fluid and fluid dynamics [73]. The results will then be corrected with losses on a second iteration.

<u>Methodology and Matlab© tool</u>

The losses due to interaction with ambient pressure (namely, *under-expansion* and *over-expansion*) impact the overall performance in case that the exit pressure is higher or lower w.r.t. the ambient pressure. This can be evaluated in terms of thrust (F) and thrust coefficient (C_F), this latter defined in Eq. (1) [73] [61]:

$$C_F = C_{F_{opt}} + \frac{A_e}{A_t}\left(\frac{p_e}{p_c} - \frac{p_{amb}}{p_c}\right) \qquad (1)$$

with $C_{F_{opt}}$ as *optimum thrust coefficient*, p_e and A_e respectively as *nozzle exit pressure* and *exit area* and p_{amb} as *ambient pressure*, p_c as *chamber pressure* (in isentropic hypothesis also assumed as $p_{c,0}$, or *total chamber pressure*) and A_t as *throat area.*

In particular, the optimum thrust coefficient is defined as the thrust coefficient correspondent to an *optimum expansion* ($p_{amb} = p_e$). Indeed, conventional bell nozzles are designed for a fixed nozzle pressure ratio ($p_{c,0}/p_{amb}$), that maximises the achievable thrust coefficient for a specific value of ambient pressure ($p_{amb} = p_e$). In that condition the optimum thrust coefficient is the only contribution to the thrust [73] in Eq. (1).

In order to evaluate the capabilities of an advanced nozzle to compensate thrust by adapting to ambient pressure, an *altitude compensating factor* ($\in$) [74] [75]. is defined, so that results:

$$0 < \in < 1 \qquad (2)$$

$$p_e = \in \cdot p_{amb} + (1 - \in) \cdot p_e|_{o.d.} \qquad (3)$$

with $p_e|_{o.d.}$ defined as the nozzle exit pressure at design point, fixed by the exit Mach number (M_e) for net flowrate and mixture ratio at design point and (formerly) independent from ambient conditions. This value can be obtained experimentally, derived with CFD simulations or, in early-step analysis, estimated with a 1-D conventional bell nozzle model with same geometrical expansion ratio, flow properties and chamber conditions. When forcing an altitude compensation efficiency by selecting a specific $\in$, the calculated values of p_e and A_e are then used to evaluate the thrust and thrust coefficients. In this case, the values of p_e and A_e are no more the ones on-design, but rather the values that concur to realise the selected $\in$ (i.e., A_e is not the geometrical area, but the flow-tube exit area that realises the requested expansion). The analytical definition of $\in$ is offered by the author, while the concept is taken from Taylor [54] [75]. As for A_e, the *nozzle area ratio* ($\varepsilon = A_e/A_t$) is not the geometrical one, but recalculated in hypothesis of isoentropic expansion through the nozzle [73], in order to realize the p_e associated to the specific value of $\in$.

The 1-D ANC Simulator is a Matlab© tool under development at TU Dresden. It is predisposed to handle a discrete variety of ANCs. Realistic losses depending on the specific nozzle type are not yet considered, even though some qualitative results can already be obtained. More specifically, some of these ANCs are:

- Ideal untruncated annular aerospike nozzle
- Ideal truncated annular aerospike nozzle (UD)
- "Rubber-like" nozzle [73]
- "Rubber-like" nozzle (w/t upper limit to ε)
- Ideal expansion-deflection nozzle (UD)

In particular, the ideal adaptive nozzle, namely "rubber-like" nozzle in literature, realises the maximum adaptation level at any altitude by constantly changing its area ratio (therefore, it is handled as a reference ideal case and not as an actual concept).

The following results consider an ideal aerospike nozzle, equipped with a full-length spike (isoentropic contour). The aerospike nozzle compensates the ambient losses in over-expansion regime, up to its *Nozzle Pressure Ratio* (NPR) of design. Beyond that altitude, the aerospike nozzle does not compensate the ambient losses (that is a reason why usually aerospikes are designed for higher altitudes w.r.t. a comparable bell nozzle). In this instance, eventual losses due to not-ideal expansion over the spike are neglected (they would be limited anyway, if considering a full-length spike with isoentropic contouring).

Gains on Thrust Coefficient with Compensation

A first result comes from a quantitative evaluation of the impact that ∈ has on the performance gains. In particular, this evaluation considers the vacuum version of a Merlin-1D engine (mounted on 2nd stage of SpaceX's Falcon 9 Block 5). Some available engine properties are reported in Table 2.

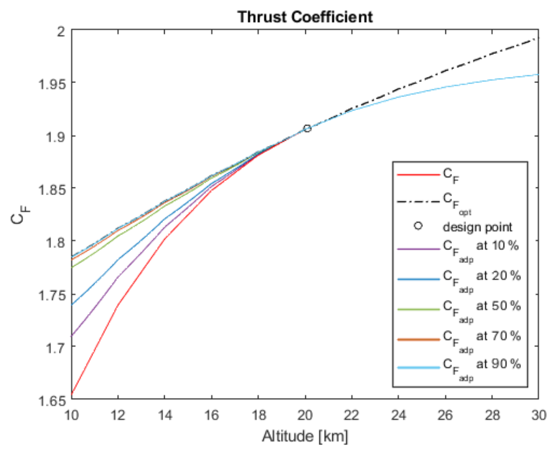
Table 2 – Available data on Merlin-1DV [69].

	Merlin-1DV
Mixture ratio	2.36
Net flow-rate (kg)	236.56
Thrust @vacuum (kN)	805.13
Isp @vacuum (s)	347
Chamber pressure (MPa)	9.72
Pressure exp. rate	3240
Throat area (m²)	0.042
Nozzle exit area (m²)	4.90
Area exp. ratio	117

From a first comparative at 10 km of altitude (off-design conditions for the Merlin-1DV), seems that a 10 % of altitude compensating factor (∈= 0.1) already determines more than 40 % of the total thrust coefficient gain (see Table 3). A 50 % of altitude compensating factor (∈= 0.5) determines more than 90 % of the ideally achievable thrust coefficient, in good accordance with Taylor et al. [74] - [75] and his analysis on expansion-deflection nozzles. The C_F increment reported in Table 3 is defined as $\Delta C_F = \left(C_{F\,adp} - C_F\right)/\left(C_{F\,opt} - C_F\right)$, where $C_{F_{adp}}$ is the thrust coefficient associated to a specific value of ∈.

Table 3 – Thrust coefficient (C_F) increment for different altitude compensating factor (∈) values, for the Merlin-1DV case study.

Altitude compensating factor (∈)	ΔC_F [%] @10 km altitude	
0.00	0.00	%
0.10	+ 42.47	%
0.20	+ 65.12	%
0.50	+ 92.23	%
0.70	+ 97.86	%
0.90	+ 99.81	%
1.00	+ 100.00	%



Thrust coefficient (C_F) for different altitude compensating factor (∈) values at different altitudes close to Merlin-1DV design point (~20 km).

The results from the 1-D analysis available in Table 3 are encouraging, because show that is not necessary to aim to a full-compensation with altitude for experiencing substantial performance gains. This behaviour could support the adoption of ANCs on RLVs, as long as it might result unrealistic to presume a full-compensation during critical manoeuvres such as a Supersonic Retro-propulsion Phase (SRP) or a landing burn.

Section C Fatigue-life Analysis and Health Monitoring of RLV Systems

For the LPRE and the reusable units, the choice of the engine cycle is dictated primarily by the propellant injection pressure, which directly translates to the combustion chamber achievable pressure. Due to the larger chamber pressure and consequently higher thrust, the pump-fed cycles (expander, gas-generator or staged-combustion cycle) are the recurrent choice for LPRE. As these cycles typically operate with a larger number of components, the more demanding control system requirements are enforced. On the condition of selected cycle type, in particular for the transient phases, the sequence planning and engine's fitting features must be envisaged – that includes energy and timing attributes optimization, as well as initial conditions or perturbations (start up in vacuum) [5]. A decisive element of the reusable LPRE, pertaining to multidisciplinary design optimization, is therefore fatigue life assessment of the engine components. Determined by calculated flight performance parameters (w.r.t. component's life, systems response, etc.), the global performance is directly influenced by any change in element's life characteristics, failure margins, etc.

As shown in Figure 4, the direct impact on how the engine cycle is optimized, is often dependent on fatigue life performance of the given component and vice versa. As an example, in case of the fuel-rich staged combustion (FRSC) cycle, the preburner can be operated at a lower mass flow rates, as the turbine can withstand the higher temperature of fuel rich combustion gases. Assuming the same enthalpy of FRSC vs. oxidizer rich staged combustion (ORSC) cycle, the higher mass flow is needed in case of the ORSC, as the turbine inlet temperature must be set to lower. Furthermore, the control over burner gases quality must be assured in case of the oxygen rich gases, where the partial pressure of the oxygen is very high with accompanying fire risk as well as a risk of aggravation of the structural surface by oxidation. Therefore, a FRSC cycle may be considered a more reliable and safer choice for a reusable engine as it does not operate in the oxygen-rich preburner environment. [76]. In case of the SC cycle, a much higher pump outlet pressure on the fuel side is needed to enable a smooth propellant pass through the thrust chamber cooling circuit before entering the preburner. Consequently, it is crucial to avoid sudden drops in the coolant pressure, which has a direct influence on the chamber wall lifetime – as the significant drop of the pressure could result in the rapid increase of the thrust chamber wall temperature, resulting in the life reduction of this component [77].

The control over the principal operating quantities of pressure and mixture ratio in case of the critical components, such as the combustion chamber, must be therefore assured. It may be achieved by means of e.g.: flow-control valve adjustment under given operating limitations which ameliorate some of the features w.r.t. performance and reliability. Within an alternative approach, the combination of the conditional sequences with a constant control over mixture ratio and thrust may be utilized. The wider throttling domain in the thermally and structurally challenging transient phases, is often within the open loop what enforces a low correction margin. Notwithstanding the implemented method – linear or non-linear, these must account for transient behaviour, gain-scheduled switched controllers, large off-line optimised-behaviour, etc. [3] [5] [8].

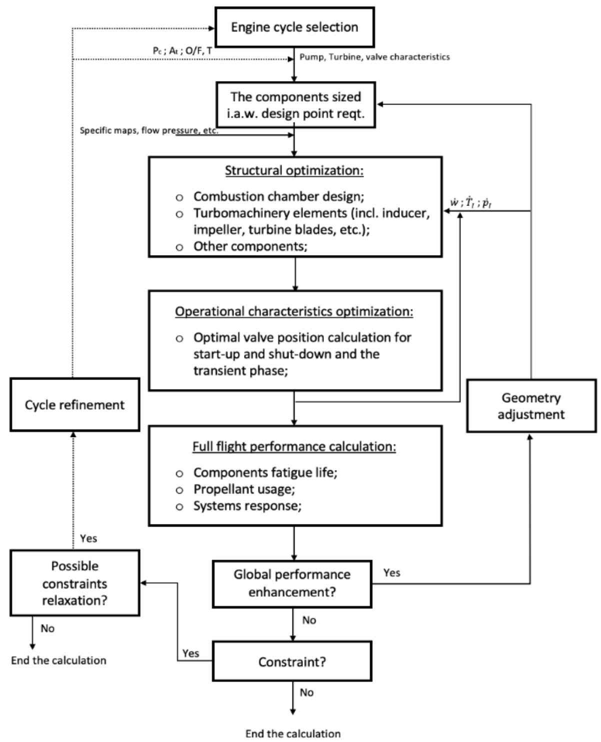


Figure 4 Hierarchical Engine's Multidisciplinary Optimization Flow Chart. The diagram is based on the diagram presented in the [8].

In this context, where the main operating parameters must be evaluated for being able to operate within the pre-defined margins, Health Monitoring plays a crucial role. The fundamental aspect related to HM [78] [79] is its ability to both evaluate the working conditions (referred also as condition monitoring) and predict the remaining useful life (RUL) of the system. Having these capabilities as a reference, it is interesting to denote the benefits and drawbacks of this technology [80]. The former includes: increased safety and operational margins, increased time to respond in emergency states, increased mission success rate, enhanced maintenance scheduling and feasibility (moving from time based to event based), decreased costs, reduced workload for human operators and ground personnel, promoted effective and technical training of the personnel, optimized resource management, increased system life expectance, increased predictivity about the possible future system states. With respect to fatigue life analysis, one of the main aspects is the enhancement of the safety margins. The adequate margin of safety in the component is characterized by the design limit load being greater than the maximum expected load and smaller (due to potential inexactitude of the stress examination) than the calculated damage load. Increasing the analysis precision will lower the allowable margin between the design limit loads and the damaging loads (which encompass: endurance limit, yield and ultimate load). [81].

As mentioned in Section A, the commonly used approach for safety margin evaluation of the critical structures, such as one used in human rated space flight missions, is realized through definition of the Fatigue Analysis Factor (FAF) defined by multiplication by the limit stress or strain e.g. 1,25 for rotating components & 1,15 non-rotating components, and Service Life Factor with demonstration of minimum calculated life of 4x service life for LCF and 10x service life for HCF [60] [58]. These, together with stress concentration to account for alternating and mean stress/strain to encompass for the impact of the stress concentration factor, ensure the effective estimation of the fatigue damage under cyclic loading conditions. With regards to HM, the safety margins can be covered with two different concepts, from which the first one is focused towards promoting an active system reconfiguration and adaptation w.r.t. the operating conditions. This allows for an overall reduction of the required safety and operational margins, given the enhanced capability of tracking the optimal operating point. The second concept is connected with extracting and collecting data in a meaningful way. Once the data is extracted, the system design can be modified to adjust the real operating curve w.r.t the theoretical one. The drawbacks related to the HM subsystem implementation refer to: increased design complexity, increased overall system weight, increased instantaneous power consumption (even if the mean value can be decreased), increased computational performances requirement, increased electronic integration density within the system. Therefore, considering benefits and drawbacks, it is clear that a trade-off in terms of complexity and computational power requirements has to be considered in accordance with the increased analytical capabilities.

Referring to the first of the two main components of HM [81], the condition monitoring part is designed for: being able to detect the specific working parameters in real-time, evaluating the extracted data adopting specific methods (usually based on a thresholding system) and store the reduced indicators of the evaluated condition (on-board or off-board). Clarifying, with the term reduced indicators is considered the entity of minimal size representing the meaningful information related to the extracted data. In the context of condition monitoring, the most interesting part for fatigue life analysis is the parameters investigation section. To define the model, the system parameters can be extracted through: ground testing; design specifications and margin evaluation; flight missions' analysis; literature-based knowledge. In particular, the fundamental analytical methodologies useful to define the parameters are: Finite element analysis (FEA); Fault Tree Analysis (FTA); Fault Mode, Effect and Criticality Analysis (FMECA) and Risk Probability number (RPN) [78]. Consequently, the resulting modelization can based on the following methods, of which the main ones are [82] [80]:

- in model-based algorithms, the system is described by a mathematical model that can have different levels of approximation. This is the most adopted method in HM because of the trade-off in terms of complexity and creation time/efforts. In fact, thanks to the different approximations, the system description can be simplified to the required level, thus reducing the time and computational efforts required for its definition. The simplest implementation of this method, also referred as rule-based method, consists in the definition of rules to be respected by the system;
- the physic-based model is characterized by an empirical approach. In fact, in this case the knowledge of the real physical behaviour of the system is required, and this is the sole approach directly correlating the obtained data with the system physical properties. However, the drawbacks are about time and efforts required for structing the model as well as the computation power required to handling the high number of parameters derived from this approach;
- the data driven method is the latest approach toward system analysis. It is based on two steps: a mathematical model defining the core of the system modelization and a machine learning solution applied with the aim of improving the accuracy of the model according to the incoming operational data. The main advantage of this approach is the ability to adapt different conditions that can be verified during the mission (e.g. forced modification of vehicle trajectory). On the other hand, the main drawback is that severe restrictions are imposed on intelligent computer (e.g. machine learning algorithms) adoption in space systems due to the limited ability of validation. As proposed by Waxenegger-Wilfing G. et al [83], one of the alternatives here could be a usage of e.g. the Bayesian neural networks as a tool to quantify predictive uncertainties, which helps to make the predictions robust to overconfident extrapolations. More about the data-driven methods especially w.r.t. early detection of thermoacoustic instabilities can be found there [83].

In the following table, a summary of the modelization methods is presented.

Method	Main Advantage	Main Disadvantage
Model-based	Relatively simple method to be implemented with the design model of the system	The accuracy of the model depends on the approximations.
Physics-based	More precise model of the system derived from the empirical analysis.	Associated potential high cost and time for establishing the model.
Data driven	Flexibility and adaptability to the operational conditions.	The reasoner is intrinsically less reliable than a fixed model of the system.

Table 4: Summary of the three main system modelization methods.

With respect to the system reusability and a second principal of HM component, the prognostic [84] component consists of: using the extracted data for being able to define a system trend analysis and consequently use various possible methods for defining an index about the remaining useful life (usually based on a comparison between a baseline or a fatigue model with the actual assessed condition). Regarding fatigue life analysis, the most important HM component is the prognostic one with the final goal of predicting the future system condition. To achieve it, prognostic algorithms are required and considering the different possible application cases, the methodology [82] adopted for extracting prognostic data can be based on different approaches:

- the reduced indexes mentioned as result of the condition monitoring phase can be directly used for prediction estimation. This alternative can be adopted for limiting the computational complexity and enhancing the response time at the expense of the accuracy;
- the complete step by step real-time or quasi real-time data extracted from the sensors can be used with the aim of being able to have a considerable coverage of the possible operating parameters, resulting in high accuracy. In this case, the main drawbacks are connected to the increase of power consumption and data management complexity;
- a mix of the two solutions can be selected for having different analytical capabilities w.r.t. the specific application case. This solution corresponds to a trade-off between the previously mentioned alternatives and it allows for a more efficient management of the resources.

With reference to fatigue life analysis, high accuracy is desired for understanding the modifications in material properties and thus, among the mentioned options, the last two are the most adopted. In the following table, it is possible to denote the differences among the different basic implementations for prognostic analysis data manipulation.

Approach	Main Advantage	Main Disadvantage
Reduced Index	Limited set of data in terms of size and number.	Less accurate when compared to other available methods.
Complete data set	Precise estimation data can be featured.	Associated potential high cost and time for processing the data.
Mixed	Optimizable to the application.	Possible additional optimization process needed which could result in the loss of generality.

Table 5: Summary of data extraction approaches for prognostic analysis.

Considering the overall HM architectural level [82], the monitoring capabilities can be based on different approaches:

- monitoring the system as a whole: in this case the goal is to be able to monitor the whole system for detecting overall trends, at the expense of the accuracy and an increased power consumption (considering a comparable coverage w.r.t. the following methods);
- focusing just on some critical units: the purpose here is to be able to extract the most accurate data possible w.r.t. the available resources. This translates in a limited coverage and a higher number of sensors considering a comparable area of analysis;
- structuring a hierarchical model adapting the analytical depth to the specific conditions and computational resources: this is characterized by a sensing distribution relying on the resource capabilities management according to pre-defined guidelines. In this case, the system is based on two main levels: a first layer of analysis, identifying the coarse operating conditions in macro areas and a second layer, focusing on the areas of interested (derived from the coarse analysis).

As in the previous cases, in the following table it is possible to see a summary of the different alternatives about where to focus the analytical capabilities related to the HM architecture.

Methodology	Main Advantage	Main Disadvantage
Focusing on the critical parts	Most accurate data on the critical units.	Limited information or lack of the overall trends.
Complete	Getting data from the entire system.	Potentially less accurate analysis of the system conditions.
Mixed	Optimizable hierarchical system. Application sensitive.	The sensing distribution must be planned carefully.

Table 6: Summary of the analytical approaches with reference to the HM architecture.

At this point, with reference to the presented different implementation strategies for the HM implementation, it is possible to define the one considered as the best approach to address the fatigue life analysis. It is characterized by the establishment of a physics-based model algorithm for the operating parameters evaluation and a hierarchical approach in terms of architecture. The physical-based model is selected because, as mentioned above, it allows a direct correlation between the obtained parameters and the physical properties of the system. Then, in terms of the approach through which to extract the prognostic data, a step-by-step real or quasi-real data methodology can be used for promoting a capillary analysis of the system conditions. Regarding the architecture, the choice is for a hierarchical structure because, in terms of fatigue life, it is necessary to evaluate the system according to different insight levels given that different targets can be present at the same time.

Considering the defined system, based on a hierarchical architecture, the requirements for the sensing units [85] are split according to the architectural level at which the distinct sensors belong. In a multi-layered system concept, the sensors included in the higher layer have to be characterized by high area coverage capability and low to mid resolution. Instead, going down in the layers distribution, more and more accurate sensors are demanded, at the expense of coverage area, for being effective in terms of extracted data assessment. In this way, the total number of sensors required for the application depends on several factors and it must be defined according to a set of rules related to the desired accuracy and system coverage capillarity.

Section D <u>Environmental impact of propellants on RLV lifecycle</u>

The explosive growth of the sector is pushing not only market changes but also policy makers and public interest towards new challenges defining Space Safety and Sustainability. [86] With an eye on Sustainability, the propellant choice for the new generation of launchers raises awareness and brings multiple novel challenges to face, especially when envisaging the vehicles reusability. Indeed, while the performances, cost and availability of propellants remain key parameters during the design of both the main engine and the attitude control system, many other inputs are gaining importance during the trade-off process and may become crucial for future architecture developments.

When involving sustainability, the main ground operations aspects to consider during the propellant selection are, between others, the lifecycle study of the propellant itself, its production, toxicity, storability and handling. Most of these aspects are covered by local government policies. However, despite the many treaties in place, there is still a lack of clear and defined international rules. Regulations have a strong impact not only on the effective use of the propellant itself, but also on its cost and market availability. Europe is, indeed, pushing for a revolution in the sector with the aim of consolidating the “green” approach, which, in case of rocket design, involves, between others, considering effects on the environment [87]. This is only possible through extensive international collaboration.

Toxicity of chemicals is, for example, a well-recognized threat, but still differently regulated around the world. The International Panel on Chemical Pollution (IPCP) is pushing to insert Chemical Pollution at the same level as Climate Change and Loss of Biodiversity as major threat for the planet [88]. Indeed, strong regulations are in place in an increasing number of countries with extensive schemes for both production and importation of materials, but the lack of an international and independent authority makes each government acting on its own with big disparities around the continents. While the very existence of these regulations is indeed pushing the market to reach out for new solutions, the mitigated stringency of these rules leaves a problematic grey area on knowing whether or not dangerous chemicals will ever be banned for good.

Table 7 is an example of how some of the most common propellants have different Global Harmonized System (GHS, [89]) classifications around the world. For example, while there is a worldwide agreement on the toxicity of Hydrazine, other species, like ammonia, display various levels of toxicity and hence are regulated in different ways worldwide. Some other countries do not have strict regulations on these chemicals yet.

Propellant	GHS label	WHO	EU	USA	AUS	JAP
Hydrogen Peroxide	**Corrosive**	X	X	X	X	X
	Acute Toxic	X				X
	Health Hazard	X				X
	Env Hazard					
Hydrazine	**Corrosive**	X	X	X	X	X
	Acute Toxic	X	X	X	X	X
	Health Hazard	X	X	X	X	X
	Env Hazard	X	X	X	X	X
Ammonia	**Corrosive**	X	X	X	X	X
	Acute Toxic	X	X	X		
	Health Hazard					X
	Env Hazard	X	X	X	X	
Hydrogen	**Corrosive**					
	Acute Toxic					
	Health Hazard					
	Env Hazard					
RP-1 (Kerosene)	**Corrosive**					
	Acute Toxic					
	Health Hazard	X	X		X	
	Env Hazard	X	X			
Methane	**Corrosive**					
	Acute Toxic					
	Health Hazard					
	Env Hazard					

Table 7 - Different GHS classifications of common space compounds around the world

Sources:
International: World Health Organization (WHO) and International Labour Organization (ILO) website
Europe: European Chemical Agency (ECHA) website
USA: Hazardous Substances Data Bank (HSDB) website
Australia: Hazardous Chemical Information System (HCIS) website
Japan: Japan Chemical Management Center (NITE-CMC) website

Another often neglected field is the impact of the production of propellants. The focus is usually brought on combustion exhaust products. However, with an expected increase of launches in the future and stricter regulations entering in place to reduce human impact on the planet, the entire lifecycle of a propellant is expected to assume a more important role, which might impact both the cost and availability of some substances. This is especially valid for some common propellants that require very complicated and energy intensive refining and storage processes as well as for others for which current production processes are still far from clean. Considering the lifecycle of a propellant is crucial to understand its real impact to the environment and avoid neglecting important contributes.

The impact of these aspects is increasing with the raise of public attentions and novel regulations in place. The market will therefore need to address these challenges especially during the development of new reusable launch systems that plan multiple launches over short amounts of time, where the cost of handling and storage could then have an increasing significance.

Working Operations Aspects cover an equally crucial role in the choice of a propellant. Indeed, while the propellants performances and properties remain key parameters when considering a new propellant, the increased public and regulator's attention to emissions might make this another crucial aspect to deal with.

While airplanes remain in the troposphere, launchers, instead, emit as well in the upper-stratosphere, which can be more problematic as species emitted there tend to last longer due to the absence of atmospheric convection.

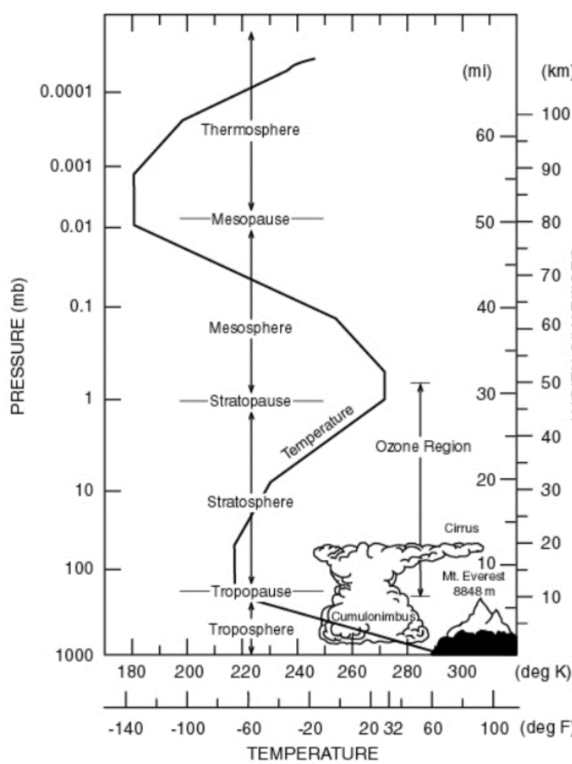


Figure 5- Evolution of Temperature and Pressure with atmosphere altitude [Oxford University Press, 1999]

As shown in Figure 5, in the stratosphere, the temperature remains roughly constant for approximately 20 km before increasing due to the formation of ozone in 40-50 km altitude. Exhaust products directly emitted at very high temperature in these areas can endanger the fragile ozone layer which protects Earth against harmful radiations. In addition, these can also affect the Earths radiative properties and contribute in unexpected ways to anthropogenic climate change. This issue becomes more concerning at a time where space tourism is growing so popular and where space travel will boom in the next years/decades. As referred to in [33], rocket launch exhaust plumes, regardless of the propellant type, all contain nitrous oxides (NOx), hydroxide (OH), and water vapor (H_2O), which lead to ozone depletion, and some contain non-negligible quantities of black carbon and other aerosols which may contribute to climate forcing [119], [33]. In addition, certain exhaust gasses contribute to localized toxicity levels and affect air quality. While the impact of rocket emissions on the environment may vary significantly from one propulsion system to the other, this issue needs to be carefully looked at and quantified in order to safely boost space activities without damaging our environment [91]. Indeed, while there were some significant studies made on Solid Rocket Motors rockets, the lack of information on LREs is concerning. The effect of these aforementioned chemicals on our atmosphere is still unknown, but may be dramatically harmful. This issue requires more data to first be quantified and then controlled to approach launchers in a greener way.

Foreseeable green developments

New developments are needed not only for the booster engines but also for the entire propulsive system, including attitude and reaction control thrusters of the launching vehicles. Indeed, since during the early stage of a generic Reusable Launch Vehicle (RLV) reentry flight, the atmospheric forces are still too small to allow a complete vehicle control, the presence of a Reaction Control System (RCS) as major attitude control device is necessary [92]. Currently used technologies are cold gas, mono-propellant or hypergolic bi-propellant systems, depending on mission requirements and necessary thrust level. Each one has advantages and disadvantages from a performances point of view, but one of the main problems of the mono- and bi- propellant systems is that most of the applications rely on hydrazine or its derivatives like Monomethyl hydrazine (MMH). Hydrazine is a well-known space propellant used since the 1960s, it has good performances and supports cold start, which means it ignites when put in contact with a catalytic bed. Unfortunately, it is also a very toxic agent, harmful for both the humans and the environment, which requires elaborate safety measures to be handled [87] [93]. This increases the overall cost and complexity of the systems, as well as extends the health and safety risks. Hydrazine is currently in the EU's list of Substances of Very High Concern (SVHC) even though it has been the most commonly used rocket propellant for decades.

A lot of efforts are made in various research centers to find a valid alternative to hydrazine, using substances usually referred to as 'green propellants'. Defining and categorizing these substances together with their effects on human health and environment is a complex and multifaceted task, but it is nonetheless a key passage to identify worthy alternatives to current technologies. Some substances are known from decades and some related technologies are certified. However, the majority of applications are still immature and need more developments and tests. This is especially valid considering that some of the alternative substances, such as Hydrogen Peroxide or some ionic liquids, have materials compatibility issues or generate a very high combustion temperature.

It is clear that an alternative to Hydrazine is foreseeable and possible, but money and effort must be invested on its development and use. Progressing the Technology Readiness Level (TRL) of alternative propellant technologies will allow not only the replacement of dangerous substances, but also a potential reduction of cost and increase of performances.

While the effects of main stages emissions in the upper atmosphere are yet to be fully understood, the consequences of using some other toxic substances are well known. A shift from these harmful compounds to safer ones is foreseeable not only for main stage applications but also for other space operations such as upper stages and satellites propulsive systems [91].

Section summary

With an increasing number of launches expected in the near future, identifying a non-toxic and environmentally-friendly propellant becomes truly important. However, the current lack of international consensus on toxicity and environmental regulations makes this task a real challenge which must be addressed. Indeed, understanding the effects of the chemical fuels on human health and on the environment is crucial to foresee a sustainable long-term development of space activities. First, the effects of LREs exhaust products must be evaluated to then be minimized in a second time. Many parameters and still unknown or not well-understood regarding that issue but there are already some alarming signs that the problem may be significant.

IV. SUMMARY AND CONCLUSIONS

Within this paper various design strategies for reusable launch vehicles which are currently being developed within the ASCenSIon consortium were presented. The capabilities to thoroughly compare different RLV concept at early design stages aims to leverage on fast and efficient engineering methods suitable for early conceptual stages in combination with surrogate and multi-fidelity approaches. In addition, different systematic design methodologies for reusable launchers based on parametric design methods, and deterministic and uncertainty based MDAO were synthesised. Furthermore, the main aspects of the modern RLV systems were discussed including:

- MDAO methods for RLVs – MDAO shows promising characteristics that can increase system design loop efficiency while achieving larger optimality. It is also fundamental to quantify uncertainty in our engineering models and include it in the design process at early design phases;
- impact of reusability on high-level requirements for the propulsion system – which favours novel approaches and concepts from the early phases of design. These requirements come as consequence of boost-back manoeuvres and within our paper have been organized in lists: one specific for the engine and a more general one for the overall propulsion system;
- the current SOTA for aerospike engines, dual-bell and expansion-deflection nozzles with references to the most recent studies and European projects;
- methods towards fatigue life analysis of the most critical LPRE components and health monitoring implementation using methodological decisions – w.r.t. space systems as well as fatigue life analysis for RLVs. It was shown that the best solution is represented by a hierarchical and physics-based system. The distribution of sensors capabilities following from the hierarchical level is based on an inverse trend of analytical coverage and data extraction accuracy moving from the high to the low architectural system layers;
- environmental impact in the context of the increasing number of launches and the importance of identifying a non-toxic and environmentally-friendly propellant. The possible approach to launcher system from a propellant point of view could be greener concerns the attitude control thrusters included in the propulsive system of main stages. While this kind of system is often relatively simple and located in the upper stage, it holds in store many future innovations with e.g. the switch from the most common but very toxic hydrazine to new and more human- and environmentally-friendly compounds often referred to as "green propellants".

Outlook

The future work within the ASCenSIon will address the integration of reliability considerations as the ones described in within the MDAO process. With these activities, it is expected to advance the state of art of MDAO with applicability to large scale synthesis of reusable launchers at conceptual and preliminary design stages. Furthermore, the development of concepts connected with propulsion and mission analysis are currently researched. This includes the trade-off studies on the RLV architectures with a particular focus on the LPRE as well as recovery strategies. In the frame of our research, the propulsion modelling for reusable LPRE application incorporate 3 main aspects:

- ability to evaluate the health status of a given component including diagnostics techniques regarding fault – detection, propagation analysis, isolation and identification with the aim of specifying the category, source and severity of the fault [94] as well as, prognostic tools for extrapolating the parameters about remaining useful life of the system;
- tailored design methodology suitable for designated number of missions with given engine architecture supported by the system level simulation (SLS) and EcosimPro ESPSS - European Space Propulsion Simulation Toolkit used for propulsion modeling;
- in-depth studies with evaluation of the remaining life of the critical components (e.g. combustion chamber or turbine blades) through damage accumulation/creep life prediction models combined with and FEA and programming tools.

These methods and programmes allow for the holistic level representation of the compound engineering problems, accounting for aspects connected to fluid-, structural-, and thermodynamics. The methodologies explained in the previous section will be applied to perform architecture trade-offs of RLVs considering also TSTO and 3STO vehicles, and various recovery strategies from vertical landing to horizontal glide back of main stages.
Future investigations on advanced nozzle concepts for main stages applications will be conducted, aiming to both experimental and numerical results, so to enlarge the database on advanced nozzles in retro-flow scenarios. The current version of the Matlab© tool assumes chamber temperature, pressure ratio, molecular mass and specific heat ratio as constant. Nevertheless, these factors have a critical impact on the evaluation of c, c*, A_e/A_t, v_e/v_t and Isp and further iteration of the simulator will consider also variations for off-design performance, different chemical equilibrium models, mixture ratios and propellant combinations (in general, the more complex the molecule, or the higher the temperature, the lower the value of γ [73]). The models will also include realistic losses due to transition between operative modes [38] [52], non-isoentropic expansions and realistic exit condition (3-D phenomena).

Nomenclature | Acronyms | Abberviations

Nomenclature

γ	Isoentropic exponent
ε	Nozzle area ratio
ϵ	Altitude compensating factor
A_e	Nozzle exit area
A_t	Nozzle throat area
c	Effective exhaust velocity
c*	Characteristic Velocity
C_F	Thrust coefficient
C_{Fadp}	Adapted thrust coefficient
C_{Fopt}	Optimum thrust coefficient
F	Thrust force
Kg	Kilogram (mass unit)
I_{sp}	Vacuum Specific Impulse
m	Meter (distance unit)
N	Newton (force unit)
p_{amb}	Ambient pressure
p_c	Engine chamber pressure
p_e	Nozzle exit pressure
p_w	Wall pressure
Pa	Pascal (pressure unit)
s	Second (time unit)
v_e	Gas velocity leaving the nozzle
v_t	Gas velocity at nozzle throat

Acronyms/Abbreviations

1-D	One Dimensional
3-D	Three Dimensional
AE	Aerospike Engine
AM	Additive Manufacturing
ANC	Advanced Nozzle Concepts
ASCenSIon	Advancing Space Access Capabilities Reusability and Multiple Satellite Injection
BD	Dual-Bell
CFD	Computational Fluid Dynamics
ED	Expansion-Deflection Nozzle
FAF	Fatigue Analysis Factor
FEA	Finite Element Analysis
FMECA	Fault Mode Effect and Criticality Analysis
FTA	Fault Tree Analysis
GEO	Geostationary Orbit
GNC	Guidance, Navigation & Control
HCF	High Cycle Fatigue
HM	Health Monitoring
LCF	Low Cycle Fatigue
LOx	Liquid Oxygen
MDAO	Multi-disciplinary Design Analysis & Optimization
NASA	National Aeronautics and Space Administration
NPR	Nozzle Pressure Ratio
RLV	Reusable Launch Vehicle
RPN	Risk Probability Number
RUL	Remaining Useful Life
SITVC	Secondary Injection Thrust Vectoring Control
SOTA	State-of-the-Art
SSSP	Space Shuttle Synthesis Program
SSTO	Single Stage To Orbit
STD	Standard
TSTO	Two-Stage To Orbit
TRL	Technology Readiness Level
TVC	Thrust Vectoring Control
VTVL	Vertical Take-off, Vertical Landing
XDSM	eXtended Design Structure Matrix

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