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New Strategy to Preliminary Design Space Launch Vehicle Based on a Dedicated MDO Platform

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Abstract

This paper presents the methodology and the optimization strategy applied by Bertin Technologies for over 10 years to perform space launch vehicle design and implemented by using the property software platform HADES V15.0. The problem formulation consists in finding the best launch vehicle concept i.e. the one minimising launch cost while satisfying technical, mission and architecture constraints (payload mass on final orbit, number of stages, propulsive technologies…). The strategy is based on a Multidisciplinary Design Feasible (MDF) approach coupled with the use of Genetic Algorithms (GA) for global optimization, and Gradient-Based Algorithms for final tuning and results refining. HADES V15.0 platform provides the associated software environment integrating a number of technical and economic modules consistently interconnected within a system optimization loop. The main disciplines taken into account in the platform are related to the launcher's propulsion, structure, aerodynamics, trajectory optimization and costs. The use of an integrated platform for multi-objective and multi-disciplinary optimization enables an efficient process and quick optimization. This methodology is particularly well fitted to the design of a small space launch vehicle, allowing to take into account the multidisciplinary nature of such a complex system and to manage the inherent sensitivity for this kind of vehicle. This platform was particularly used to design Bertin Technologies' cost-effective expandable Space Launch Vehicle (SLV) for Microsatellites, ROXANE, and to design the space launch vehicle in the H2020 ALTAIR project.

1. Introduction

A Space Launch Vehicle (SLV) is a complex system [1], and its design demands close involvement of many disciplines and strong interaction between constitutive subsystems in order to satisfy mission requirements. As showed in Fig. 1, propulsion, structure, aerodynamics, flight mechanics, navigation, guidance and control, vehicle avionics, stage auxiliary systems, thermal control, integration and test aspects, all participate together to the definition of a launch vehicle. Disciplines and subsystems design and performances are closely interdependent. That makes final SLV design and performance optimization a complicated problem to solve, which includes some specificities like equality constraints and very sensitive parameters. Historically, launch system designers used to apply an analytic approach to initiate an iterative design process [2] with the only objective to maximise performances. Actually, this was the right method at the time when launch vehicle constantly evolved thanks to technology progresses supported by huge economic investments. Today, space sector undergoes a genuine revolution and in this new space era, market needs require both high performances and cost-effectiveness of the space assets. This led to an evolution of the system design and exploitation approach strongly oriented to find the best compromise between constraints and technical and economic objectives in order to ensure both reliability and profitability (Fig.1). In the last decade, the number of space missions based on relatively low-cost small satellites has increased and, most recently, several commercial projects based on huge constellations of micro-satellites (< 250 kg) are in development. This opens the door to a new market opportunity for services providing dedicated orbital access to this class of satellite. New small launch vehicles are then necessary to fulfil this new need. In this new context built around lightweight and cheap payload, the development of such a system does not necessary require the best performances. The main development driver becomes the capability to offer an affordable launch service. It is then clear that applying a design approach purely based on performances criteria, designers can pass through more interesting concepts in terms of cost. Using direct cost criteria has however, some disadvantages and it adds complexity especially on the initialization of the process. Hopefully, Multidisciplinary Design Optimization (MDO) techniques can handle this complexity by providing a series of tools well adapted.
The design of a Space Launch Vehicle (SLV) is a multidisciplinary problem dealing with the need to handle several

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physical phenomena, a multitude of variables, complex interfaces and strong interdependencies at system and subsystem level. Multidisciplinary Design Optimization (MDO) techniques allow simultaneous handling of all relevant technical disciplines (trajectory optimization, aerodynamics, propulsion, structural mechanics, etc.) as well as economical drivers (Design-to-cost based module) ; indeed they provide the capability to identify the optimal solution by fast exploration of several design concepts and limiting design iteration loops. This leads to a final design ensuring optimized performances together with substantial costs saving and risks mitigation.
The work presented in this paper relies on ten years works and improvements to demonstrate the interest of a MDO approach for the design of new projects starting from the early phase (preliminary design), especially used for space launch vehicle design [2][3].

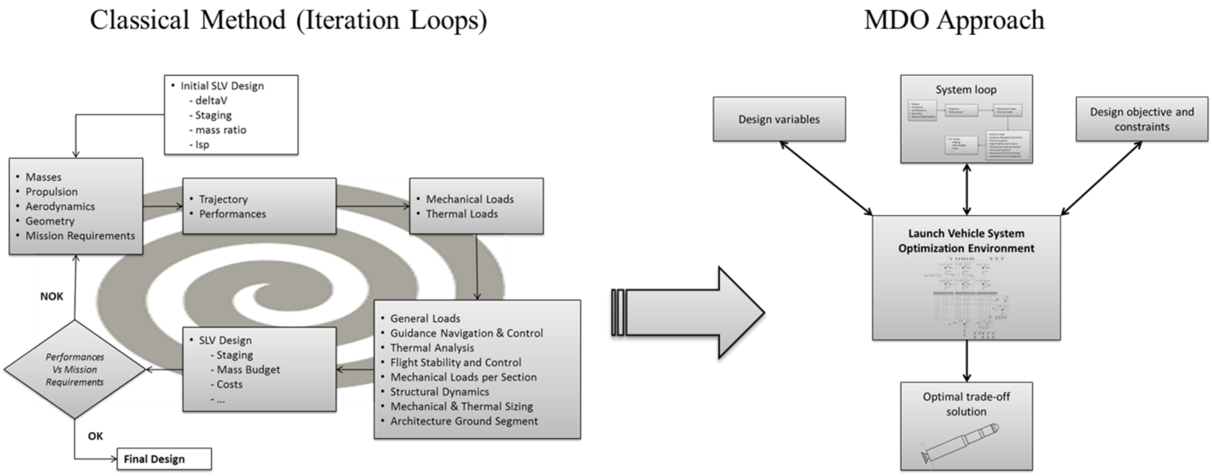

Figure 1: Comparison of the classical method with iteration loops and the MDO approach

2. Launch vehicle design problem

The mission of a launch vehicle consists in carrying a payload (e.g. one or multiple satellites) from Earth's surface into the targeted space orbit. An orbit is defined by a point and a velocity vector. Therefore, the launch vehicle shall provide to its payload the required velocity increment, the so-called ΔV (delta-V), to pass from the initial static conditions to the orbital state. ΔV is the measure of the impulse the launch vehicle shall ensure to reach the orbit. This is achieved thanks to its rocket engines which develop thrust by combustion of propellants and continuous expulsion of the resulted hot gas for a given burn time, leading to a sustained decreasing of the launch vehicle mass.
The Tsiolkovsky rocket equation [1], or ideal rocket equation, relates the ΔV to the effective exhaust velocity and the initial and final mass of a rocket by considering only the propulsive force (flight in vacuum, without gravitational field or aerodynamic forces):

$$\Delta V = V_e \ln\left(\frac{m_i}{m_f}\right) \tag{1}$$

Where V_e is the ejection speed of the exhaust gas, m_i the initial mass and m_f the final mass.
The first SLV designer objective is to define a system able to deliver the payload to its final target orbit by minimizing the propellants consumption required by the propulsion system to generate the thrust to overcome the weight of the rocket itself. A peculiarity of launch vehicle is the very small ratio between payload and lift-off mass as well as the proportion between propellant mass and dry mass. Classically, the payload mass represents only few percent of the total mass and more than 85% of the vehicle mass is made by propellants while only less than 15% is inert mass (structure, electronic equipment, etc.). As the propellants are burned off during powered ascent, during the flight a larger proportion of the mass of the vehicle becomes the near-empty tankage and structure that was required when the vehicle was fully loaded. In order to lighten the weight of the vehicle to achieve orbital velocity, most launchers discard a portion of the vehicle in a process called staging. The principle is to avoid the presence of unused structures in the vehicle to increase the efficiency of the system and reduce propellants mass. A multi-stage launch vehicle is then a rocket that uses two or more stages, each of which contains its own engines and propellant. The propulsions modules are progressively activated and once the stage propellant is finished, then the residual structure is released to lighten the total mass.
The velocity increment provided by the SLV is then the sum of the contribution of the velocity increment of each stage (sum of the ΔV). The ΔV allocation between the stages and the associated propellant mass distribution are

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fundamental design parameters, which are matter of optimization. A slight change of the masses between the different stages can have significant impact on the performance.
As already mentioned, the design of a SLV does not deal only with propellant mass and ΔV but it is naturally multidisciplinary (aerodynamics, combustion, mechanics, flight dynamics, etc.). It requires dedicated modelling for several subsystems sizing (propulsion, avionics, structure, etc.). Design parameters, physical variables and technical-economic constraints are of various natures and each of them may cover a wide range of value. The use of MDO is very interesting for this kind of application ensuring the capability to handle the large amount of data and the inherent interdependency between disciplines and interconnected subsystems sizing models.

3. Presentation of the approach

As previously mentioned, future launch vehicle shall be designed taking into consideration both technical and economic optimization drivers. For this reason, the optimization problem here presented aims to design a SLV that can place a given payload into a well-defined target orbit by minimizing the launch cost. The methodology retained and applied is a nested optimization process consisting in two integrated optimization levels. This results in a global system level optimization, aiming to satisfy the objective by finding, in particular, the best repartition of propellant masses between the different stages while satisfying design constraints.
The nested optimization is dedicated to the optimization of the trajectory of the launch vehicle. The optimization of the trajectory is a key part in the design of Space Launch Vehicle. It consists to optimize the command law along the trajectory and has its own optimization algorithm with its own objective (maximising the payload for a given architecture) and own constraints (orbit targeted). The main output is the performance in terms of actual payload mass delivered into the targeted orbit. This specific problem is formulated as an optimal control problem that requires dedicated formulation and optimization [4]. Given the complexity of the design of space launch vehicle, the strategy adopted was to use a dedicated trajectory optimization tool with its own integrated optimization process [5], instead of managing this optimization as part of the global process. This modelling ensures a more robust process.
The general problem is written as a Multiple Discipline Feasible (MDF) approach and it uses multidisciplinary design analysis (MDA). MDF is especially suited to engineering problems. Actually, MDF allows the sustained monitoring of the process by controlling and tuning the design parameters contrasting the natural sensitivity of the launch vehicle design problem. With a Genetic Algorithm (GA), we can get rapidly a feasibility zone (relative flat optimum) and afterwards use local optimization to refine the parameters. Therefore, our strategy is to run several consecutive optimizations by refining gradually the design variables and constraints.
Finally, at the global process level, the problem can be written as (for a three-stage rocket):

Minimize	$f(z)=c$	(2)
With respect to	$z=\left\{\sum_{j=1}^{7} x_{j_i}\right\},\ i\in\{1,2,3\}$	(3)
Subject to	$g_1: M_{pl}=M_{pl,\,target}$	(4)
	$g_{2..4}: \gamma_i\leq\gamma_{max},\ i\in\{1,2,3\}$	(5)
	$g_{5..7}: D_{nozzle_i}\leq D_{stage_i}, i\in\{1,2,3\}$	(6)

Where c is the launch cost, z the design parameters, g the design constraints, M_{pl} the payload mass, γ the longitudinal acceleration, D_{nozzle} the nozzle diameter, and D_{stage} the diameter of the stage.
Note that, as presented previously, the parameters of the targeted orbit are constraints of the nested optimization and so, they don't appear at system level.
The rationale of the MDF approach applied to HADES V15.0 platform is showed on Fig. 2.
The overall integration and optimization is performed with modeFRONTIER™ [6]. modeFRONTIER™ is a commercial tool providing an effective MDO environment including several optimization algorithms as well as powerful pre and post processing tools. In the frame of the SLV design, Genetic Algorithm (GA) and gradient-based algorithms (for instance Broyden–Fletcher–Goldfarb–Shanno algorithm, BFGS) have been used. GA provides the possibility to explore a large design space and rapidly find the feasibility zone while BFGS algorithms provides local optimization to refine parameters and designs in a further optimization phase. The applied strategy has been built on several consecutive optimizations manually run by adjusting design parameters, variables and constraints, leading towards more and more refined concepts.

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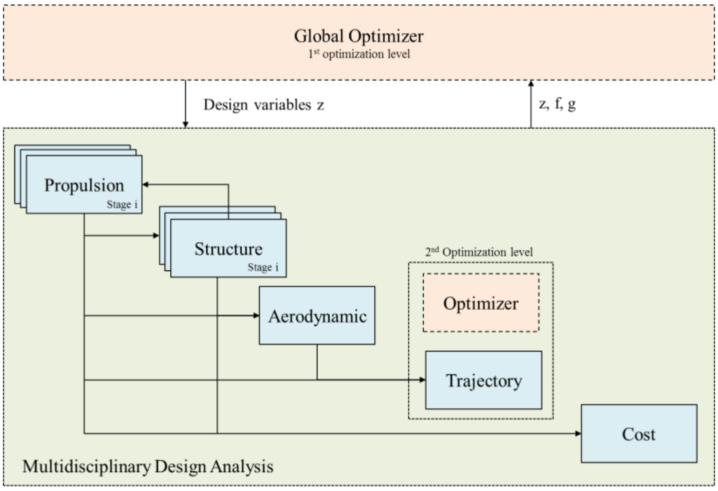

Figure 2: MDF approach for Launch Vehicle design

4. Modelling in HADES V15.0 platform

The MDF approach results in the HADES V15.0 platform. It consists in several software modules, interconnected in a system optimization loop exchanging input and outputs. Each module is a self-standing "black box" tool able to provide the preliminary sizing of a sub-system and/or to compute a specific physical or economic parameter. For each simulation, a design of a launch vehicle is obtained and real performances are calculated by the trajectory tool that includes a dedicated optimization process. Thanks to its modular structure HADES V15.0 is a flexible platform, able to evolve according to specific projects needs and to integrate new features or updated models. For a specific discipline, a module can be replaced by more or less refined model or tool (including CAD, CAE or CFD tools) according to the level of detail we want to reach in the design. The complexity and fidelity of the models used depend on the application foreseen and the level of maturity of the concept on which we are working. Of course, more complex models would increase the duration of the optimization and a balance between precision and rapidity has to be taken into account. For the application here described, a preliminary SLV design was addressed. In consequence, relatively fast adapted models have been used in HADES V15.0. Fig. 3 presents the general workflow of the platform.

HADES V15.0 allows the definition of the MDF optimization target (payload mass) and optimization objectives (launch cost minimization). Furthermore, various design parameters and their associated ranges of variation can be defined. Also MDF constraints are integrated in HADES V15.0 as well as some additional constraints useful to orient the design towards a realistic design. For a three-stage launch vehicle, we set:

$$\mathrm{M}_{\mathrm{p}_\mathrm{i}} < \mathrm{M}_{\mathrm{p}_{\mathrm{i}+1}},\ \mathrm{i} \in \{1,2\} \tag{7}$$

$$\varepsilon_\mathrm{i} < \varepsilon_{\mathrm{i}+1},\ \mathrm{i} \in \{1,2\} \tag{8}$$

$$\delta_\mathrm{i} < \delta_{\mathrm{i}+1},\ \mathrm{i} \in \{1,2\} \tag{9}$$

Where ε is the nozzle expansion ratio and δ is a feasibility criterion for the geometry.

HADES V15.0 integrates a complete library of technical and economic modules. These modules are interchangeable, adapted to MDO process, robust and fast, to ensure a complete system loop in few tens of seconds. They also can be replace by more detailed programs if required (including CFD and CAD/CAE nodes). Table 1 provides a short description of the modules integrated.

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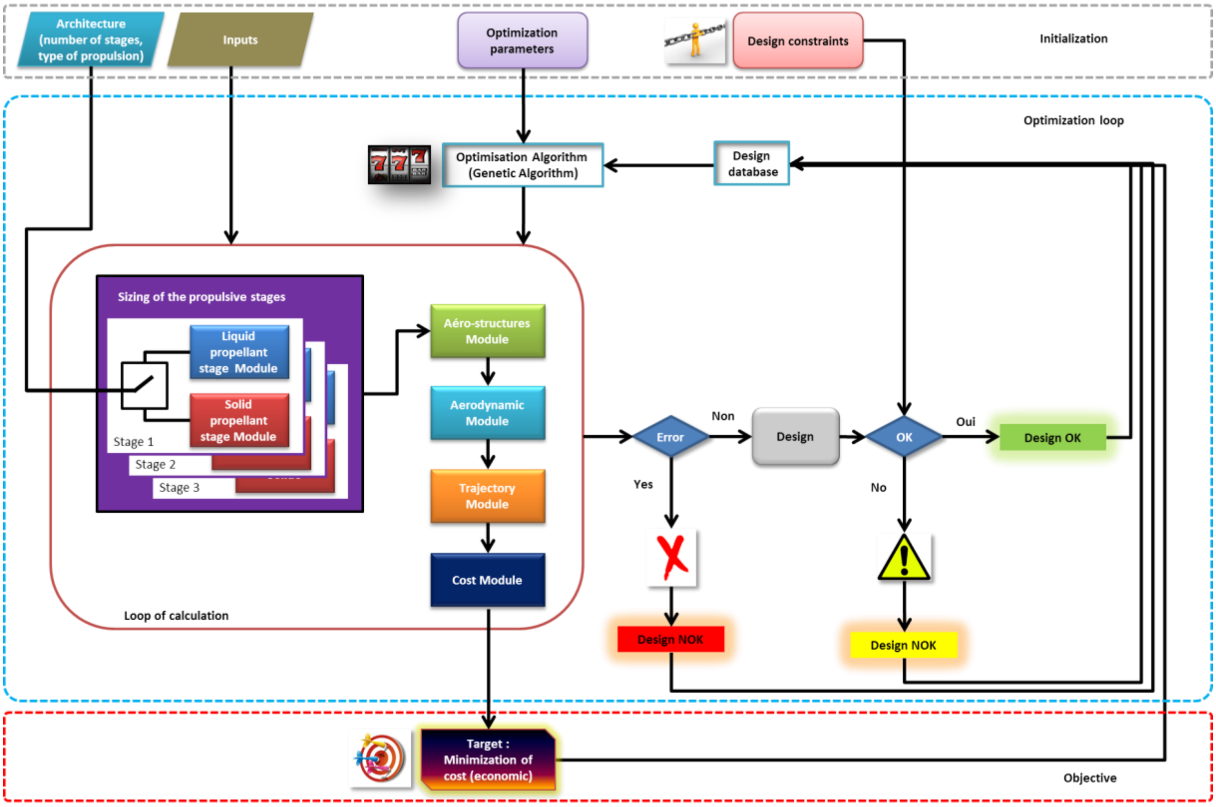

Figure 3: Workflow for the design of a space launch vehicle

Table 1: Description of modules integrated in HADES V15.0

Name	*Presentation*	*Description*
DRAGON	Solid rocket motor stage design	Calculation of the performance of the engines (thrust law, efficiency, engine design…) and design the main structure of the propulsive stage
CYGNUS	Liquid rocket propellant engine stage design	Calculation of the performance of the engines (thrust law, efficiency, engine design…) and design the main structure of the propulsive stage
CHIMERA	Hybrid rocket propellant engine stage design	Calculation of the performance of the engines (thrust law, efficiency, engine design…) and design the main structure of the propulsive stage
ICARUS	Aerodynamic calculation of the launcher	Computation of the aerodynamic coefficients of the launcher (drag and lift coefficients, center of pressure)
PERFOL	Trajectory optimization (ground launch)	Optimization of the trajectory of the launch vehicle that maximize the payload into the targeted orbit [5]
AQUILA	Trajectory optimization (air launch)	Optimization of the trajectory of air launch vehicle that maximize the payload into the targeted orbit
PEGASUS	Launcher Structures design	Design of the aerostructures of the launch vehicle (skirts, inter-stage, fairing)
ATHENA	Economic assessment	Assessment of the launch cost for the considered launch vehicle

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HADES V15.0 allows automatic run of hundreds, thousands or more consecutive system optimization loop. For each run, the GA generates a set of value to feed the system loop. SLV design is very sensitive and numerous simulations are not only non-feasible (i.e. they do not satisfy the constraints) but also unrealizable (i.e. one or more module errors are issued). That is to say, the limits of the models used conduct to have no possible solution for the associated set of design parameters (no admissible trajectory, physical impossibility…). The initialization is so on first order of magnitude and need careful attention. The solution adopted is to use a constraint design of experiment (C-DOE) to have feasible solutions to initiate the global optimization. A series of constraints are added before the optimization for the construction of the C-DOE and disabled after for the global optimization. The difficulty to obtain feasible solutions is highlighted in Fig. 4. Actually, during the first optimization loop, GA has been used in order to explore the domain of solutions with a chosen range of design parameters. More than 50% of the analyzed combinations produced an errors message and the associated computations were stopped even before the end of the full process. 26% of the computed designs were classed as unfeasible, i.e. they did not satisfy the design constraints. Finally, only about 22% of feasible design were identified. This is a classical result encountered and a particularity of this design case. This result is strongly linked to the initialisation, so, if the domain of feasibility is already known, we can go more rapidly in the feasibility zone (in green on Fig. 4).

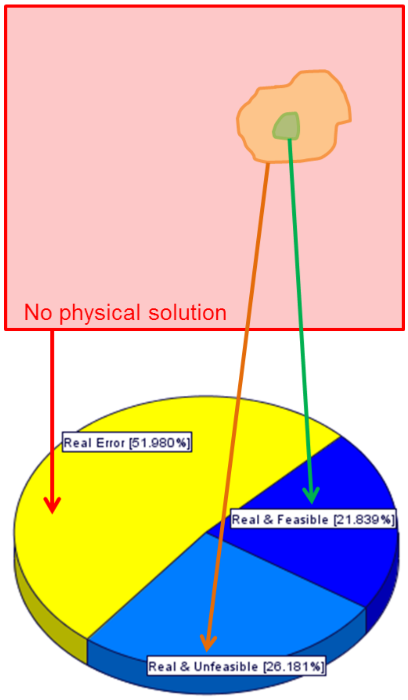

Figure 4: Example of statistic results during an optimization loop with a GA

5. Application to small launch vehicles trade-off

HADES V15.0 platform and the MDO strategy previously described have been applied on several projects and launch vehicle designs. In this study, the objective was to analyse different propulsion architecture of launch vehicle and their applicability to different kinds of mission according to three market objectives.
The trade-off has been carried out by considering a cost based comparison criterion among different architectures. For all the missions, the nominal orbit considered is a Sun-Synchronous Earth Orbit (SSO) at 600 km, while three payload classes have been assessed:

- NanoSat: payload mass of 20 kg,
- MicroSat: Payload mass of 150kg,
- MiniSat: Payload mass of 400 kg

Four launch vehicle architectures have been studied in order to take into account two staging options (2-stage and 3-stage launch vehicle) and two propulsive technologies (bi-liquid propulsion -K- and solid propulsion -P-), as represented on Fig. 5:

- KK: Two-stage architecture with only liquid propulsion technology

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- PK: Two-stage architecture with a mix of solid propulsion technology and liquid propulsion technology
- KKK: Three-stage architecture with only liquid propulsion technology
- PPK: Three-stage architecture with a mix of solid propulsion technology and liquid propulsion technology

In total, twelve study cases have been studied and compared to take into account the four architectures applied to the three payload missions.

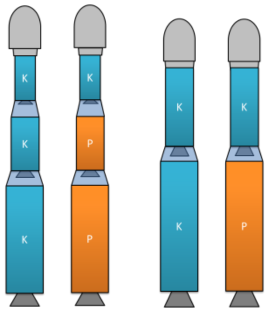

Figure 5: Architecture studied (P: solid propulsion, K: Liquid propulsion)

For each study case, a complete optimization has been performed by addressing, as constraint target, the payload mass, and, as optimization objective, the minimization of the launch cost. This results in the definition of twelves launch vehicle optimized concepts, which are able to place their payload into the targeted 600 km SSO. An example of optimization loop results is presented in Fig. 6 by highlighting the relationship between launch cost and Global Lift-Off Mass (GLOM). The results presented in Fig. 6 relates to the optimization process run for the KKK architecture with a payload of 400 kg. It presents all the feasible results (dots) found during the multi-disciplinary optimisation process in terms of achieved performances, optimisation objective and technical constraints. In particular, the graph shows the payload mass (performance target of the optimization) as a function of the cost (objective of the optimization), while dot colours and dimensions are representative for GLOM and maximum diameter of each feasible design. This graph is a powerful tool to identify design responding to the required performance and characterized by the lowest launch cost. The feasible designs are grouped behind a pareto front along which all the “cheapest” concept are aligned. An acceptability region (green rectangle) is then set around the nominal 400 kg researched to allow some small deviation from the nominal payload target. The best design shall be researched inside the green area and alongside the pareto-front as some feasible design may result cheaper but not enough performant to achieve the required target. Finally, the chosen “best” design is the concept minimizing launch cost in the feasible area. As we can see, the correlation between GLOM and recurring cost is obvious, i.e. the lighter is the SLV, the lower is the launch cost for a same launch vehicle architecture. The same kinds of results are issued at the end of each optimization loop for all the different study cases presented before. For each study case, the best design is then selected by using the same principle, i.e. by selecting the feasible concept issued by the MDO achieving the payload mass target and showing the lowest cost. Finally, the optimization has provided, for each configuration, sizing details and performances as stage geometry and dry mass, propellant masses, aerodynamics properties and propulsion performances (thrust profile, Isp, etc.). Fig. 7 gives an overview of the best design found for the twelve study cases, highlighting their (schematic) geometry, architecture and staging.

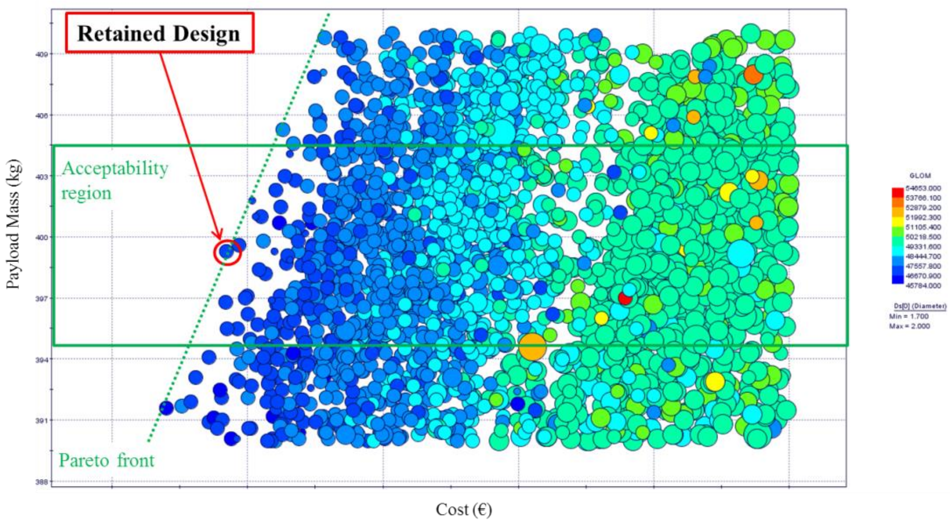

Figure 6: Example of solutions obtained for the KKK architecture

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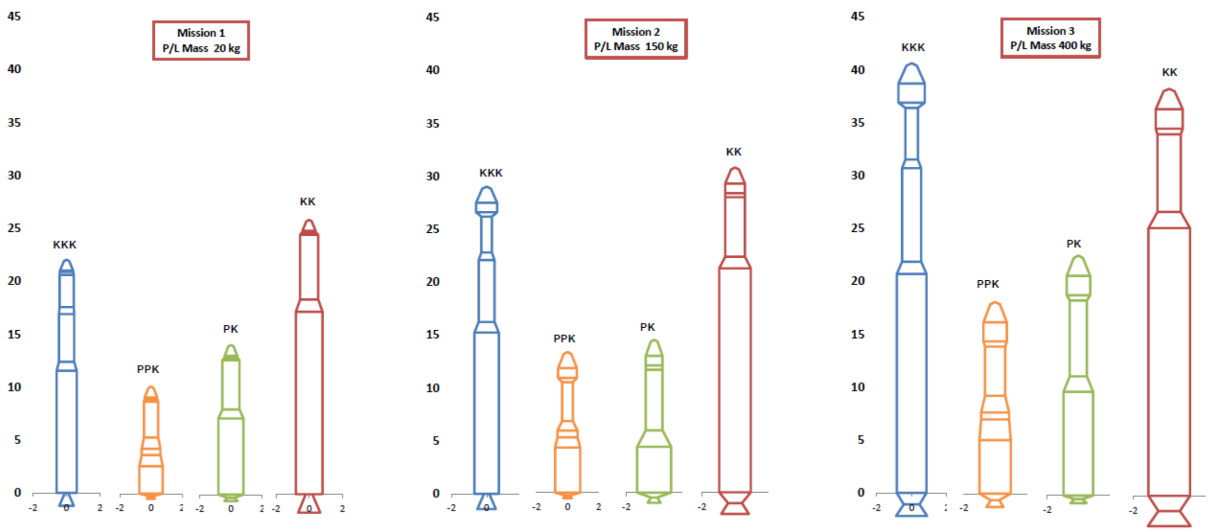

Figure 7: Example of solutions obtained

Fig. 8 and Fig. 9 summarise the results for all the configurations studied in terms of GLOM, Costs and Payload Mass. According to this synthesis, some interesting considerations can be done. We can see that, for all the missions, the best architecture is the same, i.e. PPK architecture, in terms of both GLOM and cost. On the other hand, by comparing Fig. 8 and Fig. 9, the ranking of the concepts in terms of GLOM criteria and cost criteria are significantly different. Furthermore, best designs issued for the 400 kg payload study case are very close in terms of costs while varying significantly in terms of GLOM. These results show the interest in using an MDO approach tacking into consideration both technical and economic aspects from the very beginning of the design phase of a new SLV. Actually, the above results show how an approach fully oriented towards technical parameters (GLOM) can be different with respect to an approach considering also economic aspects. Moreover, it shall be noticed that the time required to perform the entire study, identifying the twelves designs (including subsystem early sizing and preliminary performance evaluation) and finalizing the trade-off, has been of few weeks. This represents the same time required to carry out a single preliminary design of launch vehicle with a comparable level of detail by applying a classical manual iterative approach. With the classical approach, the same overall trade-off would then last several months. This means that application of HADES V15.0 based MDO process can significantly reduce the time required for the initial SLV trade-off and feasibility phase providing an optimised concept (both in terms of performances and costs). Then, this design can be used as input for more precise refinement or for an upcoming detailed design phase. The estimated time saving factor provided by MDO with respect to classical design methods is between 5 and 10.

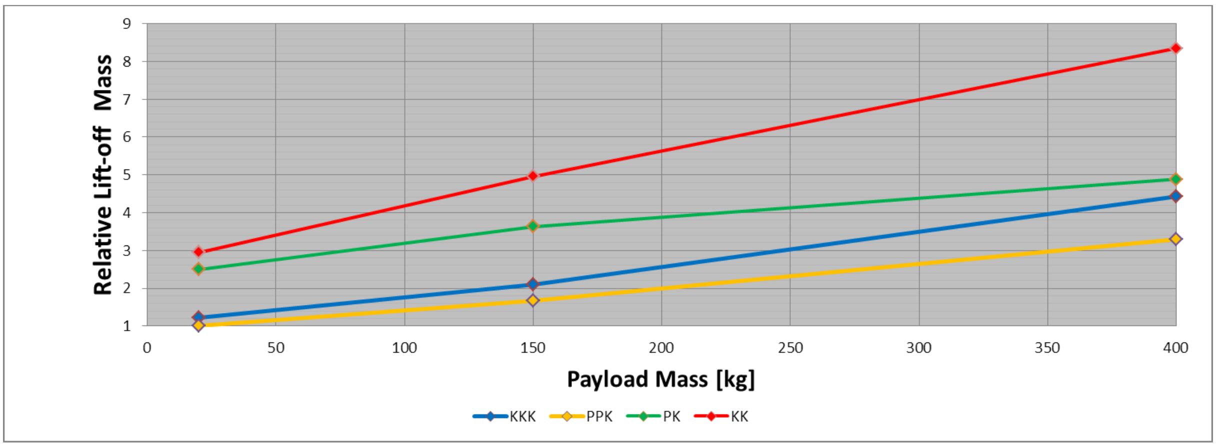

Figure 8: Graphical results of the lift-off mass obtained

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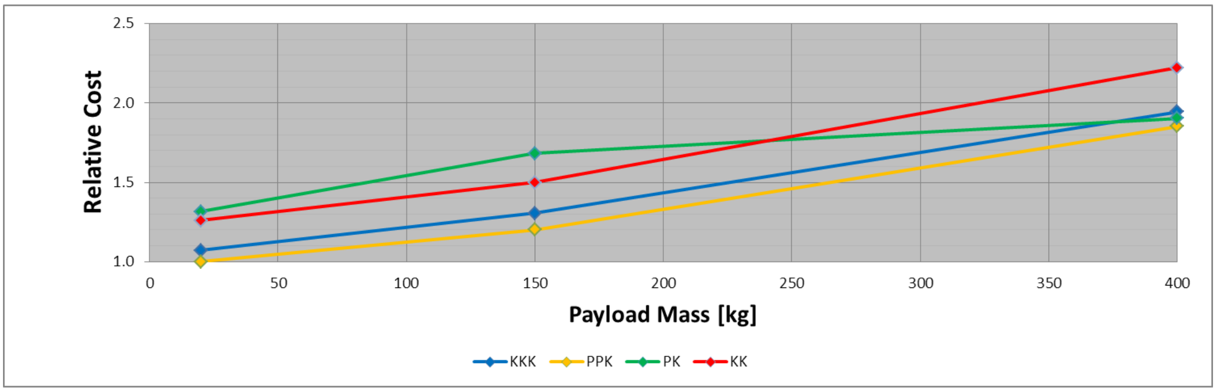

Figure 9: Graphical results of the relative cost obtained

Table 2: Optimization results

	GLOM	COST
SMALL	KK > PK > KKK > PPK	PK > KK > KKK > PPK
BIG	KK > PK > KKK > PPK	KK > KKK > PK > PPK

The technical and economic study and the trade-off results here shown have been used as starting point for the more detailed design of the ROXANE Micro-Launch Vehicle. In a following phase, HADES V15.0 platform has been used in order to go further in the launch vehicle design. Of course, compared to the cases previously presented, a more detailed concept has been defined by using a more complex optimization process and more precise tools. The new system loop integrated then more complex and refined models for subsystem sizing, performance and mass evaluation. Furthermore, more constraints, particularly concerning industrial and economic feasibility, have been added to ensure a realistic and manufacturable concept. This concept can be seen on Fig. 10.

Figure 10: ROXANE Launch Vehicle designed with HADES V15.0 MDO software platform

This methodology is also currently employed to design the space launch vehicle of the H2020 ALTAIR project [10]. ALTAIR is a H2020 project that aim at designing an innovative and low cost air launch system. For this specific application, some modules have been adapted to take into account some particularities (aerodynamic et trajectory particularly). The first results of the launch vehicle design are presented in [11].

Figure 11: ALTAIR Launch System

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6. Conclusions

This study showed the interest of an MDO process for the design of new space launch vehicle starting from the very early phase of a project. By applying this MDO process, which allows optimization of both performances and launch costs, it is possible to reduce significantly the time required by the technical and economic feasibility study and explore a wide trade-off scenario. This leads to the selection of the best concept responding to technical requirements and by minimizing the costs. The MDO process presented relies on a ten years' experience gathered by Bertin Technologies with the development of HADES V15.0 MDO platform and with the participation on several launch vehicle projects in particular micro-launch systems.

The use of an integrated platform for multi-objective and multi-disciplinary optimization enables an efficient process and quick optimization maintaining the required precision. This methodology is particularly well fitted to the design of a space launch vehicle, allowing to take into account the multidisciplinary nature of such complex system and to manage the inherent sensitivity for this kind of vehicle. This methodology brings a new way of conception for space launcher and change the classical methodologies currently used. However, this is completely transposable to other application in space or other fields like automotive, aeronautics and so on. Future improvements, currently in progress, are dedicated to the optimization strategy reducing the human interaction within the process by fostering automatic tuning of parameters in a single optimisation loop. This will allow having a unique optimization process including a first global optimization with a GA, directly coupled to a gradient-based optimization for the final refinement. Other improvements are focused on the extension of this methodology to other applications and the integration of complex CAD/CAE and CFD tools by providing always an effective computation time.

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