TURBO-BOOST FOR LAUNCHABILITY ANALYSIS TOOL (LAT)

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ABSTRACT

Early during the conceptual design of a space mission, designers must select a launch system. A wide overview of the launcher market helps to find whether there are available launchers with enough capability to place the satellite into the desired orbit or escape trajectory. With a long experience in the simulation and optimization of launcher trajectories, Astos Solutions presents an update of its Launchability Analysis Tool (LAT) for a fast choice of the adequate launch system. Based on launcher performance tables from Space Launcher System Data-Base (SLSDB) of ESA/TEC-ECN, LAT computes the payload capability of existing launchers for the desired orbit and it compares that with the user required payload mass. To provide values for every orbit required by the user, LAT uses an interpolation algorithm or, where necessary, an extrapolation algorithm.

The innovation introduced is the inclusion of a kick-stage module that could be based on common chemical propulsion or on electrical low thrust propulsion: the user may select an already existing kick-stage of he can define the module characteristics via a dedicated GUI. The computation of the payload capability considers losses function of the initial and final orbit shape, of the number of revolutions and of the maximum burn time. Additionally the code of conduct for upper stages is taken into account. With this approach a wider range of launcher systems will be presented to the user with the possibility to reduce the launch cost.

With its variety of optional choices, the Launchability Analysis Tool from Astos Solutions offers to customer versatile and fast help for launch system determination without the tedious search through launcher user manuals.

1. ASTOS SOLUTIONS

Astos Solutions is a young company with a long history and expertise in simulation and optimization of ascending trajectories and spacecraft orbits. Its AeroSpace Trajectory Optimization Software (ASTOS) is a widely used tool for solving launcher, re-entry and orbit trajectory problems without any programming. A General Environment for Simulation and Optimization Platform (GESOP) is also available for not aerospace related problems. In recent years small tools have been created to target specific applications: GAMAG for magnetic cleanliness, GRAVMOD for interplanetary propagation and ALWA for launch window analysis.

2. MOTIVATION

In the early phase of a concept study the spacecraft parameters, e.g. the mass and the dimensions, change frequently until the best design is found. Similarly, the static and dynamic loads that the spacecraft can support. Every small change in the design entails a lot of additional changes. One of the frequently asked question is: Which space launcher is able to launch this spacecraft?

Therefore a simple and fast tool is needed to answer this question without the tedious search through launcher user manuals or the handmade solving of equations. Adding a kick-stage to the launcher increases the possible launch systems.

3. STATE OF THE ART

According to [1] there are several launch vehicle selection tools. This chapter gives a short description of their features and identifies their advantages and disadvantages.

SMAD Design Template is an Excel file based on the book Space Mission Analysis and Design [2]. It is possible to select one by one all the launch vehicles and obtain several parameters about payload capability for some standard orbits (LEO, GTO and GEO), launcher reliability, injection accuracies and payload accommodations.

The user needs to select each launcher and check whether the information matches the payload requirements. No tool is provided to select all possible launch vehicles that fulfill certain constraints and no interpolation/extrapolation algorithm helps to calculate the payload capability for a special orbit.

CDF Mission Workbook is another Excel sheet that is oriented towards the computations of launcher's performances for elliptic and escape orbits by computing simplified ΔV formulas. Calculations are performed on the upper stage of a launcher (including the payload) from the moment it departs from the LEO parking orbit to a higher elliptic orbit.

This tool provides a rough estimation for the launcher's performances for elliptic and escape orbits. But the user needs to verify by himself which launcher matches the payload requirements. No tool is provided to select all the possible launch vehicles that fulfill certain constraints.

ESA Launch Vehicle Catalogue [3] is a summary of very valuable information of any launch vehicle from USA, Europe, Russia, Ukraine, Japan, China, India, Brazil and Israel. This information is in PDF format with a navigation function. Again, the user needs to go one by one among all the launchers to find out which are suitable for a given payload and no interpolation/extrapolation algorithm is available.

Launcher Selection Module (LNCHR) Orion [1] is a software tool that is intended to help the mission analyst to plan a generic constellation, taking into account a wide range of possible mission requirements and constraints like the target orbit inclination, the launch sites available, the launcher capabilities and some spacecraft related aspects.

The LNCHR uses a Launchers LEO Performances Database and its output file comprised a list of applicable launch vehicles for the constellation. No interpolation/extrapolation algorithm is available.

It is clear that exist several tools which shall help the user to choose an appropriate launcher for its payload and the desired orbit. But no one of them provide the combination of automatic comparison of all launcher inside a database, the possibility of interpolate/extrapolate the payload performance for the desired orbit and the launcher selection procedure based on user specific requirements. This is exactly what LAT will do.

4. DESCRIPTION OF LAT

The idea behind LAT is that the user can identify which commercial available launcher is able to transport its payload to the desired orbit - with just one tool and within few seconds.

Instead of going through the user manuals of each launcher, the user simply fills the program with the required parameters. This is done via a clearly arranged graphical user interface that will be accurately described in chapter 6.

Some specifications are optional and help to constrain the launcher pre-selection in the forefront of running the interpolation/extrapolation algorithm. These are the maximal acceptable launch cost, the requested launch service provider, details about payload dimensions and/or tolerable payload environment. This information is not necessary, but can reduce the computation time significantly: filtering some launchers before the interpolation/extrapolation process.

Other specifications are necessary. These are the payload mass and important orbit information: perigee and apogee altitude respectively the infinite velocity when an escape orbit is chosen and the orbit inclination. The use of a kick-stage is an optional input that is not used to filter the launchers, but to increase the capability of them.

With this information the interpolation/extrapolation algorithm is feed and the computation of possible launcher can be activated.

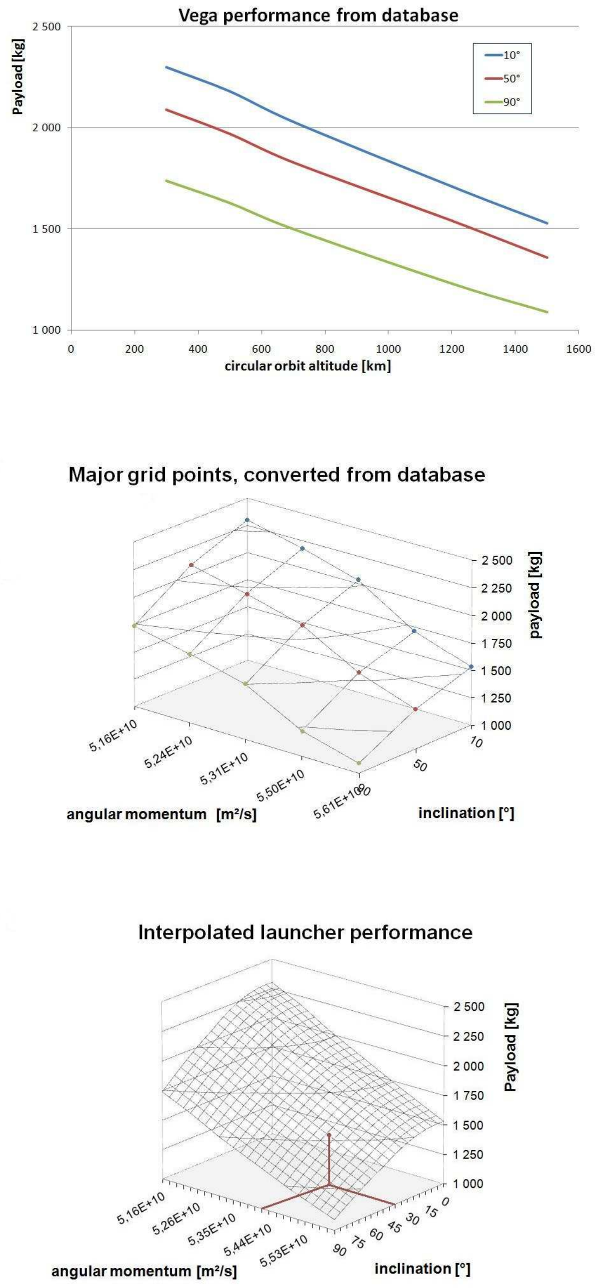

Figure 1. Interpolation process

LAT uses a Space Launcher System Data-Base (SLSDB) [1] that contains a huge amount of specifications of available commercial launch systems. This database includes a performance table for several orbits. If the user desired orbit is identical with one from

the SLSDB no further calculations are needed and LAT simple compares the payload mass from the search criteria with the payload capability of the launcher. This case is not so frequent, since usually the desired orbit is different from those in the database. In this situation, the interpolation/extrapolation algorithm applies.
The user specifications of desired orbit perigee and apogee altitudes describe the orbit type; both these parameters can be incorporated in the mass specific angular momentum *L*.

$$\vec{L} = \vec{r} \times \vec{v} \tag{1}$$

Where *r* is the space craft position from the center of Earth and *v* is its inertial velocity.
This reformulation reduces the parameter size to three (angular momentum, inclination and payload), simplifying the interpolation/extrapolation.
As second step the values in the performance table of SLSDB (grid points) can be arranged over a three dimensional surface as shown in Fig. 1. Via an interpolation algorithm the payload capability of the launcher can be computed for every orbit included in the surface range.
In case the user requested orbit is outside the value range of SLSDB, an extrapolation could be performed. It should be clear that the further the desired orbit deviates from known grid points, the less realistic will become the computed payload. Therefore, the user needs to explicitly allow the application of the extrapolation algorithm and a warning is raised for extrapolation results that are far away from the available SLSDB data.
During the computation process two different interpolation algorithms are implemented: one for the angular momentum of the desired orbit and one for the inclination. Several approaches have been investigated and are compared in chapter 7.
In the case of a kick-stage implementation, additional computations are performed based on the final orbit of the launcher, the user required orbit and the ratio between the kick-stage thrust and the payload weight.

5. LAUNCHER DATABASE

The database used by LAT is a key factor for the final result of the computation. First of all it has to contain all necessary information about the launchers: fairing dimensions, typical payload accommodations during the launch operation, estimated launch price, general information about the launch service provider and the launch site. Optional information about launcher's reliability is advantageous. Moreover the performance tables should be as updated and comprehensive as possible. Those tables determine how accurately the performance of the launcher for the desired orbit will be computed.
Therefore it is important that the database is always kept up to date.
In principle, the user can interface LAT with any database that is available to him or even compile his own catalogue. Astos Solutions uses a database for space launcher systems from ESA/TEC-ECN, SLSDB.

6. GRAPHICAL USER INTERFACE

The present chapter should be intended as a fast "User Guide" for LAT. After connecting to a database through the *file* menu all necessary inputs for computation can be entered in the *Search Criteria* sheet shown in Fig. 2.

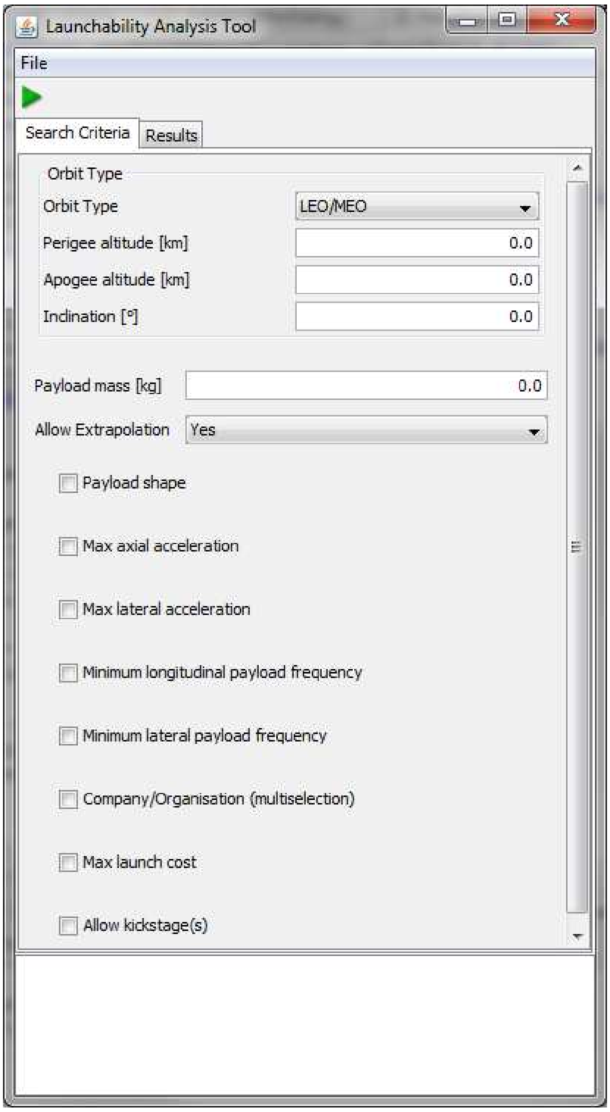

Figure 2. Graphical user interface of LAT

Required inputs are the orbit type and the payload mass. In the drop-down menu of *Orbit Type* LEO/MEO, GTO, polar, SSO and escape trajectories can be chosen. Depending on the choice made, up to three specifications of the orbit must be inserted.
If no extrapolation is allowed, no launcher will be considered for computation which performance data from the linked database does not enclose the desired

orbit.
The other entries are optional and can be activated by selecting the associated check mark.
In particular *Allow Kick-stage* (see Fig. 3) opens a long selection area containing the market available kick-stage and the possibility to define an own module.

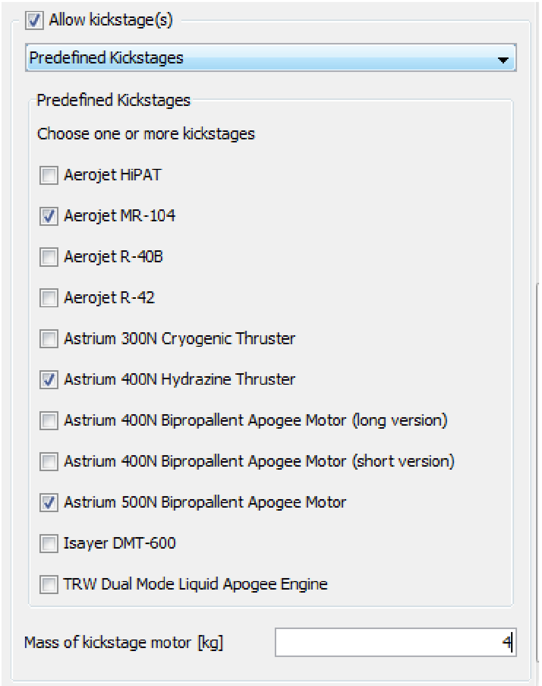

Figure 3. Kick-stage input interface

Details about the payload shape are used to determine whether a suitable payload fairing is available. Dimensions of cylindrical and cuboid payloads can be entered.
Several optional specifications define the acceptable payload environment during the launch operation. If a launcher exceeds these values it will not be considered for further computation.
In the field *Company/Organisation* the user can select the preferred launch service providers, multi-selection is allowed. If this box is not activated all providers are considered.
The last option allows the user to set the upper limit for the launch cost.

6.1. Results Window

After filling the search criteria the computation is started by the green button below the *File* menu. The waiting time depends on the dimension of the connected data-base: with the actual version of SLSDB it takes few seconds to compute suitable launchers that can fulfill the specified mission.
The results are presented in the *Results* sheet (next to the *Search Criteria*). It contains all the launchers that are capable to transport the user defined payload to the desired orbit in alphabetical order. For each launcher some basic information are listed.

- The type of the payload fairing; if more than one suitable fairing is available, they are listed separately.
- The company/organisation and the operator of the launcher.
- The location of the launch site and available azimuth range.
- The estimated launch price.
- The reliability of the launcher and its status.
- A summary of payload accommodations during the launch operation.

The results can be saved to a file for further study and comparison. Therefore the listed launchers can be selected individually or in groups.

7. INTERPOLATION/EXTRAPOLATION RESULTS

For LAT several interpolation algorithms have been studied. It was searched an approach that can be used for both interpolation and extrapolation computation.
Fig. 4 shows two interpolation approaches for the angular momentum. The linear approach is simple and reasonably accurate when the grid points are relatively near to each other. Unfortunately the nature of this approach forces the extrapolated values to underestimate the real ones. The deviation constantly increases with the increasing distance from the grid points making the computed payload not realistic.
The second approach is described in Eq. 2:

$$payload(L) = a + \frac{b}{L} \quad (2)$$

where a and b are variable coefficients and L is the angular momentum.
The coefficients are computed from the performance information of the database, in particular the payload for two orbits with same inclination but different angular momentum.

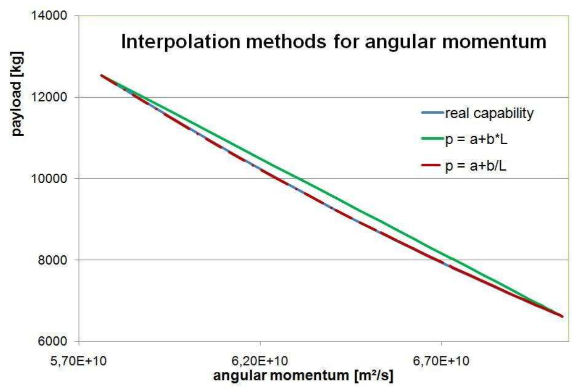

Figure 4. Interpolation of angular momentum

This approach provides a perfect match with the real performance table, so good that the difference is not visually detectable (in Fig. 4 the red line covers the blue one). Also the performances for near extrapolation are acceptable, therefore this approach is implemented in LAT.

The Eq. 2 describes the interpolation of the required payload for the desired angular momentum (i.e. perigee and apogee) for an orbit inclination already defined in the database. In the next step the payload capability for the user specified inclination has to be computed. Several approaches have been evaluated.

The linear approximation provides satisfactory results only when a close-mesh grid points are included in the database, situation rarely present. For extrapolation the computation is really inaccurate.

A second analyzed interpolation algorithm is the Lagrange polynomial interpolation as shown in Eq. 3. This method has the advantage that it can handle any number of data points. If the database contains a number of nodes (*n*), this polynomial interpolation will create a *n-1* degree polynomial. Furthermore the degree of the polynomial increases by adding new performance data to the launcher's database. With this approach all data points are included in the computation.

$$payload(x) = \sum_{i=0}^{n} \left(f_i \cdot \prod_{k=0,k\neq i}^{n} \frac{x - x_k}{x_i - x_k} \right) \quad (3)$$

where x is the user desired orbit inclination, f_i is the payload capability for same angular momentum but different inclinations from database, x_i and x_k are orbit inclinations from database.

On the other hand the polynomial interpolation has two serious disadvantages.

The first one is displayed in Fig. 5. The real curve of the payload performance for the Vega launcher is displayed in blue. Ten reference grid points are marked. For the test of the algorithms only the inner six of them were used as input data points; the interpolation-extrapolation capability can be appreciated respectively in the internal-external part of the curves.

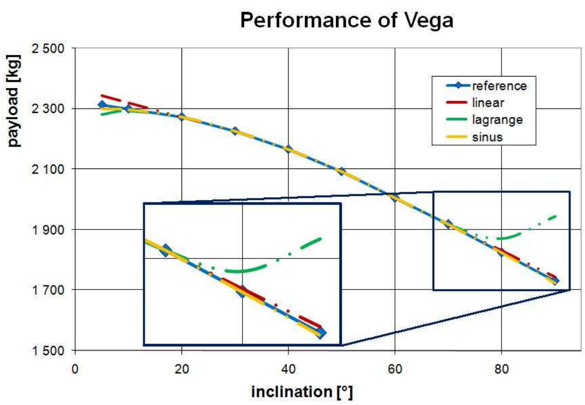

Figure 5. Interpolation of inclination

The green curve (Lagrange) has a satisfying correlation with the original values as long as it lies between the input data points (interpolation). But on the edges it is diverging from the real performance data: bad extrapolation.

The second disadvantage is visible only if more data points are taken into account. Where more then ten input data points are considered, the curve becomes oscillating; known problem for high degree polynomials.

For these two reasons the Lagrange polynomial interpolation has been discarded.

The method implemented in LAT for computing the payload capability depending on desired inclination is a trigonometric interpolation, as shown in Eq. 4.

$$payload(i) = a + b \cdot \cos(i) \quad (4)$$

Where a and b are variable coefficients and i is the orbit inclination.

The coefficients are computed by using the performance information of two grid points with same angular momentum but different orbit inclinations.

The use of trigonometric interpolation is in line with the physic involved: the required ΔV for plane change depends trigonometrically on the difference in inclination between the two orbits [4]. The correlation is shown in Eq. 5.

$$\frac{\Delta V}{V_1} = 2 \cdot \sin\left(\frac{\Delta i}{2}\right) \quad (5)$$

Where V_1 is the orbit velocity before the plane change and Δi is the inclination difference between the two planes.

The trigonometric interpolation is the yellow dashed curve in Fig. 5: the computed performance is in line with the real grid points both during interpolation and extrapolation.

Interpolation is always performed considering the two nearest data points. Instead for extrapolation the outer points are used.

An extensive error analysis for the Delta IV family of launchers indicates that the deviation between the computed and the real payload performance does not exceed five percent during extrapolation and is more accurate for interpolation. It is clear that the deviation depends strongly on the distance between the known point (performance table in database) and the user desired orbit. Further information about the error analysis can be found in [5].

7.1. Kick-stage computation

The additional of a small stage with variable propellant mass will increase the overall ΔV of a launcher. In this way the desired orbit could be achieved with a launch system that naturally has not the required performance.

In order to perform the orbit transfer, the start orbit and the final orbit have to be defined. The final orbit equals the user-defined desired orbit. For the start orbit, the orbit out of the launcher database that comes closest to the desired orbit regarding orbit energy and inclination is chosen. Furthermore, LAT checks that the initial orbit energy is lower than the final orbit energy. The next step is to calculate the required ΔV for the orbit transfer, including inclination change. For the calculation the orbit transfer is treated as a Hohmann transfer, consisting of three impulsive maneuvers: raise of the apogee, inclination change, raise of the perigee. The ΔV for the raise of apogee and perigee can be calculated by using the Vis-Viva-Equation, Eq. 6

$$v = \mu \cdot \left(\frac{2}{r} - \frac{1}{a} \right) \qquad (6)$$

Where v is the inertial velocity, $\mu = 3.986 \cdot 10^{14}$ m³/s² is the gravitational constant of the Earth, r is the distance to the Earth's center and a is the semi-major axis. The ΔV for the inclination change is calculated by Eq. 5 where V_1 is the inertial velocity at the apogee of the Hohmann ellipse and Δi is the difference between start orbit inclination and final orbit inclination. As in reality the maneuvers are not impulsive, the resulting ΔV is incremented by losses.

An extensive optimization work has been performed to evaluate the losses resulting from orbital transfer. The result of these optimizations are summarized in a table function of: the energy difference between the initial and final orbit, the orbit inclination difference, the range of true anomaly during burn time and the code of conduct for upper stages.

The next step is to calculate the mass of the required propellant for the orbit transfer. Therefore, the burnout mass of the kick-stage after the transfer needs to be calculated first by applying Eq. 7.

$$m_b = \frac{m_0}{e^{\left(\frac{\Delta V}{I_{sp} \cdot g_0} \right)}} \qquad (7)$$

Where m_b is the burnout mass of the kick-stage, m_0 is the maximum payload mass the launcher can bring into the start orbit of the orbit transfer, ΔV is the required change of velocity for the orbit transfer (including the losses), I_{sp} is the specific impulse of the kick-stage motor and g_0 is the standard gravity acceleration. The mass of the required propellant is then the difference between m_0 and m_b. The mass of the kick-stage tank is assumed to be 10% of the propellant mass. Finally, the maximum payload mass for the desired orbit can be calculated as:

$$m_{payload} = m_b - 0.1 \cdot (m_0 - m_b) - m_m \qquad (8)$$

Where m_m is the motor mass of the kick stage.

The payload mass so computed is then compared with the user requested one and in case the request is Eq. 8 is higher the launcher with the specific kick stage is included in the list of the result window.

8. CONCLUSION AND FUTURE REMARKS

Up to now there is no tool on the market that enables a comfortable and fast computation of launcher performance. Therefore Astos Solutions developed LAT. To facilitate the handling LAT offers a friendly user graphical interface. Numerous selection criteria allow the search of appropriate launchers for the desired orbit and payload mass.

A comprehensive database with performance tables of commercial launchers has to be linked to LAT. Between the data points from the database LAT interpolates the payload capability with the best fitting algorithms. Where the required orbit is external to the database, an extrapolation is performed. In the case the presence of a kick-stage is requested additional computations are performed according to the user selection. Interesting is the extensive optimization work performed to define the losses as function of typical parameters.

All launchers that fulfill the user requirements are presented in a clearly arranged result sheet with some additional basic information about launch site and launch provider. The kick-stage with variable propellant mass will increase the overall ΔV of a launcher: in this way the desired orbit could be achieved with a launch system that naturally has not the required performance. With this approach a wider range of launcher systems will be presented to the user with the possibility to reduce the launch cost.

For future outlook the kick-stage could be based on electrical low thrust propulsion with a new optimization task to identify the losses in this different scenario.

Additional work can be performed on the interplanetary scenarios, with the definition of typical target function of the required ΔV to achieve them: payload mass in Mars orbit.

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