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Trade-off study of green technologies for upper stage applications

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ABSTRACT

As an emerging trend, Green Propulsion has been exponentially growing over the last decades in the space sector.
This paper assesses different technologies in a trade-off study weighting their applicability to a specific class of upper stage systems currently developed by many companies and often referred to as kick-stages or orbital stages.
In a generic two-stage-to-orbit scenario, many launchers require a system able to go the 'extra-mile' to deliver one or multiple payloads on orbit(s). That is where the kick stage comes into playing a crucial role.
The trade-off study reported here is based on a well-known decision-making tool, the Analytical Hierarchy Process, and is divided into two parts: low-thrust class engines such as monopropellants, including pre-mixed blends, usually employed for attitude and reaction control; and high-thrust engines such as hypergolic bi-propellants combinations used for apogee manoeuvres.
Hybrid thrusters are also considered in the analysis with a dedicated parallel trade-off.

1. INTRODUCTION

Storable and performant propellants are investigated since the start of the space era: good storability properties and hypergolicity are two of the most wanted features for new propellants.
As a matter of fact, the ideal system would be indefinitely storable without any time constraints nor dedicated hardware, and would always be operational, possibly ignited only by mixing a fuel and an oxidizer.
The latter property, usually referred to as hypergolicity, was discovered almost by chance. Since then, hundreds of combinations have been tested experimentally in order to measure their respective response time.
Around the 60's, a fuel asserted its position in the sector for its good properties, namely strong performance, good storability and hypergolicity with a low response time. This fuel is Hydrazine.
Hydrazine was initially discovered in Germany just before the Second World War and was initially recognized as potentially exploitable. Its difficulties of production and danger of storage, however, quickly discarded it. After a few years, USA researchers made its production and storage easier and commercially available, discovering its derivatives of Unsymmetrical dimethylhydrazine (UDMH) and Monomethyl hydrazine (MMH) [1].
Since then, these Hydrazine-based fuels, hereafter referred to as Hydrazines for simplicity, conquered the space sector and still represent the most used propellants for space applications that cannot involve cryogenic operations, for which more suitable fuels exist. One of the most appealing advantages of the compounds is that pure hydrazine can also be easily decomposed through a catalyst and has good performance as monopropellant.
Despite their outstanding properties, Hydrazines also have a major draw-back: they are mildly toxic and require specific handling care.
In general, a fuel development evolves very closely to its coupled oxidizer(s). Storable oxidizers are very rare. Most of the suitable compounds are either extremely toxic, explosive, or hard to handle and in general dangerous. Human compatibility with the substances becomes a problem if the compounds need to be daily handled in big quantities. Hence, the long-term storability requirement acquired a new shade: it is more affordable to handle a hard-to-manage compound occasionally if it is stable and can stay in place for long periods without excessive surveillance.
The historical candidates where research focused were members of the Fuming Nitric Acid family (Red, RFNA; White, WFNA; and the safer brother Inhibited IFNA), but their extreme danger and corrosion features, together with their not optimal performance, made them inconvenient to use [2].
The other prominent substance, easy and cheap to produce, well-performant and storable is Nitrogen Tetroxide (N_2O_4, hereafter referred to with its acronym NTO) that has become the primary storable oxidizer. The only non-negligible

disadvantage is that it is extremely toxic and dangerous, very incompatible with humans.
The most used propellants for space applications which require long-term storability and good performance such as the in-space propulsion scenarios are, indeed, Hydrazines and NTO.
Over the years, the number of safety procedures around these propellants has increased, stimulating the research on easier-to-manage alternatives. These alternatives are, usually, referred to as "Green Technologies" although some of them show high, but not comparable, level of handling risk [3].
Very often, these alternatives are reviewed as stand-alone technologies. In this study, they are instead assessed as possible replacement of toxic propellants-based engines for a specific class of upper stages: the kick-stages.
The kick-stage is firstly described as a system, outlining its main requirements, in Section 2.
The following section describes the type of technologies assessed in this study. The candidates have been selected using a holistic requirements approach not only focused on performance.
Section 4 then provides a description of the method used for the trade-off: the Analytic Hierarchy Process (AHP).
Section 5 is a discussion of the analysis results. The two main outcomes of the study are:

- The definition of an evaluation framework, specifically refined for kick stages purpose, but applicable to more generic systems. The framework is flexible and can be customized and tailored in future iterations but it is also robust, being based on general requirements of the system.
- The trade-off results for the kick-stage system. The analysis outlines three classes of selected technologies: low-thrust, high-thrust and hybrid rocket motors.

2. KICK-STAGES

A new class of space system is currently being actively developed worldwide with the perspective of optimizing the launch cost for each specific payload: the kick stage. Sometimes referred to as tug stage, it is a modular element of the launcher, mounted below the fairing on top of the upper stage, with the role of increasing the versatility of the launcher in performing a wider range of missions.
A relevant example is the kick-stage developed by the New Zealand company Rocket Lab, powered by the brand-new Curie engine, that has already extended its capacity since its first flight in 2018 from delivering a specific satellite on a precise orbit to becoming a re-ignitable system capable of placing multiple payloads onto diversified orbits, [4].
This ride-sharing capability has the potential, like any public transport, to cut the price of launching a single payload to space while increasing the probability of safe delivery.
With the drastic increase of the space activities and the limited access to orbit resources currently available, the kick stage services have the potential to stand as a key profitable actor of the upcoming space market.
The rising number of similar systems currently being developed plainly highlights the need of increasing space access efficiency. A non-exhaustive list of the systems in development around the world that have, between others, the goal of multi-payloads delivery is shown in Table 1.

Company	**Device name**	**Location**
Avio [5]	Space Rider	EU
Ariane Group [6]	Astris	EU
Rocket Factory [7]	Orbital Stage	EU
Skyrora [8]	Space Tug	UK
Rocket Lab [4]	Kick Stage	NZ – US
MOOG [9]	SL-OMV	US
Andrew Space [10]	Sherpa Tug	US
Launcher [11]	Orbiter	US
Momentus Space [12]	Vigoride	US
Northrop Grumman [13]	MEV	US

Table 1 - A non-exhaustive list of kick stages with similar capabilities in development or in-use around the world

Currently, small satellites have to rely on other bigger payloads to be able to afford the launch. This practice is usually referred to as *piggy backing* and satellites that follow this procedure must rely on their own propulsive system to reach their final orbit. For them, sharing a common propulsion system onboard of the kick stage that will place them into – or close to – their final orbit not only simplifies the design of the satellites, but also allows to either reduce the propellant on-board or to use that extra-propellant mass to stay on-orbit, generating reward.
In addition to the generic increase of the payloads delivery capability, the kick stage also stands out by the diversified types of missions it can accomplish. On top of the multi-orbit deliveries, it could also execute new missions tackling the emerging needs of the space environment, such as space debris removal missions.
Optimising the GNC strategy for this multi-orbit delivery is not an easy task as both the visitation sequence and the transfers must be optimized. The direct requirements to the propulsion system coming from the outlined capabilities pose new challenges to designers. The propulsive systems should, indeed, have multiple re-ignitability capacity and must possess a very high Δv capability. The kick-stage must, moreover, possess a full and reliable thrust-control to perform these series of manoeuvres.
Together with the more "classic" functional requirements, the set of demands that a kick stage system must execute to fulfil the mission is challenging at least.
From a mission point of view, following the detachment from the launcher, the kick stage is on its own, and behaves as an added stage.

The purpose of this study is not to show a complete nor technically accurate set of requirements, but instead to consider a use-case scenario to identify points of view and demands possibly neglected during the analysis. A relevant mission envelop is used as a method to validate the identified propulsive system requirements and show that they are representative for the system.
The selected case for this study is a delivery to GEO mission with 5 payloads. The injection accuracy will be key here, as each payload only has onboard a limited capacity for orbit correction.
The main function allocated to the propulsive system is then to provide the right amount of thrust in the right direction the right number of times. Following the GNC sequence established, the kick stage can then go on and deliver the first payload on its orbit, raise the orbit to deliver the second payload and so on until the end of the to-orbit mission.
A detailed mission analysis will give more specific inputs on the mass of propellant needed onboard. Rough estimations assessed that a Δv of about 4 km/s for high thrust systems (such as chemical rockets considered in this study) and of 6 km/s for low thrust systems (typical continuous thrust, electric systems) are required to reach GEO orbits if injected in LEO.
However, these numbers shrink to 1.4 km/s and 1.7 km/s respectively if injected directly to the Earth-Moon Lagrangian 1 (EML-1).
Since the previous upper stage propulsion system is likely to deliver more thrust than the kick stage, the ride onboard of it should be maximised and the propellant tanks loading onboard of the kick stage should be flexible to accommodate different types of missions starting from different injection orbits.
The payload distribution onboard is an important input for the establishment of the GNC sequence and therefore the kick stage design should be carefully examined already in the early stages.
Reliability has recently positioned as an important input to consider early on in the design of any space vehicle as more user-friendly tools are currently developed. This should especially be accounted for in the design of the kick stage as it is the part of the launcher that stays the longest in orbit. Enabling propellant tank passivation at the end of life also comes as a direct requirement for the propulsive system.
This innovative service-provider will significantly enable space access and hopefully allow new actors, especially emerging companies, to expand their activities. Developing this novel system, also offers the opportunity to implement novel, and more eco-friendly, technologies such as green propulsion, which will be the focus of this paper. While the opportunities offered by this new type of space vehicle are truly promising, successfully performing these new missions comes with a hard set of new requirements.
This gives the possibility to re-think the propulsive system design since the project initial phases, integrating green alternatives.

3. TECHNOLOGIES CONSIDERED

Technologies referred to as “Green” are multiple, and the definition itself loses its strength when many fundamentally different concepts are included in the same definition.
Finding a good replacement for Hydrazines is a goal that many research centres and companies around the world have embraced [14], [15].
The approach followed to select the most suitable technology for a new kick-stage system in this study is entirely based on system requirements [16].
Performing a system analysis using the widest possible point of view, the starting point of any basic design, allows to identify the main system requirements.
While these requirements may significantly vary depending on the system developed and on the customers, many of the desired features for novel technologies are very similar. The analysis of the desired features allows to distinguish between what in this study is referred to as ‘Mandatory Requirement’ and ‘Trade-Off Requirement’. The main difference between these definitions is the type of boundaries they apply to the analysis: the former applies hard limits to the considered technologies while the latter gives more freedom.
Mandatory Requirements are used to exclude unsuitable candidates, Trade-Off requirements to choose the best possible prospect.
The main mandatory requirements, or hard limits, used to exclude technologies from the analysis revolve around three main pillars:

- Health & Safety
- Storability
- Performance

The first criterium, from which, to some extent, derives the definition of “Green” technology, is the danger for the personnel involved in the handling of the propellants and their related technologies. It is commonly recognized that compounds employed in space propulsion are dangerous, and the use of propellants that possess some level of risk is accepted. Nevertheless, the primary goal of this study is to find the best option that has the least impact on human health and safety with the least use of protective suites or dedicated devices.
The labels of “Toxic” or “Dangerous” are based on the Global Harmonized System (GHS) for Acute Toxicity Classification (ATC) and Explosives.
In particular, substances are classified based on their Lethal Dose (LD_{50}) in case of oral or dermal exposure, and Lethal Concentration (LC_{50}) in case of inhalation. Substances can be allocated a grade, in a 1 to 5 scale, that defines the Acute Toxicity Estimation (ATE). Category 1 is the most toxic and category 5 is the least toxic.
For direct comparison, Table 2 explains the categories while Table 3 shows the categories

containing most of the used compounds according to the European Chemical Agency (ECHA): Hydrazines and NTO.

Category 1	Substances with high acute toxicity. Fatal if swallowed, in contact with skin or inhaled, even at the lowest doses.
Category 2	Substances with high acute toxicity. Fatal if swallowed, in contact with skin or inhaled, at mild exposure.
Category 3	Substances with mild acute toxicity. Toxic if swallowed, in contact with skin or inhaled.
Category 4	Substances with mild acute toxicity. Harmful if swallowed, in contact with skin or inhaled.
Category 5	Substances with relatively low acute toxicity but which, under certain circumstances, may nevertheless pose a hazard to vulnerable populations

Table 2 - Toxicity categories according to the Global Harmonized System [17]

Hydrazine	**MMH**	**UDMH**	**NTO**
Category 3	Category 2	Category 2	Category 1

Table 3 - Toxicity categories of most used propellants according to ECHA [18], [19]

The following analysis excluded substances with a toxicity score lower than 4 [18].
The other high concern regarding health and safety is the fire and explosion hazard. While rocket propellants must be inherently energetic to fulfil their purpose, this study does not consider substances labelled as Unstable Explosive by the GHS.

Regarding the second source of mandatory requirements, storability, the requests come directly from the customers and eventual users of the system.
As previously mentioned, a kick-stage is integrated in the launcher system inside the fairing and hence assembled a considerable amount of time before the launch. It follows that, as soon as the system is loaded, it is vital that it remains stable without supervision while waiting for the conclusion of ground operations and during the launch phase.
Another challenge to consider in order to fulfil the main requirements of the kick stage is that the system operates in orbit with manoeuvres that may last hours if not weeks. During this time period, the propulsion system must always be reliable and working at its best, without any loss of performance. NASA is actively researching on cryogenic compounds storage for space applications that are energy-efficient, mass-efficient and cost-efficient (project eCryo [20]) but the technologies are not yet mature enough and will probably be expensive.
The above described reasons are only the major motivations for excluding cryogenic compounds from the analysis. As the cryogenic cut-off is not easily identified, this study considers as storable a compound which is liquid, in a non-supercritical form, in a specific temperature range from -50°C (223K) to 30°C (303K).
The final, but of fundamental importance, feature that is considered when looking at a propulsive system is performance. There are many metrics to measure the performance of a space propulsive system, the most used is the specific impulse (I_{sp}). While other parameters are used to select the best propulsive system and are better described in the trade-off criteria section, the I_{sp} gives a precise measure of the efficiency of the propellant usage and is used as cut-off to exclude some technologies from the study due to insufficient performance.
The picture that the specific impulse portraits is, nevertheless, considered limited for this study purposes. While a high specific impulse is key for a well-performant engine, this parameter alone does not necessarily minimize the system weight. Indeed, even though a well-performant engine requires less propellant for a defined mission, if the propellant is not dense enough, its volume and tanking mass grow accordingly and result in an overall higher inert mass of the system.
Propellants with lower specific impulse than hydrazine but higher density are often considered at the same level, if not better. For this reason, this study considers the Volumetric Specific Impulse (ρI_{sp}) as cut-off parameter since it takes into account both the specific impulse and the propellants density.
The cut-off values used in the study are the ones of Monopropellant Hydrazine, which has an estimated Volumetric Specific Impulse of 240 s g/cm^3, and the ones of the bipropellant MMH/NTO system that have a value of 391 s g/cm^3.This second value was calculated for a bi-propellant system according to Equation 1, where ρ_{fu} and ρ_{ox} are respectively the densities of fuel and oxidizer and R is the Oxidizer to Fuel ratio utilized (usually the optimal value).

$$\rho\, I_{sp} = I_{sp} \frac{\rho_{fu}\, \rho_{ox}(1+R)}{\rho_{ox}+R\, \rho_{fu}} \qquad \text{(Eq. 1)}$$

Other performance requirements come from the Use-Case scenario outlined in Section 2.
The main one is that the propulsive system must be able to re-ignite reliably multiple times.
In summary, the hard-limits described above and used in this trade-off study to exclude candidates are:

- Storable fuels: Technologies involving non-cryogenic fuels and with a reasonably high freezing temperature
- Non-Toxic Compounds
- Non-Unstable Explosive Compounds
- Volumetric Specific Impulse better or equivalent to Hydrazines
- System capable to re-ignite

3.1. Technologies included in the trade-off

The technologies assessment is divided into two main parts: the low-class thrust engines analysis, mainly used for Reaction and Attitude Control Systems (RACS); and the high-class thrust technologies survey used for apogee manoeuvres. The latter is subdivided into a study of liquid technologies and of hybrid motors.

While the technologies are often very similar and often interchangeable once scaled, the two classes have slightly different requirements.

For RACS system, low-energy compounds and related technologies used as monopropellants are often suitable, while they hardly may be applicable for well-performant apogee motors. RACS usually have requirements of small ΔV and contained thrust. For these systems monopropellants are the natural choice because of their simplicity, cost efficiency and proven reliability despite of their often low performance.

Apogee motors, on the contrary, have higher ΔV and thrust requirements and for them any added spill of performance is crucial and allows a more diverse range of missions.

It is recognized that many candidate technologies offer synergies if applied to specific architectures. The infinite dilemma of choosing the best technology for a defined architecture or the best architecture for a fixed technology is not analysed in this study.

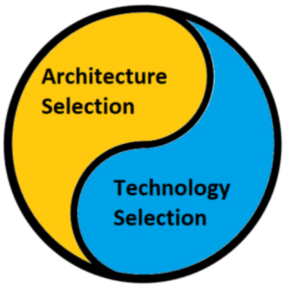

Figure 1 - Architecture and Technologies selection

The trade-off described in this study is based only on the technologies themselves. The possible opportunities and synergies arising are only partially approached during the trade-off and will be further investigated in future iterations of this study.

A potential synergy example, identified since the beginning, is the possible utilization of a bi-propellant or hybrid motor with oxidizer/fuel exploitable also as mono-propellant. This possible scenario opens to different considerations that are not studied in this trade-off.

The number of existent green propulsion technologies or under development in the low-thrust range (up to 100N) is wide [21]. As for any technology, the first iteration is usually maintained small and a few Newton-force application is the most suitable. Nonetheless, many technologies are designed to be scalable, especially the ones involving high energy compounds.

The complete description of the technologies is considered out of scope for this study.

The selected technologies for RACS systems considered in this trade-off study are:

- HAN monopropellants formulations:
  - AF-M315E or ASCENT, [22]
  - SHP-163, [23]
  - HNP225, [24]
- ADN monopropellants formulations:
  - FLP-106, [25]
  - LMP-103S, [26]
- High Grade Hydrogen Peroxide (HTP), [27]
- Nitrous Oxide-Hydrocarbon blends, [28], [29]
- Gelled monopropellants, [30]
- Self-Pressurising bi-propellants (couple Nitrous Oxide/Propene), [31]

Many of these technologies are studied since decades, but only a few of them have already flown in small satellites. Their application to bigger and more complex systems such as a launcher stage is undoubtedly a challenge, but a feasible and realistic one.

Apogee engine technologies are selected between the ones with a Volumetric Specific Impulse greater than Hydrazines but also with a vacuum Specific Impulse greater than 300s with a combustion chamber pressure of 10 bar. As mentioned, the high ΔV requirement demands a higher cut-off performance. Technologies considered are:

- Kerosene + High Grade Hydrogen Peroxide (HTP - 98%), [27]
- Ethanol + High Grade Hydrogen Peroxide (HTP - 98%), [32]
- Nitrous Oxide-Hydrocarbon blends, [28], [29]
- Energetic Ionic Liquids (EILs) + High Grade Hydrogen Peroxide (HTP - 98%), [33], [34]
- Gelled propellants + High Grade Hydrogen Peroxide (HTP - 98%), [35], [36]
- Self-Pressurising bi-propellants (couple Nitrous Oxide/Propene), [31]

For apogee motors, a parallel trade-off has been performed for hybrid rocket engines. This class of chemical propulsion systems has received increased interest over the years, due to the low cost and environmental impact, high safety, and good performance. As several sounding rocket launches and more recently the SpaceShipTwo suborbital spaceplane proved the reliability of the technology, hybrid rocket engines are currently being developed also for launcher upper stages [37], and a scaled version may also be applied to kick-stages motors.

The technologies considered are a combination of the following oxidizers:

- High Grade Hydrogen Peroxide (HTP 98%)
- Nitrous Oxide (N_2O)

And of the following fuels:

- High Density Polyethylene (HDPE)
- Paraffin-based fuels
- Hydroxyl-terminated polybutadiene (HTPB)

4. TRADE-OFF METHOD

A trade-off study is, in its core, a decision-making process. Many methods exist and have been developed in the last decades to measure and quantify human pronouncement, recognizing that also decisions taken with the most rational methods may be strongly influenced by biases or lack of information [38].

Trade-off studies are usually performed at the beginning of projects or programs, when there is not yet a clear understanding of the complexity, dependencies, and reuse potential of the product to develop.

It is the role of the system engineers to deal with complexity and guide the choices in the most rigorous way possible. As knowledge about a system develops, prioritization of choices evolves accordingly in iterations. It is often stated that in the end the numbers and choices derived from a trade-off study are not as important as the understanding that comes out from the process itself.

Trade-off studies are more effective when carried out in multi-disciplinary teams, even though this often bounces back in terms of time and resources to allocate.

The study described in this paper has been carried out using the Analytic Hierarchy Process.

The Analytic Hierarchy Process is a methodology for decision making developed by Prof Saaty in the 70s [39], but refined in the following decades. Its main purpose is to make the process of making decisions as trackable and documented as possible. The technique is based on a systematic assessment of the alternatives that concur to the defined goal by making pairwise comparisons for any chosen selection criteria [40].

As obscure as the definition may sound, it is a very effective and robust method if correctly applied. Figure 2 shows graphically the type of pairwise comparison described: the criteria are compared between themselves to find their relative weights and each alternative is, only then, individually compared with the others against all criteria.

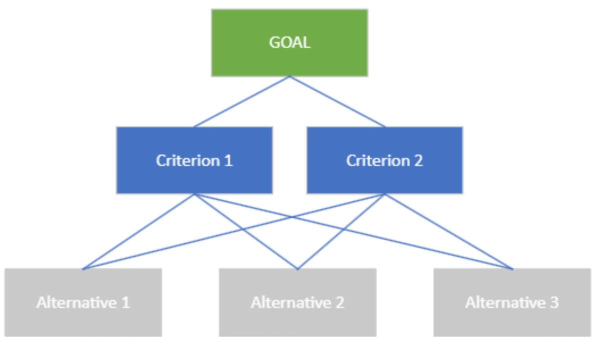

Figure 2 - One-Level Analytic Hierarchy Process with three alternatives

The processes of weighting the criteria and comparing the alternatives are very similar but independent. The latter feature represents one of the major strengths of the method: any choice may be reviewed in future iterations without modifying excessively the created framework.

One of the main purpose of the study is, in the end, to create a robust framework to judge different technologies. The application of the created framework and the deriving discussions that follow up can be considered a validation of the method itself.

The mentioned framework corresponds to the given relative importance of each evaluation criterion, and it can be modified and tailored to specific systems in future iterations.

Considered technologies and new arising candidates are in continuous development in accordance with research. The proposed framework allows modifications measuring the consistency of choices. Future iterations of the trade-off will allow a more precise and detailed choice and will require only a fraction of the time that a new analysis would request.

The AHP is considered by the authors the ideal process to identify the relative importance between requirements and to select the best option between very similar alternatives.

Its application in this analysis is constructed around the following steps:

- *Main goal identification*
  The main purpose of the study is to select the most suitable green technology for its application to a future kick-stage

- *Evaluation criteria identification*
  The desired features for the future propulsion system, coming level-down from the system requirements.

- *Construction of evaluation criteria hierarchy*
  The identified criteria are analysed by paired comparison to find their relative weights

- *Analysis of the technologies*
  The selected technologies are assessed against the criteria

- *Decision making*
  The results are analysed and discussed. The necessary checks on consistency and acceptability of results are carried out during the process.

Once the main goal and the evaluation criteria are identified, the bulk of the process is the construction of a hierarchy between them, or the assignment of importance weights.

The AHP method is based on paired comparison by assigning an importance score between two criteria using a standardized scale in a range 1-9.

While this scale is customizable, the team decided to use a generic and easily applicable range. The scale is reported in Table 4 - Comparison scores. Intermediate values can be used to express more accurate evaluationTable 4.

Intensity of Importance (score)	*Definition*
9	Extreme more importance
7	Much stronger importance
5	Essential or stronger importance
3	Moderate importance of one over another
1	Equal importance
2, 4, 6, 8	Intermediate Importance for compromises between values

Table 4 - Comparison scores. Intermediate values can be used to express more accurate evaluation

The comparison between criteria is made following the rationale:

For the goal I want to reach, is it more important Criterion 1 or Criterion 2?

If Criterion 1 scores 3 times more important than Criterion 2, the contrary will be its reciprocal and Criterion 2 will be 1/3 more important than Criterion 1. Supposing N evaluation criteria, the pairwise comparison will create an NxN matrix, called Comparison Matrix.
By using simple algebraic operations, it is possible to compute the consistency of the pairing performed and the relative weights assigned to the criteria.
By consistency of judgement it is meant that if A is 3 times greater than B and B is 2 times greater than C, automatically A should be 6 times greater than C. Unfortunately this scoring is not always applicable to real life problems and our judgement is very often, if not always, inconsistent in the big picture. Luckily, the consistency of the scoring is measurable by using a parameter called Consistency Index. To be sure to have been consistent, the Consistency Index of all Comparison Matrices should never be greater than 0.1. For a deeper description of the method, look at [38], [41], [42].
It is recognized that the mathematical justification of the method is one of its strength but also one of its major drawbacks: mathematics does not mean high quality of decisions. Factors such as bad judgement, wrongly posed questions or insufficient expertise in the decision-making team strongly influences the process.

5. TRADE-OFF RESULTS

The trade-off results reported here are divided into two sections: the trade-off criteria hierarchy and the analyses of technologies.
The creation of the evaluation framework is the first result of the study. Once the framework is created, and after a detailed survey of technologies is carried out, its application is straightforward.
One of the main strength of the AHP is that the method allows to measure the consistency of the choices made and to correct and improve the results in following iterations.
The following sections describe the results obtained.

5.1. Trade-Off Criteria Hierarchy

The identification of the main goal and evaluation criteria is, doubtlessly, the most important passage of the entire trade-off process.
Missing important details in the evaluation criteria means not considering potentially crucial requirements and performing a poor choice for the final user.
The analysis is based on a kick-stage requirements study. While it may not be the most accurate possible, as explained, the AHP is an iterative process and future iterations will allow the refinement of the analysis and the expansion to other technologies.
The trade-off criteria are all based on system requirements.
The identified goal is to select the best and most promising propulsion system for a generic kick-stage. The evaluation criteria, considerable as desired features for the future propulsive systems, used for the selections are:

- *Performance*: the alternatives must show an improvement in performance with respect to existent toxic technologies. Performance criterion is then split into sub-levels or level 2 criteria, on which all the alternatives are evaluated:
    - *Volumetric Specific Impulse*
    - *Combustion Temperature*
    - *Storage easiness*
    - *Other Features (Easiness of re-ignitability, response time)*

- *Health & Safety*: even though there is a hard requirement to the process that does not allow to select potentially harmful technologies, there are different grades of safety. The criterion is split into level 2 criteria:
    - *Toxicity*
    - *Explosion Danger*
    - *Footprint production*

- *Technology Readiness Level*: it is important for the market. A technology still immature needs more investments to be developed, and the risk of arising issues should be considered.

- *Cost Reduction:* the cost reduction that new technologies may bring to the sector is evaluated only in a “market” environment. The research cost to develop the technologies is hence not considered. The identified sub-criteria are:
    - *Production Cost Reduction*

- *Future potentiality*. The criterion is a measure of the flexibility of a technology, especially on its complexity and judged potentiality of scalability.

   - *Ground Operations Cost Reduction*

The described criteria are visually shown in the flowchart in Figure 3.

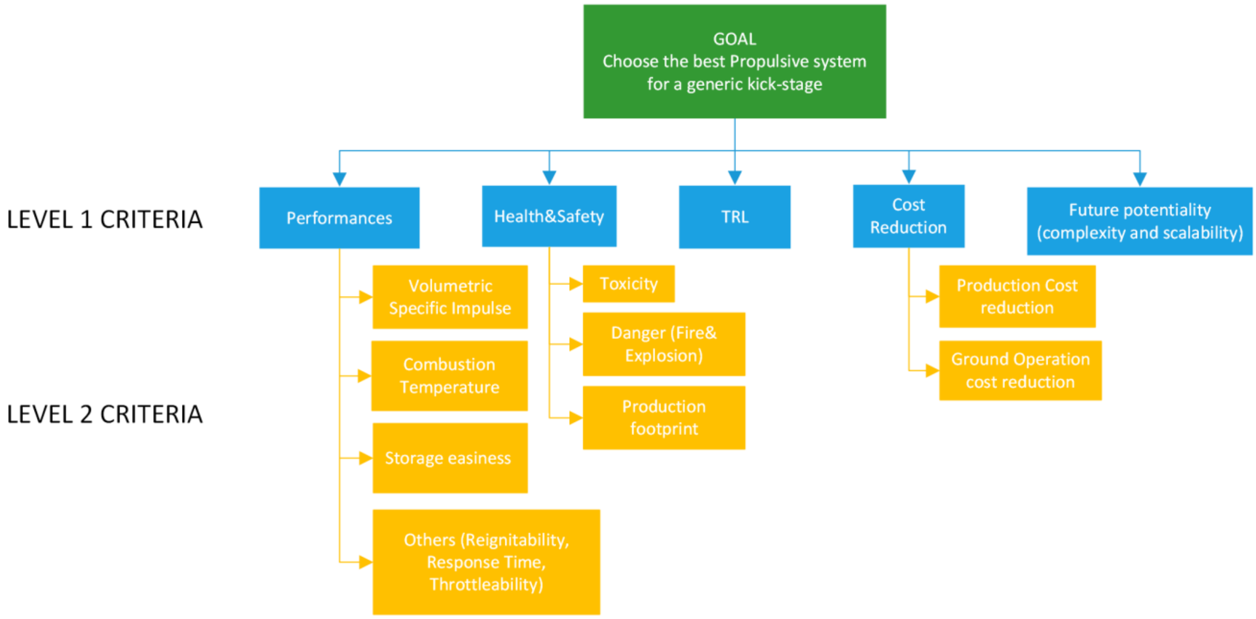

Figure 3 - Evaluation Criteria Flowchart

X/Y	**Performance**	**Health & Safety**	**TRL**	**Cost Reduction**	**Future Potentiality**	**Weights**
Performance	1.00	1.82	1.65	1.00	4.16	**0.304**
Health & Safety	0.55	1.00	2.29	1.65	1.82	**0.246**
TRL	0.61	0.44	1.00	0.84	3.11	**0.171**
Cost Reduction	1.00	0.61	1.14	1.00	1.96	**0.194**
Future Potentiality	0.24	0.55	0.32	0.51	1.00	**0.086**

Table 5 - Comparison Matrix for Level 1 evaluation criteria

An example of Comparison Matrix, for the Level 1 criteria is shown in Table 5.
The scores of the matrix are computed as the geometrical mean of evaluations made by different people. The geometrical mean is considered by experts in the field the most accurate method to consider divergent and different judgements [42].
The Consistency Index of the Matrix is 0.05 and it is hence considered reliable while mirroring the authors' judgement.
The importance weights obtained by the scoring process are shown in the last column of the table. The weights are reported also in Table 6 in percentage values for simplicity and readiness purposes. The explanation of the numbers is that good performance concur to almost one third on the final choice of the best propulsion system for the considered kick-stage, while the future potentialities have around one tenth of the total importance.

	Weights
Performance	30%
Health & Safety	25%
TRL	17%
Cost Reduction	19%
Future Potentiality	9%

Table 6 - Evaluation Criteria Level 1 Weights

The same procedure is applied to the sub-criteria, the results are reported in Table 7 and Table 8.

	Weights
Volumetric Specific Impulse	50%
Combustion Temperature	29%
Storage	10%
Other (Re-ignitability, Response Time)	11%

Table 7 - Performance Sub-Criteria Weights

	Weights
Toxicity	16%
Danger (Fire & Explosion)	75%
Production footprint	10%

Table 8 - Health & Safety Sub-Criteria Weights

5.2. Technologies Trade-Off

Once the evaluation criteria framework is set, the process of decision-making shifts to a more measurable field.
The technologies are evaluated against the criteria using defined scales. Some evaluations still required a level of judgement, which is accounted for in the final decisions.
According to the Analytical Hierarchy Process, the best procedure to evaluate all the alternatives would be to compare each technology against the others, creating a comparison matrix with all the technology for each evaluation criteria.
The magnitude of the task increases with the number of evaluation criteria. In the case of this study, there are 11 comparison matrices to create: TRL, Future Potentiality, Volumetric Specific Impulse, Combustion Temperature, Storage Easiness, Other Features, Toxicity, Explosion Danger, Production Footprint, Production cost reduction and Ground Operations cost reduction.
The method reliability is higher when the number of alternatives considered is below 7. For this study a different approach has been used that, at the price of a small loss in judgements accuracy, it allowed to not exclude any technology from the analysis a priori.
All technologies have been evaluated against the criteria using scores 1-5 in dedicated scales. An example is shown in Table 9 for the Volumetric Specific Impulse, TRL and Future Potentiality. The first two parameters are easily quantifiable by surveying research and state of the art while the latter requires a certain level of judgement.
The scoring has been performed at the best knowledge of the participants, and the level of uncertainty is discussed in the conclusions.

Evaluation Scales

Score	TRL	Volumetric Specific Impulse	Future Potentiality
1 – Poor	2-3	< target	Difficult scalability, no synergies foreseen
2 – Fair	4-5	≃ target	Possible scalability, Limited synergies foreseen
3 – Good	6-7	+10% target	Possible scalability, Existent synergies foreseen
4 - Excellent	8-9	+25% target	Easy scalability, Existent synergies foreseen

Table 9 – Examples of Technologies Evaluation Criteria Scales

After the scoring is completed, the ranges are normalized and the final score of a technology is obtained by the formula:

*∑(score * sub-criterion weight * criterion weight)*

The obtained values for the considered technologies are reported in Table 10.
Hydrazine has been included in the study for direct comparison with technologies currently in use.

Technology	**Final score**
Hydrazine	70%
AF-M315E	**100%**
SHP-163	**98%**
HNP225	87%
FLP-106	88%
LMP-103s	**96%**
H_2O_2 monopropellant	72%
Nitrous Oxide/Hydrocarbon blends	70%
Gel Propulsion	84%
Self-pressurising Combination (N_2O-Propene)	**95%**

Table 10 - Final scores of green technologies for low-thrust RAC systems

There is a "winner" but it does not clearly stand out against the others.
The technology that scored an overall higher result is the AF-M315E, a US-developed HAN-based monopropellant. The compound, now called ASCENT, has flown in a demonstration mission with outstanding results [22].
Other technologies scored above 90%. It is useful to consider all of them because, as mentioned, a high level of uncertainty connected to personal judgements is inherent to the system.
The other technologies that scored almost at 100% are another HAN-based propellant, developed by the Japanese MHI called SHP-163, the Swedish ADN-based monopropellant LMP-103s and the self-pressurising combination N_2O-Propene ([23], [26], [31]).
While these technologies are not the clear "winners" of the selection process, they should nonetheless be taken into high consideration, since a small trim of the requirements or a quick development of their

technologies could, as a matter of fact, easily change the judgements and make them the first choice.
The first four technologies listed in the table are all Energetic Ionic Liquids. This class of monopropellants is the most promising in replacing Hydrazine as monopropellant. They are a blend of different salts, water and fuels and, with great effort, can be tailored to different requirements.
Their prospect is well-known since years, and the time seems favourable for their wider application.
The outlier in the selection is the self-pressurising couple. While weaker than the fellows in terms of performance, it is an exceptionally efficient solution in terms of mass and especially cost for low thrust applications. The company Dawn Aerospace has already successfully deployed these systems.

The scores for the main engine technologies are reported in Table 11.
Contrary to the RACS analysis, the selection of the main engine is clearer and more defined. The clear winner is Kerosene coupled with High Grade Hydrogen Peroxide, with the other contenders distanced by more than fifteen percentage points.

Technology	**Final score**
MMH/NTO	**84%**
Hydrocarbon bipropellant combination (Kerosene + H_2O_2)	**100%**
Hydrocarbon bipropellant combination (Ethanol + H_2O_2)	**88%**
Hydrocarbon bipropellant combination self-pressurizing (N_2O-Propene)	79%
Energetic Ionic Liquid + H_2O_2	**87%**
Gelled Propellants + H_2O_2	**84%**
Nitrous Oxide/Hydrocarbon blends	72%

Table 11 - Final scores of green technologies for high-thrust apogee manoeuvre systems

The separation is strongly connected to TRL levels of the technologies. The couple Kerosene-HTP is studied from decades. Although it has received many stops and found issues in the years, it is cyclically re-considered. It is considered, by judgement and collected data, the most promising fully storable and "green" replacement for MMH/NTO.
As for the monopropellant case, it is very useful understanding the other high-score technologies.
The combination Ethanol-HTP may be promising, a few tests have been carried out in the past, but the technology still needs optimization and finalization work [32].
The use of Energetic Ionic Liquids as bi-propellant is currently studied by DLR in Germany [33]. The combination shows hypergolic behaviours and higher performance than kerosene, comparable with MMH/NTO. If its TRL would rise enough, the technology will doubtlessly be able to compete at the same level of Hydrazines [34].
Gelled propellants are a promise of the past not yet fully realized. Their potential is outstanding, but a few technical issues over the years have slowed down their full deployment in the market. New discoveries and studies may easily unlock their potentialities in the next few years [35].

The final analysis has been performed for another, sometimes omitted, class of green technologies: hybrid engines. The analysis is very useful to test the flexibility of the selection framework created. While it was supposed to be applied only to liquid engines, it is broad enough to be applied to diverse systems such as hybrids. The resulting scores are reported in Table 12.

Technology	**Final score**
H_2O_2 – HDPE	**100%**
H_2O_2 – Paraffin-Based	91%
H_2O_2 – HTPB	**96%**
N_2O – HDPE	**97%**
N_2O – Paraffin-Based	88%
N_2O – HTPB	93%

Table 12 – Final scores of hybrid rocket engines for high-thrust apogee manoeuvre systems

The hybrid propulsion systems analysed for the trade-off are based on propellant combinations which have been successfully proven in sounding rocket flights. Moreover, due to the physical separation between fuel and oxidizer, the fire and explosion dangers during handling and operations are lower than other solutions.
While the separation between the scores is not high, due to the similarity of the solutions, some difference in the results can be identified. In particular, Hydrogen Peroxide-based engines scored higher on average, due to the increased performance. The latter feature partially compensates the low handling easiness of HTP due to the decomposition risks during storage. The considered types of engines have a Volumetric Specific Impulse which is close to bipropellant MMH/NTO systems.
The lowest scores are obtained by paraffin-based fuels. This category of liquefying fuels have been successfully fired for long burning times [43], have a good performance and a lower production footprint. They also have a higher regression rate, up to one order of magnitude more than HDPE or HTPB, that allows to increase the thrust level of the engine without affecting the total mass of the system [44]. While these characteristics are ideal for sounding rocket and launchers applications, they

provide a lower flexibility when applied to kick-stages [45], which reflects in the final scoring.

6. CONCLUSIONS

A few words need to be spent on the results from the analysis. The applied method, the Analytic Hierarchy Process, gives a mathematical justification to human judgement, but it also creates some risks in the decision-making, summarized as:

- *Wrong evaluation framework*:
  Some important information are missing and the judgement is then incomplete. The solution and attenuation in this case is the iteration of the method and continuous improvement
- *Wrong or insufficient expertise of the judges:*
  While a great amount of attention has been dedicated to the research and review of available information, it is very easy to miss a point.

Having used mathematical artifices does not guarantee the precision of the outcome.
Iteration of the process helps to spot the missing points and helps in the prioritization and decision making, but a sensitivity analysis should always be performed before the “real” final choice.
A reasoned and justified choice includes both human judgement and technical solutions and the Analytic Hierarchy Process, if correctly applied, has the capability and potentiality to gather and merge both.

The selection analysis performed in the paper allowed two main results:

- The creation of an evaluation framework, capable and applicable to multiple and different technologies. While the accuracy and precision of the method has been studied and tested, future iterations of the same procedure will improve it and allow an even more accurate decision-making tool publicly available.
- Three technologies have been selected applying the framework
- For a generic kick-stage, the selected green technologies are:
  - ASCENT for RACS
  - HTP/Kerosene for Apogee
  - HTP/HDPE in case of hybrid engines
- Other technologies have been surveyed and thanks to the method the most promising are easily spotted:
  - Energetic Ionic Liquids as monopropellants
  - Self-Pressurising combinations for low thrust
  - Energetic Ionic Liquids in bi-propellant mode
  - Gelled propellants

Future studies will explore the possible synergies of these technologies. With Hydrogen Peroxide as oxidizer for the bi-propellant mode, it could be a natural choice to use it as monopropellant despite its poor performance. The save in terms of mass having a shared tank could, as a matter of fact, be greater than the loss of performance deriving from its use.
Great quantities of Hydrogen Peroxide are, unfortunately, dangerous for degradation of the compound and increase of internal pressure that grows exponentially with the quantity of liquid.

7. AKNWOLEDGMENTS

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Figure 4 - ASCenSIon project logo

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