DIFFERENT APPROACHES TO MULTI DISCIPLINARY OPTIMIZATION FOR PRELIMINARY DESIGN OF EXPENDABLE LAUNCH VEHICLES

Guillaume Collange*, Nathalie Delattre•, François Lemaire*, Isabelle Quinquis*

**Mission Analysis Engineer,* •*Mission Analysis Section Manager*

ASTRIUM Space Transportation, Les Mureaux, France

ABSTRACT

This paper describes how ASTRIUM Space Transportation proposes to use Multi-Disciplinary techniques to improve the preliminary design process of expendable launch vehicles. The significant in-house effort that has been devoted since 2000 allowed ASTRIUM ST to test different approaches to the problem and to compare them. The common characteristic between selected approaches is to integrate, in a single environment, a number of relevant disciplines through simplified preliminary-project type toolboxes. The different disciplines considered are stage loading, propulsion complete design (parameters and mass balance), trajectory optimisation, aerodynamic drag coefficient assessment, non propulsive stage mass balance, launcher cost. The first strategy investigated was an all at once approach based on Genetic Algorithms where the launcher architecture and trajectory command law are solved together in a single optimization algorithm. The second strategy consists in a "split method" where the global problem is split between two sub-problems. The trajectory is optimized separately thanks to in-house trajectory optimization tool based on reduced gradient method and the architecture is still optimized with genetic algorithms. The resulting software is very user-friendly and does not need an expert's eye to work.

1. INTRODUCTION

For several years, ASTRIUM Space Transportation has been involved in a Research and Development activity whose goal is to elaborate a methodology able to provide from scratch a preliminary but reliable architecture design for expendable launcher. A typical question that should be answered can be worded as simple as "given a range of accessible technologies and assuming no industrial constraint, what would be the cheapest expendable launcher look like?"

A secondary but important objective is to be able to provide this type of preliminary configuration with acceptable recurring cost, and to get a reasonable level of confidence that the solution obtained will not be degraded, in terms of performance and cost, during the development itself.

In the preliminary phases of a launcher project, the achievement of an initial coherent design is driven by several disciplines that have more or less interactions and coupling effects between each other and with more or less impact on mission requirement and global cost improvement. The overall project is therefore a typical Multi-Disciplinary Analysis and Optimisation design process.

Section 2 presents the traditional design process and its main drawbacks. The other sections describe how ASTRIUM Space Transportation proposed to use Multi-Disciplinary techniques to improve the preliminary design process. The significant effort that has been devoted since 2000 allowed ASTRIUM ST to test different approaches to the problem and compare them. Over the years, the difficulties encountered enabled to improve the tool and adapted the process to the particularities of the problem. Section 3 summarizes the common characteristics of the "all-at-once" method and the "split" method presented respectively in section 4 and section 5 with a common test case in section 6. An extension of "split" method on an optimisation of a launcher family is presented in section 7.

2. TRADITIONAL DESIGN PROCESS

Without political and industrial constraints, the problem should be simply stated the following way: given a user specification (class of payload mass to be inserted into a given main mission orbit, injection accuracy, constraints on loads encountered by satellites, operational constraints) and a high level criterion (the recurrent launch cost to be minimised, for example), find the best compromise for the resulting system. In the real world, the number of technologies available is limited for industrial reasons especially and some sub-systems have also to be reused (engine, full stage, etc...) mainly for political or economical reasons.

However, even considering the basic problem as stated above, the system design loop currently implemented today to converge to a solution is quite long. The process can be roughly described as follows: starting from the selection of technology for each stage (type of propellant, of engine, of pressurisation, etc.) based on a priori ideas on costs, a preliminary staging is assessed by ΔV evaluation assuming orders of magnitudes for orbital losses, stages structural index and engines specific impulse. In a second step, a simplified propulsive preliminary design will provide more realistic propulsion parameters (flow rate, thrust level) and low level description of the corresponding subsystem. In a third step, simplified layout exercise for each stage shall be done, providing a first assessment of the launcher mass balance, on the basis of local loads simplified evaluations (tanks, feeding lines, etc.). These three steps performed in dedicated teams are then sufficient to provide inputs for trajectory and performance optimization. A reference trajectory will then allow to start the "sizing loop", including: global loads, thermal studies, aerodynamics, control, transient phases. Payload optimization will also provide refined propellant loading and thrust level law. Eventually, these studies will result in consolidated mass balance and updated launcher constraints. The whole process is done a number of times, with more and more accurate and heavy tools, until convergence towards a "stable" design, if any.

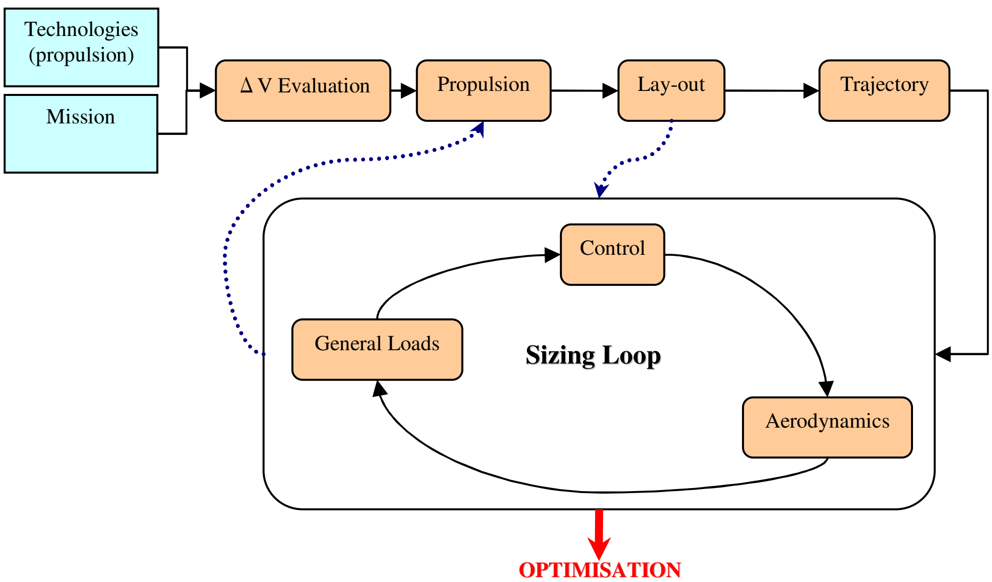

Figure 1: Traditionnal Design Proccess

The drawbacks of such a sequential and iterative method are that the overall optimum is rarely obtained, especially when some disciplines have opposite interests in order to obtain the best criterion.

Moreover, different initial simplified assessments could lead to different design at the end. The justification of the retained solution is then very difficult. Furthermore it is a long and expensive process.

3. MULTI-DISCIPLINARY OPTIMISATION

The common characteristic between selected approaches was to integrate, in a single environment, a number of relevant disciplines through simplified preliminary-project type toolboxes. The different disciplines considered are stage loading, propulsion complete design (parameters and mass balance), trajectory optimisation, aerodynamic drag coefficient assessment, non propulsive stage mass balance, launcher cost.

The tools used for each discipline are more or less simplified models, which are described in the paper.

- The propulsion module compute both liquid and solid propellant stages masses (tanks, insulation, skirts and frames, engine by itself) with high details especially for Solid Rocket Motor components, engine performances (specific impulse, thrust, etc.) and stage layout and dimensions. The module was developed from tools available in the propulsion systems department named PROPSOL for solid propellant stages and PROPLIQ [2] from liquid propellant stages

- The aerodynamic coefficients necessary for the trajectory assessment are computed through specific methods that have been developed to allow rapid evaluation of the vehicle performance in the frame of preliminary projects.

- The cost model is an estimation of the launcher recurrent manufacturing cost, based on the summation of each stage cost.

- The trajectory computation is made with more or less simplified models depending on the approach but always based on a linear by segment command law. The parameters defining the command law are the input of the trajectory module.

Regarding the main optimisation method, the choice of Genetic Algorithms (GA) was made. The main interest of that type of method is that no initial guess and no function differentiation are required. Only an objective function is needed. A nice side effect is also that these methods are able to catch multiple optima situations and to provide results for multi-criteria analysis.

4. ALL-AT-ONCE METHOD

The first strategy investigated was an all at once approach based on Genetic Algorithms. This method was investigated from 2000 and preliminary results were presented in conferences [3] [4] [5].

The optimisation problem is to find the optimal launcher architecture and trajectory together under a set of constraints. A single configuration is described by 30 relevant parameters representing the launcher architecture and command law: they are the degrees of freedom of the problem. Figure 2 provides a general picture of the data management through all the components, giving the relationship between the degrees of freedom of the global optimization problem and the objective function to be minimized.

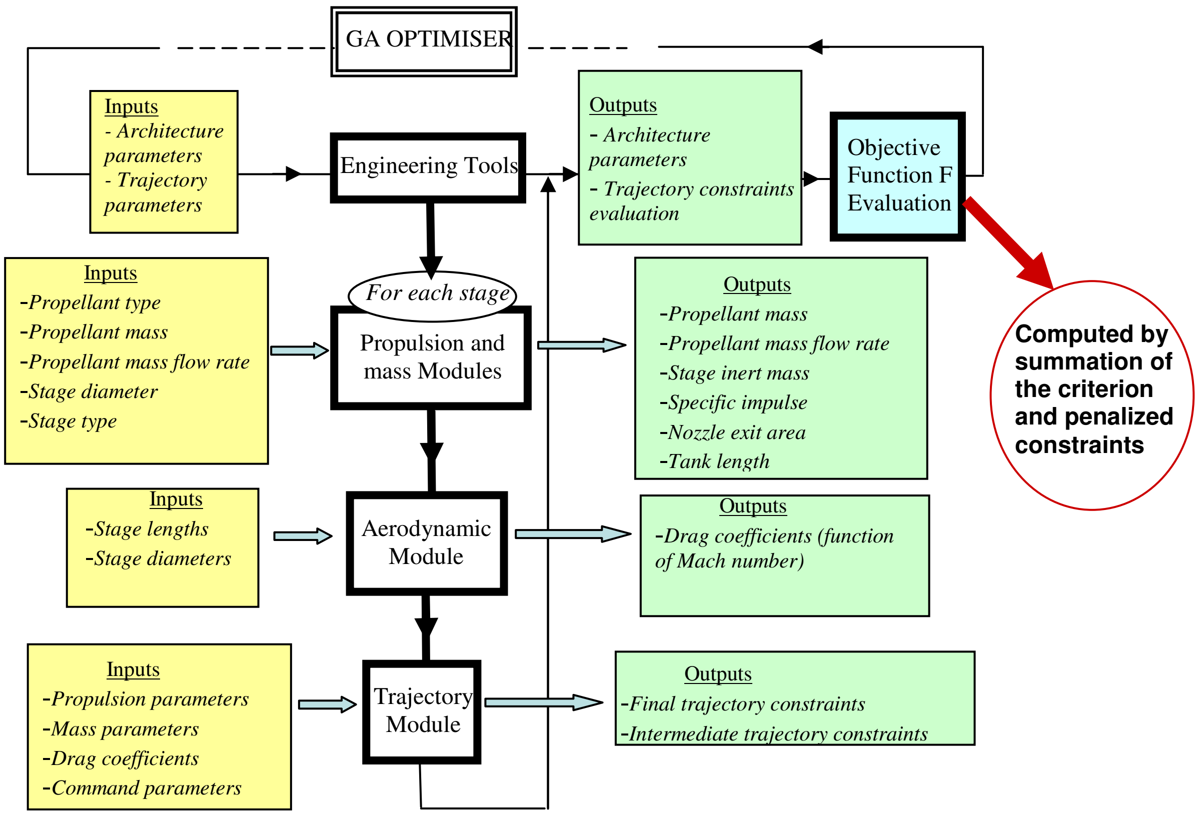

Figure 2 : data management

The fitness function optimised with genetic algorithm includes the recurrent cost evaluation of the architecture as well as penalty functions that take into account unsatisfied constraints.

$$F(x) = \lambda_C \cdot C - \sum_{k=1}^{ne}\left[\lambda_{EC_k} \cdot \frac{\left|EC_k(\text{value}) - EC_k(\text{target})\right|}{\text{Tolerance}(EC_k)}\right] - \sum_{k=1}^{ni}\left[\lambda_{IC_k} \cdot \frac{\max\left(IC_k(\text{value}) - IC_k(\text{target}), 0\right)}{\text{Tolerance}(IC_k)}\right]$$

Where:

x optimization vector,

C criterion to be maximized,

λ_C penalty coefficient for the criterion,

n_e (resp. n_i) number of equality (resp. inequality) constraints,

EC_k (resp. IC_k) equality (resp. inequality) constraints (**target** or effective **value** obtained at each step, target required with given **tolerance**),

λ_{EC_k}, (resp. λ_{IC_k}) equality (resp. inequality) constraints penalisation weights.

With a purely genetic algorithm, the first tests demonstrate that the constraints were very difficult to satisfy without initial guess and when they were satisfied, the algorithm tended to be stuck in a local optimum. To improve these results, the choice was made to add a local gradient search to the Genetic algorithm.

From various test cases on the all at once method, it appeared that

- The architecture and trajectory parameters have very different sensitivities with respect to criteria and constraints so that the good algorithm settings were very hard to find and the process stopped in local optimum.

- The constraints on the trajectory are very difficult to meet so that an admissible solution has to be provided initially. The necessity to have an admissible solution to start the algorithm is an additional constraint in the process and is not compliant with the objective of finding new configurations from scratch.

- The fact that the constraints are taken into account through the objective function makes difficult to add more constraint without changing the whole problem architecture. The penalisation weights in the objective function are very sensitive and need an expert's eye to be set. The whole process seems very difficult to use and judge by a none-expert user.

5. SPLIT METHOD

In 2007, an alternative solution was developed by splitting the global optimisation problem into two sub-problems. The architecture problem is still solved with Genetic Algorithms and the optimal control law is found thanks to a reduced gradient method.

The genetic algorithm based on non-dominated sorting genetic algorithm was provided by ModeFrontier, an off-the-shelf optimisation environment that allows to use constraints without defining penalty functions. The algorithm uses an elitism-preserving approach. Elitism is introduced storing all non-dominated solutions discovered so far, beginning from the initial population.

Moreover, an in-house trajectory optimiser could be inserted inside the environment. In order to improve the time-consumption, an automatic initialisation process was added to find more quickly the optimal trajectory parameters. Each sub-problem is solved with its own optimiser that takes into account its particularities.

The solution adopted is to integrate the trajectory tool as a 'black box' into the Modefrontier environment. The architecture problem is solved in the same way as it was separately. Test conditions are added on the velocity increment and the lift off acceleration in order to call the trajectory tool only with possible viable launchers. If a set of architecture parameters does not give a sufficient velocity increment or a sufficient initial acceleration, this particular individual is rejected of the optimization process.

Furthermore, a robust error code management system was implemented in the software in order to reject of optimization process all the individuals that do not produce a clean optimal solution with all the trajectory constraints respected.

The following figure illustrates the global integration of the two sub-problems. It can be noted that the command law parameters and the trajectory constraints are internal to the trajectory tool and do not appear at higher level.

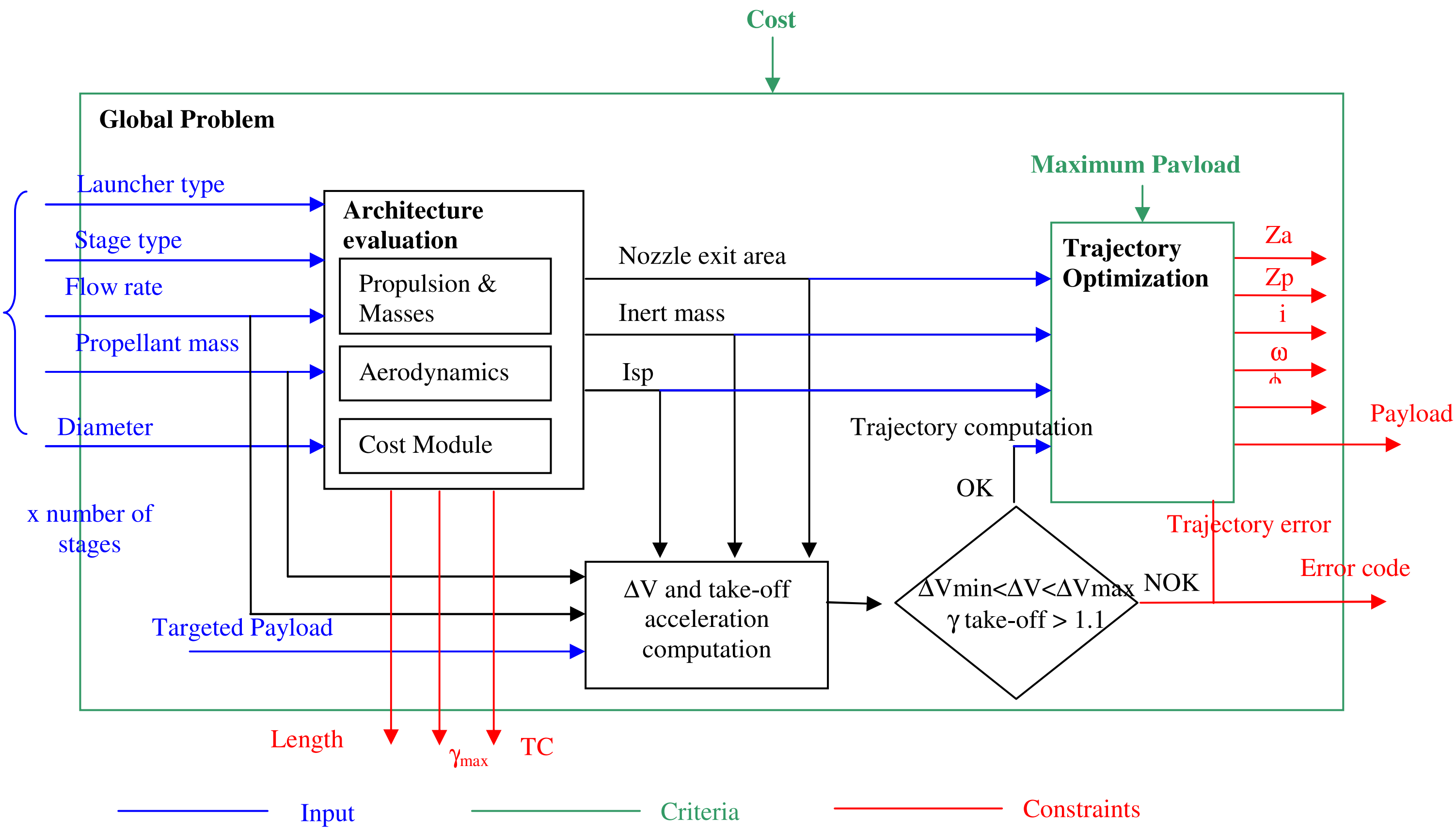

Figure 3 : Split method implementation

The main advantages of splitting the problem into two sub-problems are:

- The process is less time-consuming thanks to the in-house trajectory tool's automatic initialisation algorithm,
- New constraints can be added very easily through the Modefrontier environment without redefining an objective function,
- The convergence of the control law is obtained with a reduced gradient method so that the optimum is verified,
- Specific genetic algorithm is well-adapted to the global problem; constraint can be defined and there are no penalisation weigh to set

In summary, the splitting of the problem succeeded in solving all the problems encountered previously and the resulting software is very user-friendly and does not need an expert's eye to work

6. TEST CASE

A test case was studied with both approaches. The configuration studied is a 2 stage launcher with boosters. The targeted orbit is Geostationary Transfer Orbit (GTO) with a fixed payload. In order to get a good solution, this initial problem had to be simplified by fixing the propulsion type (metallic solid booster and cryogenic type for the main and upper stages).

For the all-at-once method, an admissible solution had to be provided to initiate the algorithm. Despite the fact that an interesting solution which improved the initial guess was found, one of the main advantages of the genetic algorithm was lost by initiating the algorithm. One of the main difficulties of the all at once approach was to set the penalty coefficients in the fitness function. Moreover, these coefficients appeared dependent on the problem. An expert's intervention would then be necessary for each new problem.

The result obtained with split method is very similar in terms of architecture but the solution was computed much more rapidly with the new method. The difference in the total cost between the two results is around 2% and the launcher parameters differ less than 5%. Figure 5 illustrates the convergence process with the genetic algorithm. Only viable launcher respecting all the constraints are represented. The best launcher with the minimum cost is represented on Figure 4.

These results enable to validate both processes with each other in terms of convergence process.

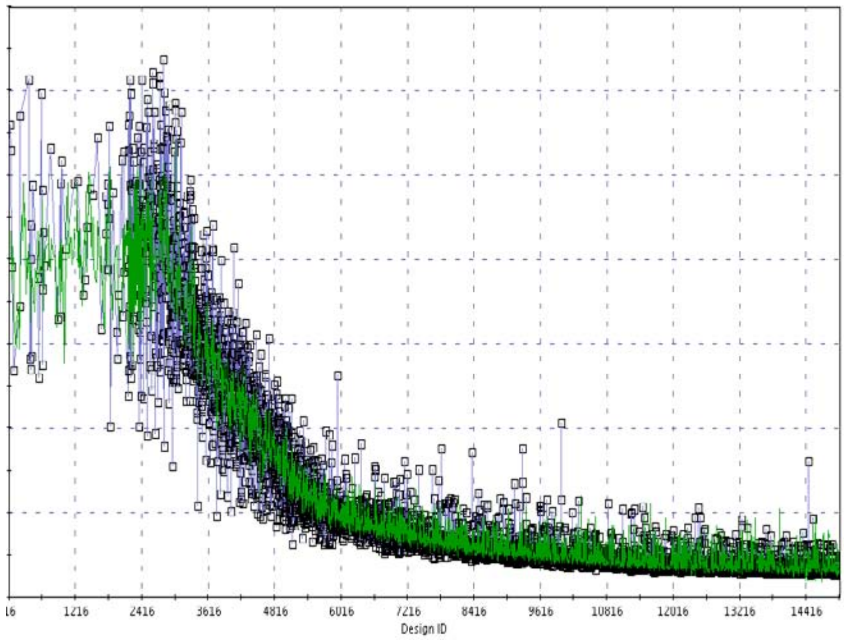

Figure 5 : Cost with respect design evaluation

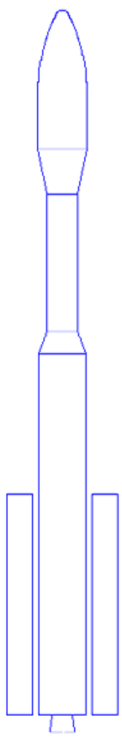

Figure 4 : Test case final design

7. MULTI-CRITERIA OPTIMISATION

With the same method presented in chapter 5, it is possible to optimize different criteria together. The platform allows an easy use of this functionality. The result of this kind of optimization is not any more a single launcher configuration but a Pareto set with a whole range of launcher design from small to large payload mass. Figure 6 illustrated a multi-criteria optimization with a cost – payload optimization. All feasible design are represented on the figure and the border of the cluster is the pareto set of the problem. It is interesting to notice that the discontinuity in the optimal solutions is due to technical limits. Between section 2 and 3, the gap is due to the limit on the size of the main stage. To reach a greater payload, the boosters have to be greater and the launcher is more expensive.

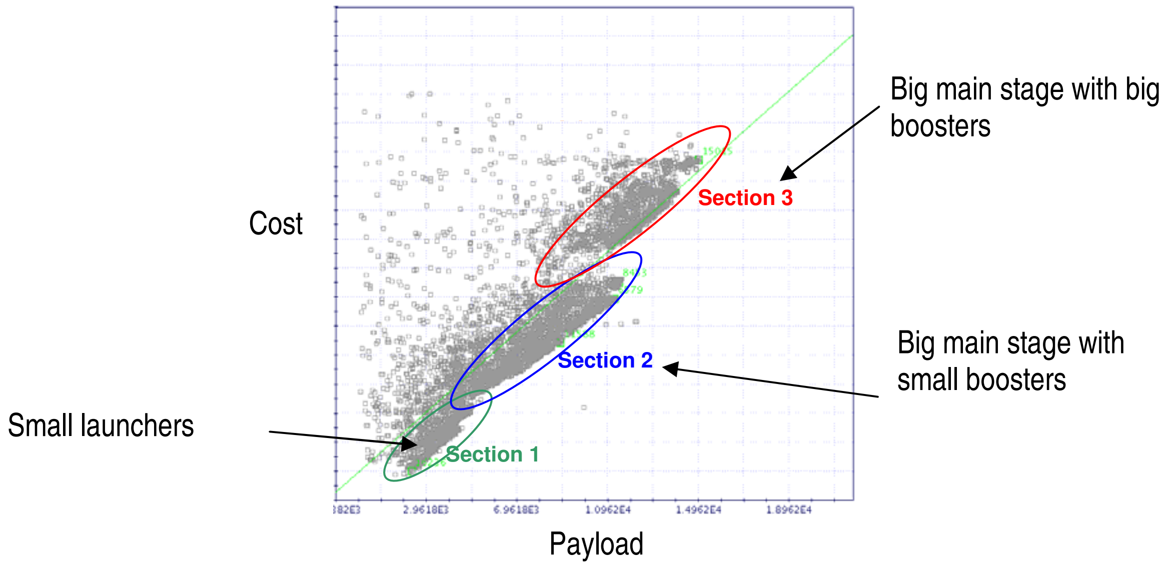

Figure 6 : Cost - Payload Pareto set

The analysis of the variations of launcher parameters along the Pareto set gives the sensitivities of the optimal design with respect to the payload. With an example of an 8 tons launcher, the pareto set will give the most interesting parameters to look at in order to have a greater performance for the less increase of cost.

8. CONCLUSION AND PERSPECTIVES

The different methodologies tested over the years has allowed Astrium Space Transportation to adopt a effective method called “split method” that perform multi-disciplinary optimization of an expendable vehicle in a quick time and user-friendly way. The tests performed with the different methods permit to inter-validate the process. Astrium Space Transportation has a new operational tool that can be use easily.

With the same methods presented in this paper, another problematic is envisaged to be solved by a process MDO. The goal would be to optimize a launcher family composed of a reference launcher and a several derived launchers. The derived launchers would be obtained by modifying the architecture of the reference launcher but by keeping the same stages. Moreover, the stages could be slightly changed as under loaded on the derived launcher. The MDO techniques could bring a new perspective to the launcher family problematic.

REFERENCES

[1] T. Bäck. Evolutionary Algorithms in Theory and Practice. New-York Oxford University Press, 1995

[2] V. L'hullier et al., Liquid stage system performancemodeling for vehicle performance global trade-off, 4th Int. Conf. on Launcher Technology, Liquid Propulsion

[3] T. Jean-Marius, Multidisciplinary Optimization for Early System Design for Expandable Launchers, AIAA-2006-7125

[4] N. Duranté, A. Dufour, V. Pain, G. Baudrillard & M. Schoenauer, Multidisciplinary Analysis and Optimisation Approach for the Design of Expendable Launchers, AIAA-2004-2441

[5] N. Delattre & O. Mongrard, The Use of Multi-Disciplinary Optimization for the Design of Expendable Launchers, 2nd EUCASS 2007