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Multi-Disciplinary Optimisation of Re-entry Vehicles from TAEM to Landing

Giovanni Medici, Alina Ionita**, Gabriele De Zaiacomo*, Davide Bonetti*, Fernando Pina**, Celia Yabar†*
** DEIMOS Space S.L.U., Madrid, 28760, Spain, giovanni.medici@deimos-space.com*
*** DEIMOS Space S.R.L., Bucharest, 011013, Romani, fpina@deimos.com.ro*
† ESA/ESTEC, Noordwijk, 2201, Netherlands, celia.yabar.valles@esa.int

Abstract
In the context of the “Terminal entry and landing Mission, System, and GNC requirements for re-entry vehicles” (ESA study REVLANSYS), the objective is to perform an end-to-end design of the terminal entry and landing phase for an autonomous re-entry vehicle and derive coherent Mission, System and GNC requirements. From a Mission and System design point of view, in order to address such a complex scenario, taking into account different system concepts, a proper mathematical model of the problem is necessary. Therefore, a Multidisciplinary Design Analysis (MDA) core has been implemented, as the instrument to evaluate the performance of the different concepts to be traded-off as function of key design parameters.

1. Introduction

Europe has been very active the last decades in the investigation and development of re-entry technologies. The most European relevant programs include different vehicles, from capsules (the Atmospheric Re-entry Demonstrator, ARD, launched in 1998), to biconic (the European eXPErimental Re-entry Test-bed, eXpert, pending launcher selection), to the more advanced lifting body Intermediate eXperimental Vehicle (IXV, that performed a flawless re-entry mission on Feb 11th 2015), which will pave the way for future re-entry capabilities based on the development and testing of critical technologies.
These European programs focused on high speed controlled or uncontrolled re-entry flight (up to transonic), to eventually end up with a splashdown on the ocean after a descent under parachute. In other European activities aspects of the TAEM and landing problem have been considered, but these have not reached a high maturity level or have had a limited scope. The next logical step towards an operational system with higher flexibility is therefore to allow the vehicle to carry out a soft landing in a runway or prepared field as a precursor for reusable concepts. Upcoming European programs will however focus on these flight phases. In particular, IXV is being followed by the development of an affordable, reusable end-to-end Integrated Space Transportation System Service (SPACE RIDER), which will fly during the TAEM and landing phases.
In this context, the objective of REVLANSYS is to develop key technologies in the field of Mission Engineering and GNC for the terminal entry and landing phase for an autonomous re-entry vehicle, and derive coherent mission, system and GNC requirements.
Within the REVLANSYS study, the reusability requirement was addressed taking into account several strategies at system level. An initial state of the art technology and missions survey led, in the initial phases of the study, to a system concept trade-off activity. Several system concepts were considered and evaluated in terms of: Turnaround time, Weight/Design simplicity, Technology Readiness Level (TRL), precise landing capability, acceleration loads (G-Load), Volume/Payload Efficiency, Autonomous system capability, and launcher compatibility. A scoring method based on the state of the art survey, has been adopted to evaluate each system concept.
The output of the trade-off, among the possible solutions, highlighted two system concepts as the most promising, namely: a Lifting Body with Parafoil, and an High Efficiency Lifting Body, with conventional runway landing gear or skids.
Then, a Multidisciplinary Design Analysis (MDA) core has been implemented, as the instrument to numerically evaluate the performance of the different concepts to be traded-off as function of key design parameters. The MDA is a software tool whose architecture is based on a Design Structure Matrix (DSM) approach to properly take into account the connections (inputs and outputs) and dependencies among the disciplines considered. Each discipline is

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modelled by a tool or a set of tools that produces as output the performance related to it. The modules are connected to each other, so to share required inputs and outputs according to the MDA-DSM. Considering the intrinsic differences between the promising system concepts considered and traded-off in REVLANSYS, two different MDA were implemented: one for the horizontal landing scenario, and the other for the parafoil-aided scenario.
The DEIMOS Space proprietary tool ESAT (EDL/GNC Sizing and Analysis Tool, successfully used in multiple MDO problems [6], [7]) manages the MDA process and provides the framework for the MDA external interface (design parameters and performance), supporting the performance analysis and the Multi-Disciplinary-Multi-Objective Design Optimization processes. ESAT relies on an efficient optimization of metamodels of the MDA problem (fitting and optimizing surrogate models of the MDA outputs) allowing the design engineers to focus the efforts on the most promising regions of the problem domain. Extensive performance-design parameters metamodels were fitted and explored with ESAT, allowing a detailed characterisation of the problem. As a final step, a multi-objective optimisation has been performed, and Pareto-dominant solutions have been identified for both scenarios. These winning solutions are the input to the subsequent final trade-off in order to select the candidate configuration for detailed Mission and GNC design.

2. Multi-Disciplinary-Analysis

To perform the end-to-end mission and system design of the terminal entry and landing phase for an autonomous re-entry vehicle, and to derive coherent mission, system and GNC requirements, is a multidisciplinary design analysis and optimization process in its nature: different disciplines contribute to the correct modelling and optimization of the different aspects of this challenging problem. The MDO result is the optimum system and mission design solution obtained as equilibrium of given conflicting objectives. In order to perform the MDA-MDO process, a proper mathematical modelling of the problem is necessary: a Multidisciplinary Design Analysis (MDA) core is the key instrument to evaluate the performance of the different concepts to be traded-off. The MDA is performed in a three-step process:

1. identification of the disciplines involved and the tools/models used for each one.
2. identification of the connections (inputs and outputs) from/to each discipline.
3. identification of structured MDA process steps.

Ideally, each discipline is modelled by a tool or a performance model that allows a numerical quantification of the related performance. The proper model definition is indeed a balance between the accuracy of the prediction and the accuracy required by the status of the current analysis, with the additional constraint of the time required to perform the analysis. A simple list of disciplines/models is not enough to achieve an MDA: the second step required is the identification and consolidation of proper links (inputs and outputs) between them. Inputs for a discipline are typically the outputs of another one: as a result, design variables are shared in such a way that all the disciplines perform simultaneously a coherent and consistent analysis. Finally, once the links are clarified, a list of design steps can be identified to allow a clear and structured flow of information across the different disciplines.
Overall this complex three-steps process is supported by the Design Structure Matrix (DSM) approach, which is a method to visualize in a single chart all the disciplines and the interactions among them, providing in a single picture an overall view of the MDA [4].
The DSM (Figure 1) shows in a matrix form the following information:

- Diagonal: disciplines and responsible
- Columns: Inputs from other disciplines
- Rows: Outputs for other disciplines

In the case of a two way interaction between disciplines (two disciplines share both inputs and outputs, meaning that an internal design loop is present) convergence to a common list of inputs/outputs is required to guarantee that coherent analyses are performed by both disciplines.
Common external inputs, fixed or variable, are identified and fed to the MDA function. The variable parameters in particular will be explored within a pre defined range during the MDO process, and are therefore called Design Parameters. The fixed parameters normally are used to define the boundaries of the problem, or design parameters that are constant for a given study case or scenario. Common external outputs define the performance associated to the MDA. Within the MDO process therefore the effects on the performance given by the variation of the design parameters are explored, in order to quantitatively map their relationship, and identify an optimum solution with respect to the considered scenario.
For the REVLANSYS project, an optimum minimum set of disciplines has been selected, covering system aspects, vehicle geometry, aerodynamics, flying qualities, mission analysis and trajectory performance. The outcome of all these disciplines is a set of figures of merit, aimed at supporting design choices for the optimisation of re-entry vehicles from TAEM to landing, in line with the project objectives. For all the disciplines listed above, DEIMOS Space has got recognized expertise and is provided with state of the art tools to perform the analyses needed [8].

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2.1 Design Structure matrix

The DSM for the MDA of the end-to-end mission and system design of the terminal entry and landing phase for an autonomous re-entry vehicle is shown in Figure 1: it corresponds to the internal core of the overall matrix. On top of it, the optimization (MDO) loop is shown adding two extra lines and columns:

- The first top line corresponds to the optimization inputs: MDO settings, fixed and variable inputs that define the optimization problem design space within which the optimum solutions are looked for.
- The last bottom line corresponds to the optimization outputs: performance/Figures of Merit computed by the different disciplines and optimization objectives.

The DSM supports the identification of a structured list of process steps, guaranteeing that the MDA has been properly set up. This complex task is simplified by the vision gained through the DSM. Starting from the DSM, the process identified is shown in Figure 2. This process diagram shows the internal design loops identified with the DSM as red blocks: outputs from a discipline are inputs for the previous one: convergence shall be guaranteed to achieve a coherent design. The classic view also includes the optimization loop on top of the MDA core.

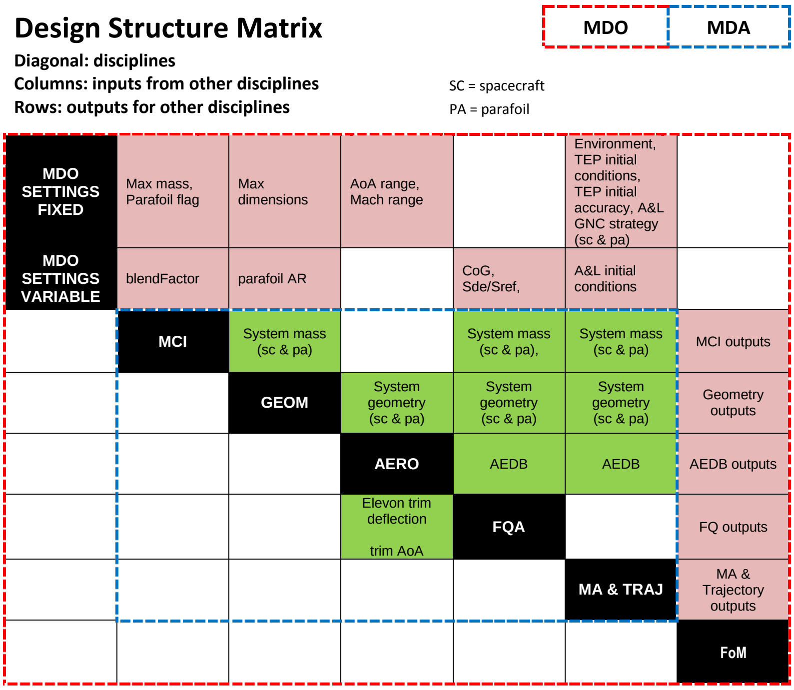

Figure 1: Design Structure Matrix (MDA and MDO) for REVLANSYS

As a synthetic output, a list of steps from 1 to 5 has been derived to organize the sequence of disciplines/models calls from the high level point of view. Prior to that, the initial trade off activity performed in the past contributed to identify some problem boundaries:

- Step 0: preliminary mission and system trade off to identify problem boundaries, constraints and objectives.
- Step 1: define which inputs are varied during the MDO; the remaining ones are fixed to given values for a given scenario/study case.
- Step 2: based on the selected set of inputs, MCI and Geometry properties of the system are computed.
- Step 3: based on the aeroshape, the reference aerodynamic model is built for a given range of flight conditions.
- Step 4: FQ computes the trimmability, and the associated surface deflection, given a desired CoG location. Once the trim is found, a loop with AEDB is done to provide the aerodynamic characteristics of the trimmed vehicle.
- Step 5: Mission analysis computes the trajectory performance associated to solution under evaluation.
- Step 6: overall performance/figures of merit are computed.

The MDA/MDO problem has been faced in details during the MDA definition activity, translating the theoretical approach described above into real models, interactions and analyses loops. More details about each model interfaces and the design parameters/performance chosen are provided in the next sections 2.2 to 2.5 of this paper.

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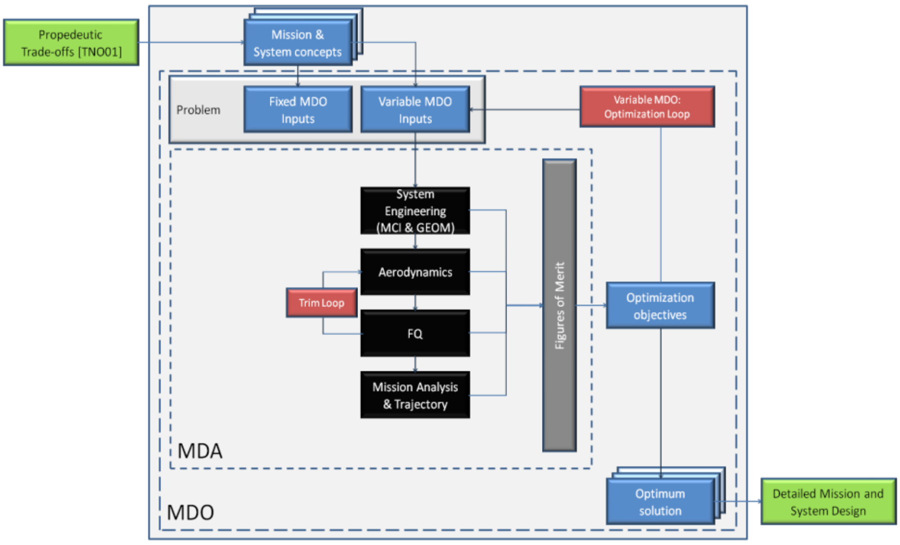

Figure 2: Process steps chart for REVLANSYS

2.2 Aerodynamics Module

The aerodynamic performance of the two system concepts, although their geometry is not extremely different from an aeroshape point of view, is expected to vary considerably, to the point that one system is expected to be capable to land horizontally, while the other one (lifting body), is expected to require an additional device (parafoil), to be able to cope with the part of the mission with the lowest energy. The need to perform an analysis with the possibility to vary continuously between the two system concepts requires the definition of an intermediate aerodynamic database (AEDB), able to be representative of the two concepts and of solutions in the middle of them.
Considering the dimensions of representative system concepts, such the ones presented in Figure 3, a trend may be identified which connects the reference volume and the weight of the spacecraft, with its aerodynamic performance.
The rationale of this approach is that ideally the aerodynamic empennages imply added surface, hence apparent volume, with lower density. Winglets, for instance, are likely to be empty (beside the structure and TPS). A Lifting body, on the other hand, can reach higher levels of density, being easier to fit in the subsystems closer to CoG. A parameter called Blend Function was therefore defined for a given vehicle to correlate the mass properties with its volume. Normalised with respect to a reference value, it provides an indicator of the aerodynamic capability associated to each aeroshape: low efficiency lifting bodies (IXV-like) have a Blend Function of 0, X-38 ~ 0.45, HL-20 ~0.6, the Space Shuttle ~0.85. Blend Function is used in order to compute the aeroshape reference dimension as well as the mass of the spacecraft. Given the maximum length available in the launcher, a first guess approximation of the reference Surface, span, height, and mass of the spacecraft can be made.
The aerodynamics module aimed to simplify the definition of the aerodynamic database of a given spacecraft, while providing representative longitudinal aerodynamic performance for the given aeroshape, given that it is not expected to match perfectly the real spacecraft aerodynamic database. Anyway, as Figure 5 shows, the L/D slope, as well as the maximum value of the L/D is modelled correctly, at various Mach numbers, for the case of the Space Shuttle, and the X-38 (with an elevator deflection of 20 [deg]). The aerodynamic module is then capable of producing representative databases for a range of vehicles, from L/D ~ 0.7 (lifting bodies) to L/D ~ 4.5 (high efficiency lifting bodies).

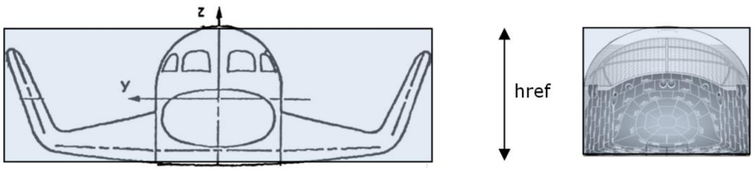

Figure 3: graphical representation of system concepts (left: high efficiency lifting body, right: lifting body)

If the vehicle presents a too low L/D in subsonic flight regime, a horizontal landing cannot be performed therefore an extra subsystem is needed to improve performance and complete the mission, hence a subsonic parafoil deployment is a possible solution. To cover this possibility, the aerodynamic module is capable of modelling the aerodynamics of

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a parafoil canopy as well (see Figure 4), with custom aspect ratios or reference surface, as well as vehicles of different sizes and aerodynamics.
As a summary, the Aerodynamics Module interfaces are shown in Table 1.

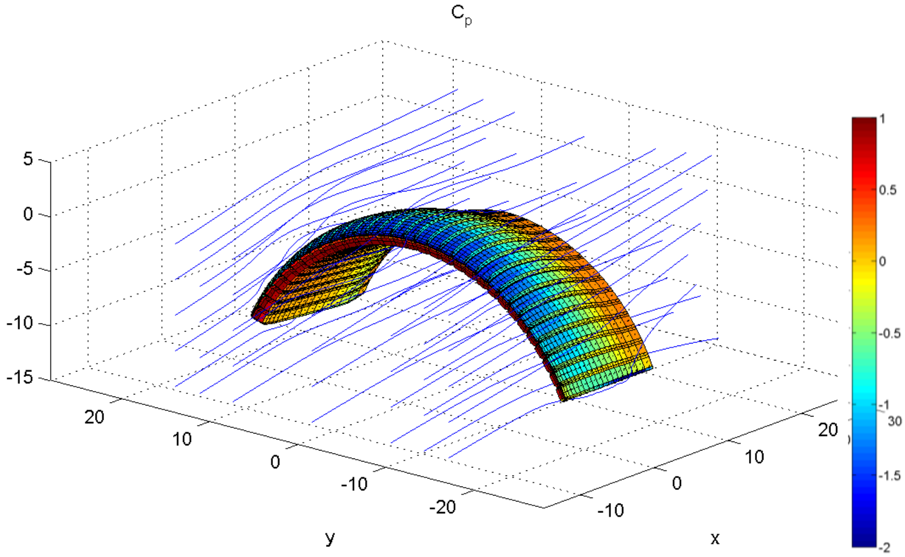

Figure 4: X-38 parafoil geometry, 3D Panel Method AoA=8.8 [deg]

Table 1: interface definition of the aerodynamics module.

Type	Variable	Description
Input	Parafoil flag	Flag indicating whether the system is equipped with a Parafoil.
	Blend Function	Blend Function for the candidate aeroshape
	AoA, Mach range	Range of flight for the mission (TEP to touchdown)
	Vehicle dimensions	Vehicle dimensions (reference surface, span, height)
	Parafoil dimensions and AR	Parafoil dimensions (reference surface, span, chord) and Aspect Ratio
	Trim AoA and Elevon deflection	AoA and Elevon deflection to trim the vehicle for a given CoG
Output	Aero Coefficients	C_L, C_D, C_M (AoA, Mach) of the vehicle and parafoil (flying in trim)

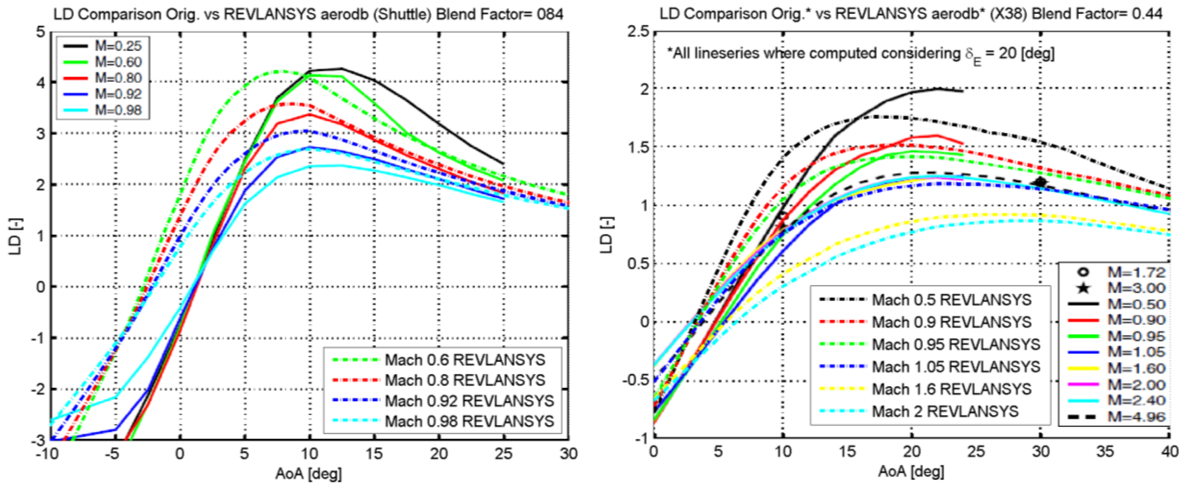

Figure 5: Shuttle (left), and X-38 (right) aerodynamic Database [1], compared to REVLANSYS Blend Function.

2.3 Geometry and System Modules

The output of the MDO study of REVLANSYS shall not only satisfy the aerodynamic and trajectory constraints, but also be consistent with several system constraints (mass and volume budgets): Mass, CoG position and Inertia level (MCI), reference Length, Surface, span of the spacecraft. Given the payload maximum weight, using the Blend

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Function, a unique combination of vehicle aerodynamic performance and dimensions (e.g. external shape, in terms of reference Surface and reference Height ratio) can be found.
The other parameters that affect the geometry and system modules are specified in Table 2 and Table 3.

Table 2: interface definition of the Geometry module.

Type	Variable	Description
Input	Parafoil flag	Flag that indicates the inclusion/exclusion of the parafoil from system design.
	Max vehicle dimensions	L_{max}, b_{max}, h_{max} (considered to take into account compatibility with available launchers fairing).
	Blend Function	Blend Function for the candidate aeroshape
	Parafoil AR	Aspect ratio of the parafoil
	Vehicle mass	Mass of the vehicle
	Parafoil mass	Mass of the parachute
Output	Vehicle dimensions	Vehicle dimensions (reference surface, span, height)
	Parafoil dimensions	Parafoil dimensions (reference surface, span, chord)

Table 3: interface definition of the System module.

Type	Variable	Description
Input	Parafoil flag	Flag that indicates the inclusion/exclusion of the parafoil from system design.
	Mass max	Maximum system mass at TEP. A limit to system mass is assumed to take into account compatibility with available launchers and possible payload.
	Blend Function	Blend Function for the candidate aeroshape
Output	Vehicle mass	Mass of the vehicle
	Parafoil mass	Mass of the parachute

2.4 Flying Qualities Analyses Module

Briefly, Flying Qualities Analyses (FQA) cover the trim and stability properties of the vehicle.
This module is in charge of computing the trim and the corresponding elevator deflection, using as input the spacecraft aerodynamics module. The module is also able to compute the static margin at centre of gravity specified by the system input. The elevators size is one of the key design parameters for the longitudinal trim analysis, driven by margins with respect to the control saturation of control means (maximum realistic elevators deflections).
With the FQ module it is possible to assess the effects of these inputs over the trim elevator deflection, the stability or the key performance for mission analysis: the Lift over Drag (Figure 6, left). Nonlinearities, such as saturation of control surfaces, are considered (see Figure 6, right, small elevators cases).
The interface definition of the FQA module, and relevant inputs and outputs it can handle, is shown in Table 4.

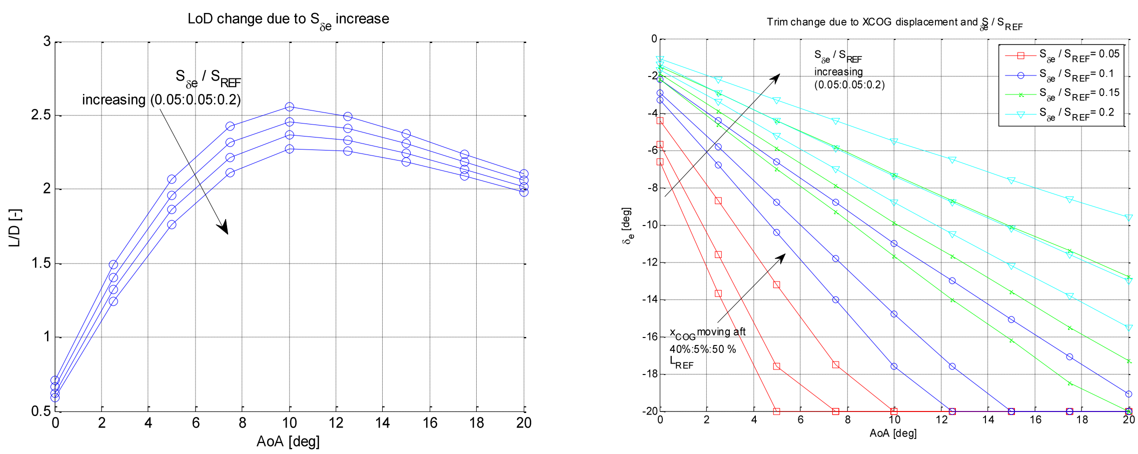

Figure 6: Elevator to reference Surface ratio effect and x coordinate of COG on trim and aerodynamics.

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Table 4: interface definition of the FQA module.

Type	Variable	Description
Input	CoG shift	Delta CoG position for trim computation
	Sde/Sref ratio	Ratio for elevon surface vs reference surface
	Vehicle/Parafoil mass	Mass of the vehicle and of the Parafoil
	Vehicle/Parafoil dimensions	Vehicle/Parafoil dimensions (reference surface, span, height/chord)
	Aero Coefficients	C_L, C_D, C_M (AoA, Mach) of the vehicle and parafoil (flying in trim)
Output	AoA range	AoA range associated to the trim that provides the aerodynamic performance
	Control surface saturation	Flag that identifies if the elevon is saturated
	Trim AoA and Elevon deflection	AoA and Elevon deflection to trim the vehicle for a given CoG

2.5 Trajectory Module

This module computes reliable prediction of trajectory performance, required to estimate the influence of the design parameters on the reference trajectory that is ultimately the final output of the mission analysis. For TAEM and landing mission design, and according to the preliminary solutions identified, three different phases are identified:

- TAEM phase
- Approach and horizontal landing with a high efficiency lifting body
- Approach and soft landing under parafoil

For each one a performance estimation module has been developed, to assess the main performance for each case depending on the design parameters.

The TAEM phase starts at the end of the entry, namely from Mach ~2.5 down to Mach ~0.5, and can be considered common for both concepts, even if with different performance or objectives depending on the vehicle solution considered (targeting runway alignment of the correct parachute trigger conditions). In the range of aerodynamic capabilities associated to the vehicle classes considered within this study (lifting body up to high efficient lifting bodies) the performance obtained at the end of the entry phase are well within the constraints considered for this type of missions. Thus, the TAEM phase does not represent from the Mission and System point of view a critical design phase. Therefore, the trajectory module focused on defining performance model for the following landing phase.

Horizontal Landing on Runway:

To define a performance model for the approach and horizontal landing trajectory, the main reference is the Space Shuttle Orbiter. The landing procedure is presented in Figure 7 separated in four different phases from ALI (Approach and Landing Interface) to touchdown, defined as follows:

1. Approaching Glide: the vehicle approaches the runway with a gliding flight with constant flight path angle.
2. Pre-Flare Pull Up: the vehicle performs a pull up to circularise the trajectory and reach the FPA for the last glide.
3. Final Glide: the final flight path angle is sustained to perform a gliding approach until a specified height.
4. Final Flare: a manoeuvre is performed with the objective of reaching the desired vertical velocity at touchdown.

Performance during the approach and landing (A&L) and at touchdown can be obtained as function of the considered design parameters (see Figure 8 and Table 5). In the figure, triangles mark those situations where it is not possible to sustain the second glide phase, with the desired FPA, for the given vertical efficiency values assumed. The yellow marks identify situations where it would be possible to fly, only in case the initial L/D was the maximum achievable (4). On the other hand, a red mark indicates points whose required L/D would be higher than 4, hence considered a not feasible solution. The model behaviour has been validated against known Space Shuttle performance.

Soft Landing with Parafoil):

To define a performance model for the approach and soft landing trajectory the main reference is the X-38 experience. At the end of the TAEM the Descent and Recovery System procedure is initiated, that is concluded at full parafoil deployment. From there, the system flies a trajectory that is defined by different phases, designed to cope with the parafoil capabilities in terms of glide ratio and limitations in terms of trajectory controllability/maneouverability (see Figure 9 and [5]):

- Acquisition: an initial turn towards the homing leg and the remainder of the trajectory.
- Homing: a straight line from initial position to where it can intercept the Energy Management Circle (EMC).
- EMC Entry: a fairly aggressive turn to transition from Homing onto the Energy Management Circle.
- Energy Management Circle (EMC): a 'loitering' circle in space that drifted with the wind field towards the target.
- EMC Exit: a fairly aggressive turn out of the EMC onto the landing heading.
- Final: the final landing phase to reduce the glide velocity prior to touchdown.

Similarly, the trajectory performance during descent is provided as function of key design parameters (see Figure 10 and Table 5). The model behaviour has been validated against known X-38 parafoil performance.

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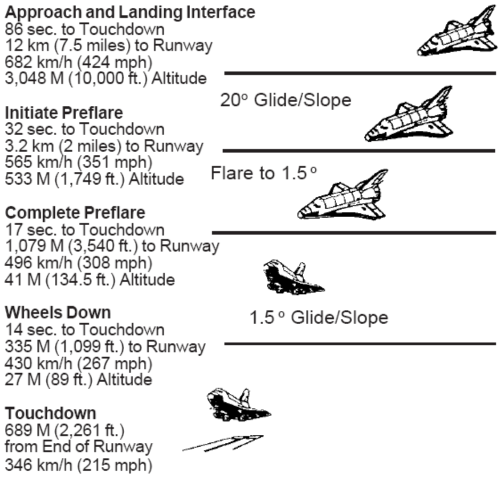

Figure 7: Space Shuttle A&L strategy (credits NASA)

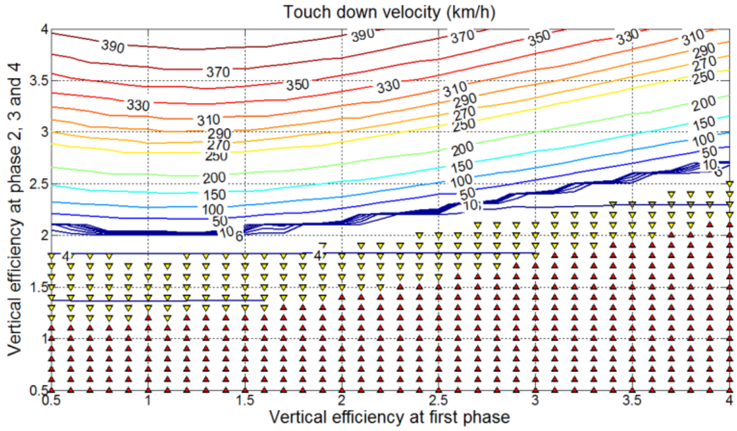

Figure 8: Touchdown velocity with respect to vertical efficiency (Horizontal Landing)

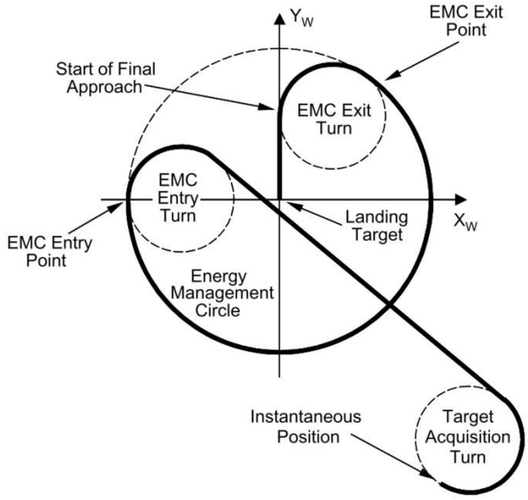

Figure 9: X38 descent strategy (credits NASA).

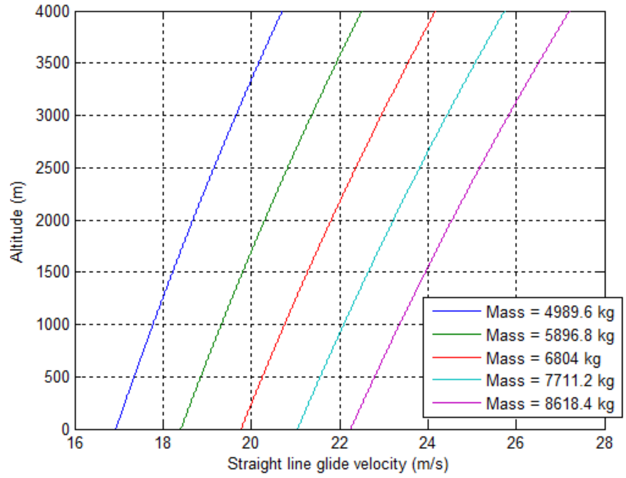

Figure 10: Parafoil glide velocity performance

Table 5: Summarizes the interface definition of the Trajectory module.

Type	Variable	Description
Input	Parafoil flag	Flag that indicates the inclusion/exclusion of the parafoil from system design.
	AoA, Mach range	Range of flight for the mission (TEP to touchdown)
	Atmospheric and Wind model	Reference models for trajectory computation
	TEP conditions	Initial conditions at TAEM Entry Point and achievable position accuracy at TEP
	A&L phase parameters	Definition of interfaces between the A&L phases , approach and final glide angles, Target touchdown velocity for a winged vehicle horizontal landing
	Parafoil descent parameters	Nominal bank to flight on the EMC circle for parafoil landing
	Vehicle and Parafoil mass, dimensions	Mass and dimensions of the vehicle and parafoil
	Aero Coefficients	C_L, C_D, C_M (AoA, Mach) of the vehicle and parafoil (flying in trim)
Output	A&L phase FoM	Velocity at touchdown, distance needed stop the vehicle, runway length required, minimum touchdown velocity required to assure that Lift = Weight, load factor experienced by the vehicle during the initial flare manoeuvre, time elapsed from LG deployment until touchdown
	Parafoil Descent FoM	Velocity at touchdown, distance needed stop the vehicle, required runway (or prepared field) length, altitude margin with respect to the minimum altitude estimated to reach the target, maximum turn rate achievable to perform manoeuvres
	Reference trajectory	Initial Reference trajectory

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3. Multidisciplinary Design Optimisation (MDO)

The preliminary mission and vehicle design is carried out by an end-to-end Multidisciplinary Design Optimisation process, that optimises given mission performance (requirements and figures of merits) by varying selected mission and system design parameters and evaluating the MDA module, that represent the integrated Mission and System design chain. The next sections cover the analysis that took place to perform the MDO activity.

3.1 ESAT Tool

The EDLS/GNC Sizing and Analysis Tool (ESAT) is a DEIMOS Space proprietary tool conceived and designed to support the system trade-offs process and the selection of optimum design solutions. It has been successfully applied by DEIMOS to the MDO of EDL systems on Mars [6] and to the MDO of UAVs for Titan exploration [7].

ESAT relies on the construction and analysis of maps of performance. Maps of performance are the core element of the ESAT and are built by calling a given external module in selected design points.

The external modules are mathematical models of the given problem (for this project, the MDA for the TAEM, descent, approach and landing system performance). In general, different external modules have different inputs and outputs. Through dedicated wrappers, different external modules can be interfaced with ESAT: this allows flexibility and in principle any kind of problem at any level of complexity can be managed.

Wrappers are functions that receive the ESAT design point and call the external module making the necessary settings and data conversions to match the required inputs for the external module. One design point (sample) is a single combination of the inputs of the external module in the N-dimensional hyperspace of possible inputs. Through the wrapper, the ESAT sees an external module as a "black box" managing only the inputs and outputs.

Maps rely on the external model results and are built by calling the wrappers in different design points (samples): predictions of performance in any point of the domain space are provided by interpolating the results in the known points. As the problem dimensions and complexity rise, more external modules calls are required to achieve the desired level of confidence and to guarantee sufficient coverage of the design space.

The advantage given by building maps is that the maps query time is much lower than the time to run an external module. This opens up a wide range of analysis, so it would not be practical, due to time constraints, if the external module, was to be interrogated each time. The use of maps is also a smart solution to manage high number of problem dimensions, given by the list of inputs considered to cover all the possible trade-off and optimization required.

3.2 Preliminary Mission and System Sensitivities Analyses

A multidisciplinary design can take advantage of optimization tools, and a great improvement in the design process can be achieved by means of computation aids, and preliminary design tools. Anyway engineers shall always be in the loop, to control the outputs as well as to identify possible modelling errors. For this reason the analysis is not only limited to a dry run of the optimization tool; but relevant performance (outputs) need to be analyzed. This approach enables the engineer to monitor solution’s trend, magnitude, and explore the solution domain.

Moreover it is possible to compute the correlation between inputs and outputs, thus evaluating the cross-dependency between the parameters. An example of such plot is shown in Figure 11: the strong correlation between blend function, X CoG, and Mach number is quite evident, as far as maximum aerodynamic performance (max L/D), is concerned. On the other hand, Wing loading depends on four different parameters: blend function, maximum mass, length and height, while the Static Margin is only correlated to X CoG position.

Once the most correlated inputs outputs are outlined, it is possible to visualize the dependency between four parameters. An example of such an approach is shown in Figure 12. The maximum L/D increases as Mach number lowers, the effect of the displacement of X CoG is due to the contribution of elevator deflection to axial and normal coefficients. The Mach, blend function and X CoG dependency of the maximum spacecraft L/D confirm that the aerodynamics module provides representative values.

Constraints limit the performance to the feasible range, easily identifying parts of the domain that are discarded. An example of the filtering effects is shown in Figure 13 for a horizontal landing on runway test case. The results were filtered so that only feasible solutions are plotted, that is: if touchdown velocity required is lower of the minimum touchdown speed (stall speed) achievable by the spacecraft, solution is not feasible. Moreover, if the L/D required is higher than the maximum L/D achievable by the spacecraft, the solution is not feasible. Figure 13 shows that for low values of blend function, the only feasible solution is constrained within a limited L/D envelope for each A&L phase (for ph.2 to 4 the same L/D is assumed). Moreover, long runways are needed to stop the spacecraft, this would limit the platform to land only on runways respecting the length constraint. A judicious filtering of the feasible solutions,

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as well as focused analysis on relevant input parameters, allows identifying, for each system concept, promising design parameter intervals for the optimisation process.

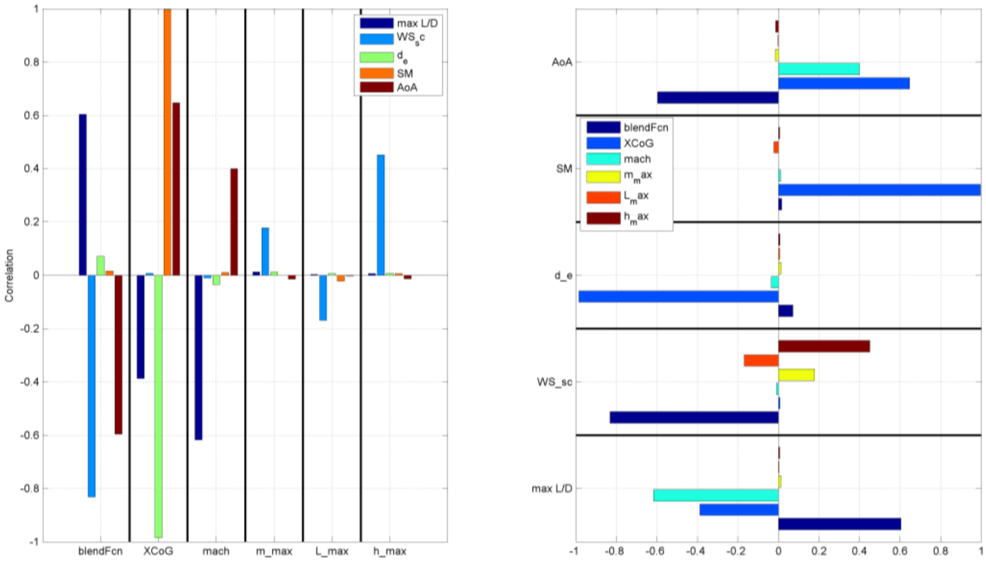

Figure 11: Input output correlation TAEM to ALI/PDI.

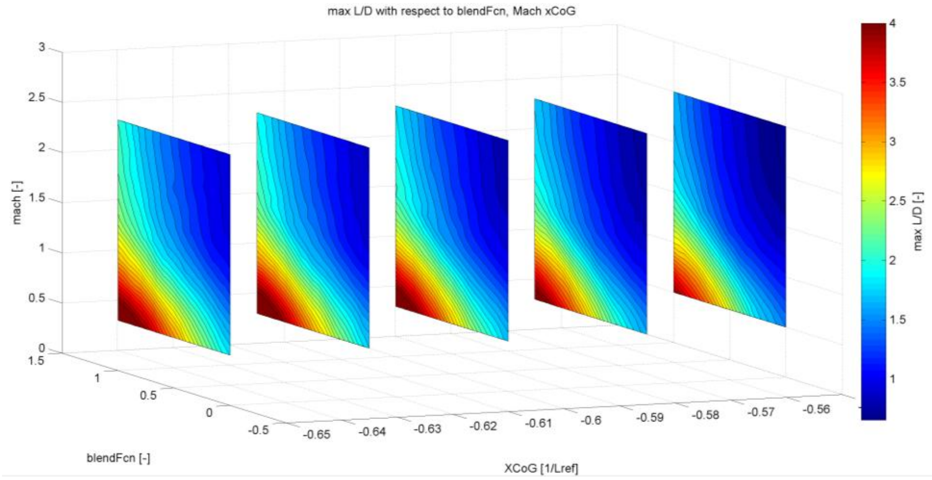

Figure 12: Max L/D with respect to XCoG, Blend function, and Mach.

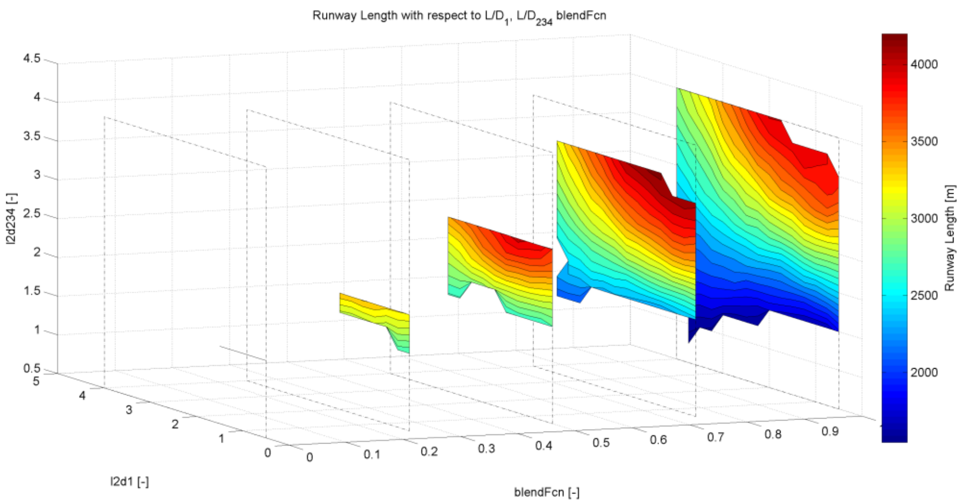

Figure 13: Runway length with respect to blend Function and L/D$_1$, L/D$_{234}$

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3.3 Multi-Disciplinary Design Optimization

Once the mathematical model described in section 2 was developed and validated against suitable test cases, and through the preliminary mission and system analysis described in section 3.2, the design parameters dependency and correlation was evaluated, and it was possible to bind the domain of the problem within a realistic parameters range. Given those preliminary steps, it is possible to perform the Multi-Disciplinary Design Optimization considering only the range of feasible system concepts. The MDO activity was subsequently separated in two phases: the first one is shared by all system concepts, and covers TAEM to Approach and Landing Interface (ALI) / Parachute Deployment Interface (PDI); the second part, on the other hand is system concept specific, and takes into account the different approach strategies of the two system concepts (namely Lifting Body with Parafoil, and High Efficiency Lifting Body with Horizontal Landing).

3.3.1 TAEM to ALI/PDI

The metamodel of the problem, computed by calling the MDA model as described in section 3.1, was used to perform the optimization of the elevator deflection and L/D. Table 6 summarizes the optimization filters criteria used in the assessment. As far as max L/D is concerned, for values lower than 2, subsequent flying phases are limited, if not compromised. High values of wing loading were filtered, as well as the lowest ones. As far as elevator deflection is concerned, a centered, and trimmed vehicle indicates a balanced design, moreover, by using only part of the control authority of the elevator for trim purposes, the remaining part of elevator deflection can be used for maneuvering. While an advanced GNC may cope with a negative Static Margin, in a preliminary design a slightly positive Static Margin is desirable. On the other hand a static margin too high may require too much control effort to change the spacecraft attitude, for this reason a range between 0 and 0.06 [1/Lref], was used as filtering criteria. High values of the angle of attack are not desired to keep the efficiency high far from stall regions.

Table 6 TAEM to ALI/PDI Optimization Constraints

Output Parameter	Unit
L/D > 2	[-]
0 < SM < 0.06	[1/Lref]
AoA<18	[deg]
|de|< 5	[deg]
100<W/S<300	[kg/m2]

In order to validate the metamodel, a three objective optimization is performed. Three parameters were chosen on one hand so to query a representative part of the metamodel domain, and on the other hand, to obtain a graphic representation of the query points.

The parameters to be optimized, and the cost function target are:

- L/D is minimized: the objective of the horizontal landing system concept is to be able to land horizontally, but, higher values of L/D can only be achieved via complex aerodynamic aeroshape, which is a penalty at system level. Therefore, the minimum L/D that allows landing horizontally (Shuttle like) is targeted.
- As far as flying qualities is concerned, the optimization aims to a longitudinal statically stable spacecraft, and to, as far as possible, a naturally trimmed spacecraft, so that flaps deflection is not used for trim purposes but only for manoeuvring.

Figure 14 (right) shows that there is not a correlation between Static Margin and maximum L/D, and that there is a region where elevator deflection is minimized and Static Margin is close to zero. In order to evaluate the metamodel accuracy, the Pareto optimum points predicted by the metamodel and shown in Figure 14 (right) are numerically evaluated through the MDA. Figure 14 (left) shows the output validation: the blue line represents the metamodel predictions, while the red line shows the MDA results; an error close to 0 indicates that the metamodel correctly predicts the output of the model.

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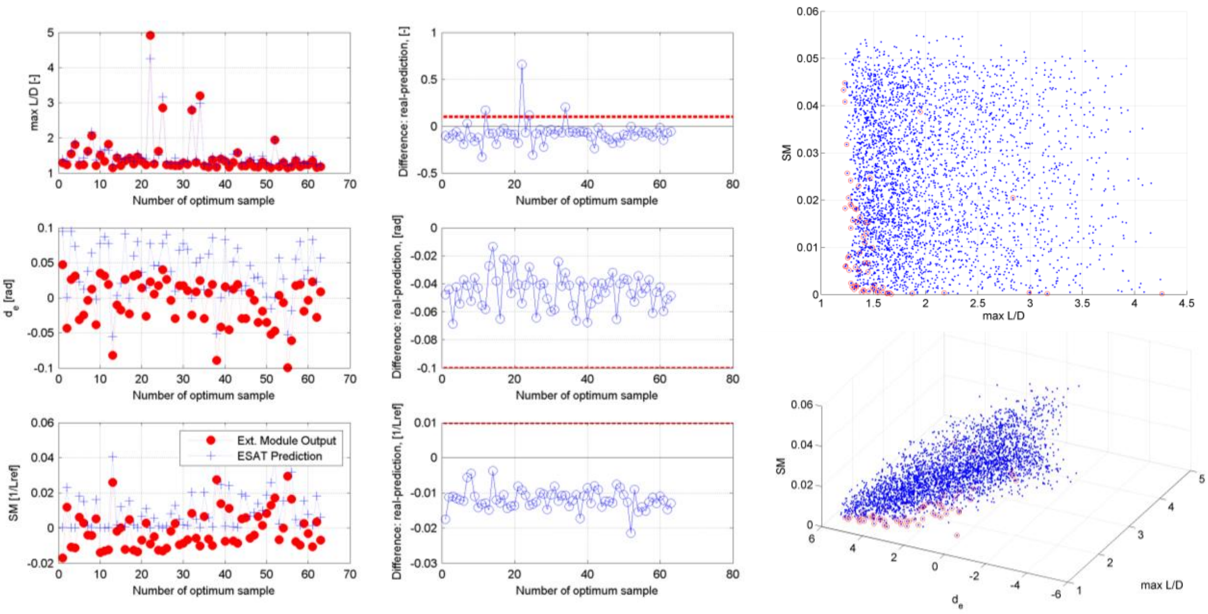

Figure 14: TAEM phase. Max L/D, Static Margin and elevator deflection: Pareto from metamodel and validation.

3.3.2 Horizontal Landing Tailored solution

The trajectories of all system concepts are comparable up to the ALI/PDI, regardless their landing strategy, and have been analyzed in the previous section. The subsequent phases of the approach shall be analyzed separately due to the vehicle and trajectory consistent differences. For the horizontal landing solution, a few constraints to the problem where identified, in particular on airspeed, to model adequately stall effects. Constraints are summarized in Table 7.

Table 7: Horizontal Landing Optimization Constraints

Output Parameter	Unit
L/D > 2	[-]
0 < SM < 0.06	[1/Lref]
AoA < 18	[deg]
Hvel > 40	[m/s]
Vstall < (V touch down)	[m/s]

In order to validate the metamodel, a three objective optimization is performed. Three parameters, were chosen on one hand so to query a representative part of the meta model domain, and on the other hand, to obtain a graphic representation of the query points. The parameters to be optimized, and the cost function target is:

- L/D is minimized (as for section 3.3.1).
- Margin between the required L/D for A&L phases 234 and the L/D the spacecraft is able to fly is maximized.
- Runway length is minimized to increase the number of suitable landing sites.

To evaluate the metamodel accuracy, the Pareto optimum points (Figure 15, right) are evaluated through the MDA. Figure 15 (left) shows output validation. The metamodel predictions are enough accurate: as far as L/D is concerned, errors are in the ±0.2 band; Runway length output range between 2000 and 5000 [m], with error within ±200 [m]. Once all the checks on the model have been done (including validation of the metamodel), a multidimensional optimization was performed, on more than three objectives (thus the graphical representation of the problem is not intuitive), taking into account the cost function reported in the bullet list:

- L/D is minimized.
- Margin between the required L/D of A&L phase 1 and L/D of phases 2,3,4 and the L/D the spacecraft is able to fly is maximized.
- The Runway length is minimized to increase the number of suitable landing sites.
- As far as other cost function targets is concerned, namely minimization of load factor, Static Margin and elevator deflection, their minimization aim to a vehicle whose landing performance and flying qualities increase.

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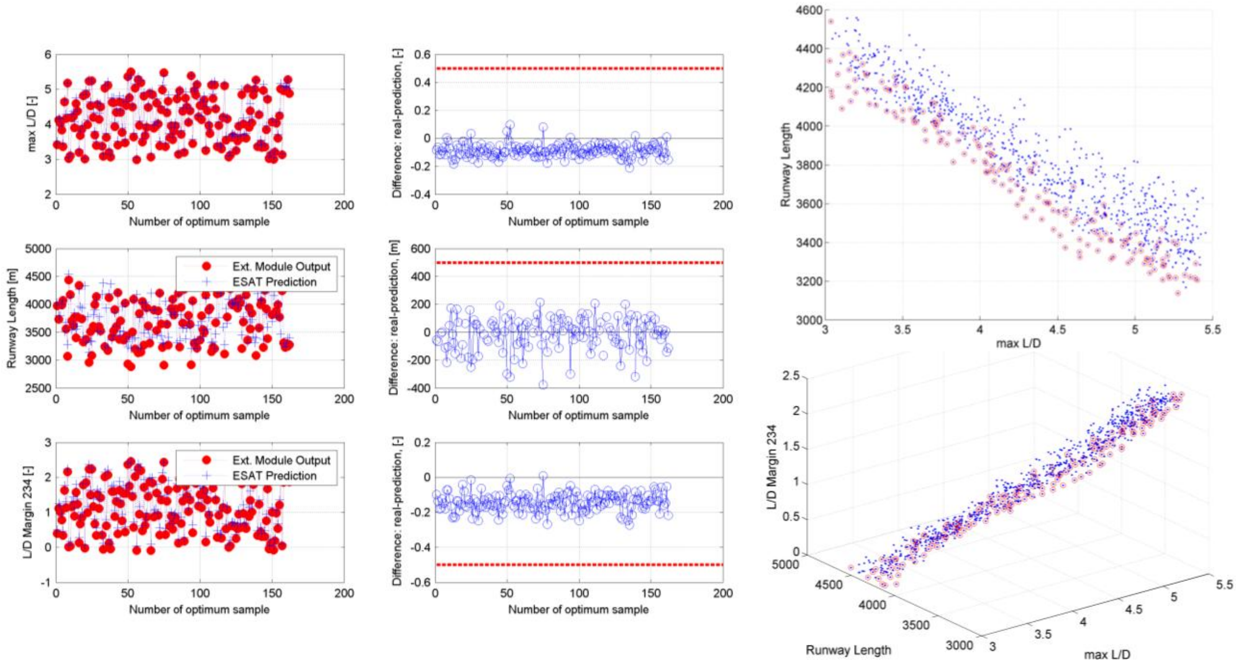

Figure 15: Horizontal landing. Max L/D, Runway Length and L/D margin: Pareto from metamodel and validation.

3.3.3 Soft Landing Tailored solution

The Parafoil system concept solution aims at a reduction of the overall complexity of the system, by introducing a rather simple mean to achieve satisfactory landing performance. Therefore the system concept does not require complex aeroshape solutions (hence high Blend Function).

The domain was explored intensively through 10000 queries of the metamodel. Optimization setting aims to:

- reduce the vertical velocity at touchdown, it would directly affect the design of the landing gear (and mass).
- minimize the parafoil mass, in order to reduce the mass of the descent system.
- minimize runway length.

Figure 16 (right) shows the random point of the query (blue dots), and Pareto of outputs (red circles), with respect to Parafoil Mass, Runway Length and Vertical speed at Touchdown.

In terms of vertical velocity, values as high as 8 [m/s] have been recorded within the X-38 testing phase. If manned flights or medical evacuation flights are considered, vertical velocities shall be in the range of 3 [m/s] to reduce injuries risks [3]. As usual, Pareto point predicted by the metamodel, were validated through the call of the MDA module.

Figure 16 (left) shows the results of the validation; the metamodel estimates correctly the runway length, as the error lies within ±5[m]. For vertical velocity, errors are limited to less than 1 [m/s], while the parachute mass evaluation error appears at most of 15 [kg], although a general bias on the negative side can be outlined.

Considering Figure 16 (left), the metamodel is representative of the MDA.

As for section 3.3.2, once the metamodel has been validated, it is possible to go through the multidisciplinary optimization. The MDO takes into account more than three objectives, thus the graphical representation of the problem is not intuitive. Several counteracting constraints apply to the Soft Landing system concept, the cost functions targets used for the Soft landing system concept are summarized in the next bullet list:

- As for the Horizontal landing system concept, high values of blend function indicates higher complexity, from an aeroshape point of view, for this reason the optimization aims to lower blend function values.
- A compact system fits easier in a launcher, hence the objective to minimize spacecraft reference Surface.
- Moreover, in order to reduce as much as possible the complexity of the system, lower parafoil masses score higher for the optimization function.
- The minimum radius and the radius of the EMC are minimized in order to maximize the trajectory controllability and the maneuverability of the system.
- The altitude margin is maximized in order to increase the trajectory controllability margin.
- Other performance parameters of the optimizer, such as Runway length, horizontal and vertical component of the touchdown velocity, aim to fulfill the mission of a soft landing.

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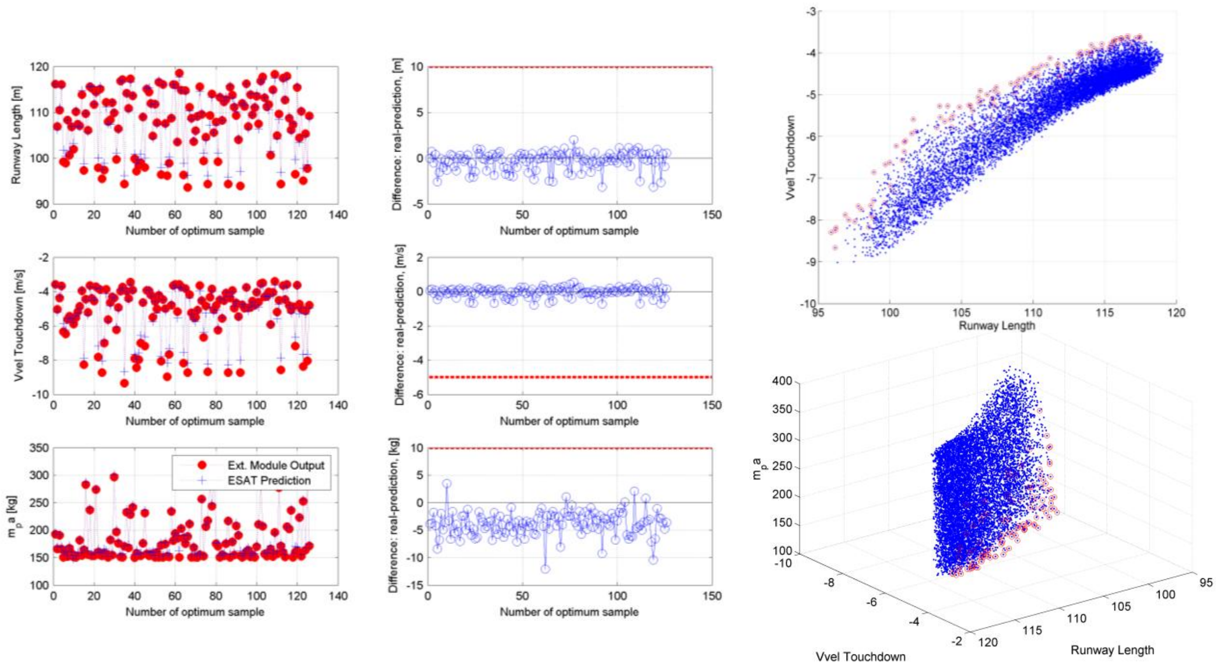

Figure 16: Soft landing. Runway Length, Vertical V and parafoil mass: Pareto from metamodel and validation.

4. System Concept Selection: Preliminary Mission and System Design

Considering the results of the multidisciplinary optimization, both promising system concepts are feasible at a preliminary design level. Anyway, the two system concepts are not easily numerically comparable. Each system concept differs quite considerably in terms of design parameters definition and numerical results, as well as in terms of output performance definition. For example, while for a parafoil-based system the Aspect Ratio is key design parameter, no comparable figure is found within horizontal landing.

Moreover, as described in sections 3.3.2, and 3.3.3, the cost function target, differs for the two system concepts. The optimization leads, for both system concepts, to the definition of several suitable input variable combinations fulfilling either cost function. The relevant parameters of the set of suitable candidates, is then averaged, and given as input to the MDA. The results are shown in Table 8, which summarizes the comparable input and outputs.

Table 8: Comparison between Horizontal landing and Soft landing.

Design Parameter	Unit	Horiz	Parafoil	Output	Unit	Value	Value
blendFcn	[-]	0.87	0.38	Runway Length	[m]	3750.19	112.58
XCoG	[1/Lref]	-0.58	-0.6	Hvel Touchdown	[m/s]	71.72	13.13
Sde/Sref	%	13	10	Vvel Touchdown	[m/s]	-0.61	-4.95
max mass	[kg]	3105.78	2753.03	max L/D	[-]	4.49	3.48*
max length	[m]	8.03	10.77	Sref spacecraft	[m²]	25.74	13.76
max height	[m]	3.72	2.38	Sref parafoil	[m²]	0	196.64
max span	[m]	3.75	3.25	mass spacecraft	[kg]	3105.78	2753.03
Volume	[m³]	95.7528	32.7488	length spacecraft	[m]	8.03	10.77
				WS spacecraft	[kg/m²]	120.68	200.01
				Sratio (parafoil/sc)	[-]	0	14.29
				Cl	[-]	0.39	0.38*
(*) Parafoil + spacecraft				Cd	[-]	0.09	0.14*

A trade off was thus performed, based on the following criteria:

- **Maximisation of heritage**. Considering the current TRL of the different Entry Descent and Landing (EDL) technologies at European level, the soft landing with a parafoil would imply a small delta comparable to the one needed to design and test a winged body performing a complete return, entry, descent and landing.
- **Design simplicity**. The blend function is related to the aeroshape, and a lower value is intrinsically related to a more simple vehicle. Simplicity is a key design parameter and can affect reliability, development effort, and maintenance costs. The soft landing solution is considered the best one in terms of system design simplicity.

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- **Aerodynamic performance**. Higher vehicle L/D, or aerodynamic capabilities in general, would allow higher trajectory controllability in previous phases (entry). The current maximum L/D of the parafoil solution includes the contribution of the parafoil, that would not be available during entry. The winged body solution is the best one in terms of aerodynamic performance, but the performance guaranteed by soft landing solution identified exceeds those required to ensure the feasibility of a precise landing mission in terms of trajectory controllability.
- **Mass/Volume efficiency (payload margin).** A lighter system, with respect to the same launcher, would allow more margin for payload. Additionally, a higher volumetric efficiency could allow in principle better payload performance and adaptability to simpler launch solutions. The soft landing solution is considered the best one in terms of system mass/volume efficiency.
- **Impact on landing gear design**. Lower velocity at touchdown, and lighter systems, would imply reduced needs in terms of landing system design, allowing therefore lighter and simpler solutions. The identified solutions present both pros and cons. The winged body solution, performing an horizontal landing on a runway, implies higher horizontal velocity and a lower vertical velocity. On the contrary, landing with a parafoil occurs at a considerably lower horizontal velocity, but with higher vertical ones. In this case the effect on the landing system damping mechanism may be partially compensated by the lower weight of the system. In conclusion, the two solutions have contradictory performance, but the soft landing performance may reduce the overall impact on the landing system design.
- **Landing site network accessibility**. Landing horizontally with a winged body would require a prepared paved runway, more than 3.5 km long. This requirement would reduce considerably the list of available airports, narrowing it to a few landing sites. On the contrary, the lower braking distance, and the still good landing precision that a system with a parafoil can provide, plus the need of just a prepared terrain to land, would allow to increase the number of candidate landing sites. Therefore, the soft landing solution is considered the best one.

Considering these criteria, the soft landing scores higher, supported by the numerical results of the MDO. The horizontal landing has an higher blend function, which means its aeroshape, and the overall system shall be more complex with respect to the soft landing solution, moreover it is heavier, which in turns implies higher launch costs. Furthermore the approximate required volume is higher for the horizontal landing solution, which indicates once more, higher launch costs and less volumetric efficiency.

5. Conclusion and Way Forward

The end-to-end design of the terminal entry and landing phase for an autonomous re-entry vehicle is intrinsically a complex multi-disciplinary problem. After a trade-off analysis of the possible system concepts, two promising solutions have been taken as reference to perform a preliminary multi-disciplinary design. The design relied on the definition of the mathematical models and interfaces between the modules identified in the Multi-disciplinary Analysis. Such analysis allowed to identify the relevant parameters and relations between modules and was the corner-stone to build the metamodel used to perform the optimisation of the system concept.

The MDO activity provided an optimised solution in terms of Mission Engineering for the two different concepts, and allowed a quantitative and qualitative comparison to identify the most suitable solutions. The trade-off is automatically performed through the optimisation process, that evaluates and compares the Mission and System performance as function of the considered design parameters.

The selection of a candidate system concept is carried out as a final step. The optimised solutions for two system concepts were evaluated according to specific criteria, and the Lifting body with soft landing under parafoil was chosen to be further developed through a detailed Mission and GNC design.

References

[1] Weiland C. 2014. Aerodynamic Data of Space Vehicles. Springer.

[2] Altmann H. 2009. Numerical Simulation of Parafoil Aerodynamics and Dynamic Behavior. In: *20th AIAA Aerodynamuic Decelerator Systems Technology Conference and Seminar.* Seattle.

[3] Stein J. 2005. Parachute Testing for the NASA X-38 Crew Return Vehicle. In: *36th Annual International Symposium.* Fort Worth.

[4] Lambe A. B., and Martins J. R.. 2012. Extensions to the design structure matrix for the description of multidisciplinary design, analysis, and optimization processes. *Structural and Multidisciplinary Optimization.*Vol. 46 N. 2. Pg. 273-284.

[5] Stein J.M et al. 2005. An Overview of the Guided Parafoil System Derived from X38 Experience.

[6] Bonetti. D, et. al. 2013. EDL And GNC Optimization of a Network of Small Mars Landers. In: *10th IPPW.* California.

[7] Bonetti. D, et. al. 2015. MDO, Wind Tunnel and Flight Tests of UAVs for Titan Exploration. *Data Systems in Aerospace.* Barcelona.

[8] D. Bonetti, C. Parigini, G. De Zaiacomo, I. Pontijas Fuentes, G. Blanco Arnao, D. Riley, M. Sánchez Nogales, PETBOX: FLIGHT QUALIFIED TOOLS FOR ATMOSPHERIC FLIGHT. 6th International Conference on Astrodynamics Tools and Techniques (ICATT), Darmstadt, 2016.