CONCURRENT LAUNCHER ENGINEERING AT DLR

Martin Sippel
Space Launcher Systems Analysis (SART), DLR, 51170 Cologne, Germany
+49-2203-601-4778, +49-2203-601-2444 (FAX), Martin.Sippel@dlr.de

The SART (Space Launcher Systems Analysis) group of the German Aerospace Center DLR has the task of examining all types of future space launch systems and the thereof required engines by means of modern, computer-aided methods. One of the fundamental aims is to reduce the cost of access to space through the identification of eligible technology. Activities range from stand-alone preliminary studies to critical analysis and assessment of foreign concepts. Thanks to integrated vehicle and engine analysis performed within the group, SART fills a unique position in Germany.

The key role played by engines in present and future launchers explains the organisational integration of SART in DLR's Institute of Space Propulsion. Together with its continuous strive to improve simulation techniques, another key aspect of SART's role is the professional support provided in the definition of the German space development strategy.

SART holds the system leadership for the ASTRA launcher concept reusable booster stage, (namely the LFBB for Ariane 5) and works in close cooperation with industry as well as with other DLR institutes on the initial outline that makes further steps in RLV development possible.

Moreover, through internal workshops, innovative proposals are developed by the space transportation engineering team. These proposals intentionally diverge from conventional ideas and concepts. The patented 'in air-capturing' method by which a reusable booster stage is captured by a towing-aircraft in flight is one such example.

This paper describes three representative cases of concurrent engineering currently carried out at SART with emphasis on their multidisciplinary nature:

- Liquid Fly-back Booster (LFBB) for Ariane 5
- Innovative method for the return of RLV: ‘in-air-capturing’
- System analysis of rocket engines: Expander Bleed Cycle

1. EXAMPLE 1: ITERATIVE SIZING PROCEDURE OF A REUSABLE STAGE

A reusable booster stage dedicated for near term application with an existing expendable core is a launcher under study in the German ASTRA research program. This partially reusable space transportation concept is investigated under DLR system lead in close cooperation with German space industry [1]. The basic design philosophy of the reusable booster is to choose a robust vehicle.

The examined partially reusable space transportation system consists of dual booster stages which are symmetrically attached to the expendable Ariane 5 core stage (EPC and ESC-B) as shown in Figure 1. As a basic requirement the EPC stage's overall dimensions are fixed at today's figures. Moreover, none of the attachment points of the boosters should be changed to avoid any structural redesign of the EPC. The selected LFBB fuselage and outer tank diameter is at 5.45 m so as to achieve a high manufacturing commonality with the EPC stage.

All the above mentioned requirements and launcher integration issues limit the LFBB total length to 42 m. The allowable ascent propellant mass of the reusable stage should be sufficiently large to ensure a payload performance equivalent to that of expendable solid boosters.

Although the above constraints already severely limit design options, the overall LFBB project revealed to be a complex iterative design process with multiple loops. The current configuration, dubbed Y-8, is based on seven previous configurations, which themselves had been already influenced by the results of numerous preliminary studies [2, 3]. This approach makes trade-offs obsolete which otherwise would have been inevitable.
1.1. Engineering Process

Before involving external institutes and industry, SART started iteration of the vehicle by already encompassing several disciplines:

1. Preliminary mass estimation and size dimensioning: While the geometric dimensions of the stage are a function of the required propellant volume and very basic assumptions (e.g. tank diameter) the stage mass is estimated using the program stsm. This DLR tool is designed for investigation of space transportation systems (STS) mass (M) estimation and analysis. The stsm-required input is restricted to an absolute minimum to support the early evaluation process at the pre-design phase.

2. Ascent rocket propulsion analysis: Actually, for the ASTRA launcher configuration propulsion data have been pre-defined by industry. In general, tools as described in chapter 3 are to be used.

3. Preliminary aerodynamic design (ascent configuration): The aerodynamic configuration is found and preliminary data sets are generated with the DLR program CAC 2.24. CAC is a powerful tool for extremely fast preliminary analysis of launcher's and hypersonic vehicle's aerodynamics. Although been based on no more than very simple basic geometry neglecting any interference, it is possible to obtain aerodynamic coefficient data in good agreement with wind tunnel measurements or with results of much more time consuming CFD-calculations [4]. It is important to select a suitable homologous geometry. For these reasons CAC is very efficient in identifying and also in quantifying a general trend, but is not well suited to study slight differences between more or less similar configurations.

4. Ascent trajectory optimization: A point-mass optimization of the ascent trajectory in two dimensions is performed with the DLR-program tosca. This planar simulation is fully sufficient to give reliable performance data of the configuration early in the design process. Gravity-, drag, and thrust-vector losses are already taken into account. Relevant input data for the trajectory calculation comprises mass, propulsion, aerodynamic, as well as flight path control and constraints information. The interfaces between the aerodynamic and propulsion programs and tosca still require manual intervention to ensure high flexibility during configuring of a launcher for trajectory analysis. However, aerodynamic data sets are already provided in the appropriate format by CAC to simplify their implementation. The mass data interface to stsm is automated by another tool: RTS. All stage
masses (e.g. propellant, at engine cut-off or separation) are transferred and adapted, if required, by the iterative process. Mass data authority is kept with stsm.

Based on an acceptable ascent performance obtained, the fly-back branch of the mission becomes involved in the further analysis. This requires the contribution of:

5. analysis of fly-back air-breathing propulsion: Thrust and specific fuel consumption (sfc) as function of Mach number and altitude are to be calculated with the DLR analysis program abp [6] as engine values from the manufacturer's data sheets are usually only available for sea-level-static condition.

6. preliminary aerodynamic design (descent configuration): For this step DLR's preliminary aerodynamic analysis program CAC 2.24 [4] is once-again used. The configuration and the angle of attack range are adapted to the re-entry and return flight section of the mission.

7. simulation of re-entry, turn and optimized powered fly-back trajectory: In this stage of the analysis the simulation loop is closed for the first time because the requirements for the return flight are estimated. The mechanical and heat loads at atmospheric entry are calculated. The turbofan engine mass can subsequently be determined more precisely than in the previous step 1 by the necessary thrust level and available engine data. Moreover, the total fuel consumption of the return cruise is integrated in a quasi-optimal trajectory [5]. All new data enable to check some of the preliminary assumptions of the prior steps and should guide any modifications. In general, some adaptations which demand an iterative process will be required. Interface data represent separation conditions, aerodynamic data sets, as well as mass, center of gravity and inertia history which can be all read automatically from the programs tosca, stsm, and CAC.

All convergent configurations obtained so far have been

8. generated in a precise but still preliminary 3D-CAD configuration. For this purpose a commercially available program (I-DEAS Master Series) is used at SART. Propellant and overall launcher integration issues are checked by means of this methodology and mass estimation is enhanced by more detailed input data. The geometrical design is intentionally not fully automated to benefit from engineering knowledge and intuition. However, most of the major components like tanks, the wing and fins etc. are parameterized to support a fast adaptation and re-arrangement process.

In the next steps

9. the center of gravity movement during the mission is analyzed: An important and powerful capability of stsm is the calculation of center of gravity (cog) displacement and pitching inertia change along the flight trajectory’s history. Any record for the depletion of tanks can be modeled by including fluid mass and inertia sets for further flight dynamic analysis. Obtained data sets are

10. subsequently used to refine the aerodynamic configuration to achieve robust trim behavior: Calculating mass, center of gravity and aerodynamic data sets, enables to perform a flight dynamic assessment for descent and fly-back. This is done with the DLR tool CACT which performs a pre-trimming based on the cog history and the calculated efficiencies of all identified trimming devices (flaps, canards, etc.). Although the program always finds a numerical solution to the problem, this might be beyond actual deflection performances due to aerodynamic nonlinearities. Acceptable and save boundaries comparable to existing flaps have to be manually verified. At this point in the study the flight envelope is determined and flyability of the configuration in a typical re-entry and fly-back mission has to be checked. In case of non-acceptable behavior or insufficient robustness against perturbations, a redesign or rearrangement of components like tanks or wing is unavoidable.

Having now achieved a convergent and feasible design, at this step of the design process external partners are to be included to benefit from their special expertise:

11. an elaborate aerodynamic analysis with CFD calculations and at a later step windtunnel measurement campaigns: This analysis is indispensable for phase A studies, keeping in mind the limited capability of CAC to model complex flow phenomena and aerodynamic interactions. Experience from the LFBB analyses shows that an aerodynamic configuration which seems to be promising in CAC and CACT is not always a workable solution after performing more detailed CFD calculations [3]. However, every lay-out deemed as infeasible by the preliminary aerodynamic examination has no reasonable chance of realization. Therefore, the approach implemented in CAC is fully justified as it is much easier and more rapidly and hence the assessment of rearrangements is done extremely fast. The final step is

12. a structural lay-out based on meanwhile consolidated load data: The structural design is based on manufacturer’s practice and procedures and is beyond the reach of the plain concurrent engineering process. Nevertheless, the latest release 1.3 of stsm is able to include sub-component data sets from structural design at any degree of detail for implementation in stage mass analyses. Thus, it becomes possible to re-integrate
results of the detailed design into previous analysis steps (e.g. step 9) to test out their effect on flyability without requiring a detailed and expensive CAE model.

The 12-step approach listed above is already quite complex because usually adaptations of the lay-out or re-iterations are required. However, the ASTRA study included a more detailed investigation on the subsystem level. These are tasks like the selection of TPS, separation motors, landing gear, and research into flight dynamic issues like stability and controllability of the reusable vehicle. The most recent analyses included propellant management and tank pressurisation simulations, defining requirements on health monitoring (HM), simulation of flight abort situations, and a first cost (LCC) estimation. All these are included in the analysis of the reusable launcher stage in a conventional way, not yet part of the basic concurrent engineering approach.

1.2. Lessons Learned

In general, the concurrent engineering process for the design and analysis of a reusable booster stage has been successful. A convergent and feasible design which proved to be robust in later, more detailed studies has been found with very limited manpower (less than two engineers on average).

As long as the iterative process stays only within SART, the interfaces between the analysis programs of the different disciplines are well established and most of them are automated to save time and to improve quality. Intervention of the engineer is always workable in order to steer the design process. A fully automatic design or vehicle optimization process has never been intended and its need was never felt during the study. Currently, SART assesses such approaches as not sufficiently supporting a robust design and even convergence on a feasible configuration might be more time consuming than in the ‘manual’ way employed here. However, any possible automation of standard calculations and data exchange to facilitate sensitivity studies or parametrical variation should be used to support the selection of a promising vehicle configuration.

The involvement of external partners considerably increased the necessary effort for data exchange. Interfaces were not yet established since it was the first cooperation of that kind of complexity.

2. EXAMPLE 2: TECHNICAL ANALYSIS OF AN INNOVATIVE PROCEDURE FOR RLV: IN-AIR-CAPTURING

Recently a new, innovative approach for the return of non-SSTO reusable space transportation vehicles has been proposed by DLR-SART: The winged stages are to be caught in the air and towed back to their launch site without any necessity of an own propulsion system. This patented procedure [7] is called in-air-capturing. The performance gain by this advanced method indicates a possible increase in delivered payload between 15 % and 25%, assuming the same structural technology level of the stages. Alternatively, the size of a reusable system can be significantly reduced compared to the standard approach, without any loss in payload mass [8].

A schematic of the reusable stage’s full operational circle is shown in Figure 2. At the launcher’s lift-off the capturing aircraft is waiting at a downrange rendezvous area. After its MECO the reusable stage is separated from the launch vehicle, and afterwards performs a ballistic trajectory, soon reaching denser atmospheric layers. At around 20 km altitude it decelerates to subsonic velocity and rapidly loses altitude in a gliding flight path. At this point a reusable returning stage usually has to initiate the final landing approach or has to ignite its secondary propulsion system.

Within the in-air-capturing method, the reusable stage is awaited by an adequately equipped large capturing aircraft. Both vehicles have the same heading though on different flight levels. The reusable unpowereed stage is approaching the airliner from above with a higher initial velocity and a steeper flight path, actively controlled by aerodynamic braking. The time window to successfully perform the capturing process is dependent on the performed flight strategy of both vehicles, but can be extended up to about two minutes. The entire maneuver is fully subsonic in an altitude range from around 8000 m to 2000 m. The upper constraint is set by the requirement to reach full aerodynamic controllability of the winged stage, which is found to cause some time delay. After successfully connecting both vehicles the winged reusable stage is towed by the large carrier aircraft back to the launch site. Close to the airfield, the stage is released, and autonomously glides like a sailplane to earth [8].
2.1 Analysis Process

In case of 'in-air-capturing' the challenge arises from its innovative nature. A dedicated analysis logic has to be defined, because no experience with a similar standard approach exists. Two paramount tasks can be identified:

- to quantify the advantage of the advanced method compared to conventional fly-back of a reusable stage and
- to demonstrate the technical viability of the method under realistic technology assumptions and possibly adverse conditions.

The quantified interest in the advanced capturing method can best be demonstrated by its possible performance gain. The calculations are based on detailed simulations, assuming the same structural technology level of all stages to be compared. Detailed mass models and ascent optimization are included in the investigation based on previous work of other launcher studies (e.g. [2]). Nevertheless, it was not possible – and also not required – within this study to fully iterate the design of the reusable stages. A relative improvement in payload performance can be easily transformed into an approximate relative cost benefit. In a similar approach but with reverse direction, the relative size of a reusable in-air-captured stage in comparison to a conventional fly-back variant is iterated under the condition of same payload performance. The reduction in RLV dry mass can be equally transformed into a relative improvement in development, production and maintenance costs. As the analysis for the improvement potential has been based on previous more detailed work, it was possible to keep the iterative process to the development steps 1 through 5 of chapter 1.1 with quite rapid convergence. However, it has to be acknowledged that the additional infrastructure and operational expenses of the capturing aircraft have not yet been taken into account. Such an important next pace has to be addressed in a separate dedicated investigation requiring much more detailed assumptions regarding operational issues.

The demonstration of the technical viability of the unusual in-air-capturing method is a long-term process which will not be possible without extensive in-flight prototype experiments. However, at the very beginning of the development of in-air-capturing technology it will be necessary to show the feasibility of the idea in the frame of a concurrent engineering approach.

The investigation starts with representative RLV separation conditions because only the re-entry segment of the stage is of interest in the in-air-capturing analysis. Therefore,

1. the approach maneuver between the returning stage and the capturing aircraft has to be simulated: The flight dynamic analysis generally is performed with the tool RFD as in the steps 7 and 10 in chapter 1.1. However, the control logic is completely different. The stage's navigation system computes the assigned flight azimuth $\psi_{\text{as}}$, which should always point at the capturing aircraft, the current distance, and the altitude difference between both vehicles. The winged stage firstly glides with a very steep angle $\gamma_{\text{gl}}$ (e.g. around -18°) and
gradually reduces its velocity, while the capturing aircraft flies at an altitude of about 8 km with a constant Mach-Number of approximately 0.55. When the returning launcher's position relative to the aircraft reaches to a certain vector point, the end phase of the approaching maneuver is initiated. Then the aircraft itself starts a descending glide path, still in front of the stage. A flight path angle $\gamma_{\text{cap}}$ is selected which enables flight with an L/D ratio, of the winged stage, slightly below its maximum. This selection requires that the normally higher lift/drag ratio of the capturing aircraft (about 15...16) to be adapted to the L/D of the reusable winged stage (around 4...6). The winged stage follows the capturing aircraft whilst reducing its distance and its velocity controlled by aerodynamic speed brakes. Simulations demonstrate that the distance can be controlled at a minimum range between 155 and 200 m for duration of 130 s [8]. The data exchange requirements of this step are limited. The initial conditions, suitable aerodynamic data sets, and vehicle masses have to be provided. To demonstrate the feasibility of the method any typical data set is sufficient. Aerodynamic coefficients can also be calculated by CAC.

2. The capturing itself has to be simulated and an optimum capturing device has to be found: The first task is to demonstrate that the capturing and connection of the two crafts by a towing rope is possible within the tight time window and with available technology. Aerodynamics of the capturing devices is assessed by the DLR code CAC and the mass, inertia, and the frictional force of the rope are also considered during the simulations. Control of the missile is performed according to the self-homing principle, calculating the required thrust vector, angle of attack, and yaw always heading the device verso the moving target. Simple solid motor thrust laws have been implemented for missiles because detailed data are not available. These assumptions were checked with the available missile mass and range information. All flight dynamic simulations are performed with RFD and data obtained show that capturing can be achieved within acceleration constraints and with a huge time margin wrt. the available window. The 3DOF analysis is accurate enough to distinguish between the different devices and demonstrates that an unpropelled, towed aerodynamically controlled capturing device (ACCD) is the most promising offering the largest time margin as well as ensuring the lowest loads [8].

3. An assessment for the requirements of the towing aircraft: The minimum thrust and acceleration performance of the towing airliners has to be determined to select suitable aircraft types. This involves more or less a simple data analysis as the intention is not to newly design such aircraft but to re-use and adapt existing airliners.

4. Simulation of off-nominal behaviour and adverse conditions: This task should prove the viability of the proposed in-air-capturing method by regarding its off-design performance, assuming different perturbations of the nominal flight, including a change in atmospheric wind or slightly altered stage-separation conditions. The analysis method is very similar to step 1 and can easily be realized due to the flexible implementation of the model. The influence of wind and gust perturbations on the missile or ACCD flight has been examined. This effect is found to be of minor importance under the conservative assumption that it only impacts the missile. Usually the wind will similarly affect the airliner and the returning stage.

Analysis of the advanced in-air-capturing method concerning its performance gain and checking its feasibility has been demonstrated in a concurrent engineering approach. The investigation procedure is different to the vehicle design process of example 1. The in-air-capturing analysis requires a less complex iteration and hence less demanding data exchange capabilities. However, the relatively unusual tasks to proof the viability of the method demand high flexibility of the tools to enable intervention or adaptation by the engineer. The next steps will be component sizing, then testing and most important subscale flight demonstration.

3. EXAMPLE 3: ITERATIVE SIZING AND ANALYSIS OF A ROCKET ENGINE FOR A REUSABLE BOOSTER STAGE

This investigation is focused on the design of high thrust bleed cycle engines for large reusable boosters. In a bleed cycle, the coolant flow having been heated while passing through the thrust chamber's cooling channels drives the turbines. Subsequently, the turbine exhaust is expelled. Lower cost and higher reliability of the turbines might be possible due to lower turbine inlet temperatures and abdication of a gas generator.

The intent to select the most promising bleed cycle rocket engine after having performed some iterative design steps and having evaluated different lay-out options. Integration of the engine into its operational environment (the launcher and its mission) is simulated to enable an assessment of its system performance.
3.1 Engineering Process

The lay-out of the reusable booster stage is derived from a configuration similar to those described in chapter 1 to ease the overall design process. The concurrent engineering procedure concentrates on the engine cycle design and analysis. Basic assumptions for the launch vehicle class and its overall mass initiate

1. the choice of general engine parameters: Extensive variations of the general engine parameters like chamber mixture ratio, nozzle expansion, and chamber pressure have been made to find the most suitable values for the booster application. This first step is done with the DLR cycle analysis tool LRP2 and subsequently performing ascent trajectory optimizations with tosca. Although still not based on a fully convergent design, the results of the sensitivity calculations allow a sound choice of the basic engine parameters. Data exchange is only required for engine data because launcher mass and aerodynamics are fixed. The pre-selection is followed by

2. the selection of major cycle design parameters: The arrangement of turbopumps and turbines and some characteristic parameters deliver some internal conditions of the engine allowing to assess the overall engine feasibility. During the early analysis [9] it became apparent that the high heat-transfer rate needed by an original cycle with coolant mass flow only used to power the turbines is linked to severe disadvantages. The conclusions of the early DLR studies on expander bleed engines [9] led to the idea of a cycle in which the heated fluid is partially used for turbine feeding, while the remainder is injected into the combustion chamber. Such a design allows for higher heat-transfer without ‘wasting’ too much fluid by expelling it through the turbines. Variants of this lay-out have been iteratively investigated [10, 11]. While the major part of the heated flow is expelled after driving the turbines, a small amount is to be mixed with the main stream of sub-critical hydrogen prior to the injector entrance. Such a promising cycle, including its overall engine performance values is shown in Figure 3. To further check technical feasibility, a next step has to be carried out for

3. the pre-dimensioning of thrust chamber and turbo-machinery: The engine’s combustion chamber and nozzle is designed by the DLR tool NCC [13] which delivers the contour design and a preliminary mass estimation. The calculation of the turbopumps and the turbines with the DLR program LRP_mass (based on previous LRP2 results) not only gives their preliminary size and mass but also indicates if the chosen cycle will be feasible with current technology. Therefore, stage enthalpy and flow indices are analysed and pump and turbine efficiencies are estimated based on empirical rotation speed relations. An iterative approach is required if the early efficiency assumptions of LRP2 are not inline with the later, more reliable data of the turbo-machinery analysis. Data exchange between the two tools is fast and convenient, but requires for each step an engineering decision on the design of the turbopumps. These analyses revealed the need for

![Figure 3: Thermodynamic conditions inside expander bleed cycle engine calculated by DLR’s cycle analysis tool LRP2 [12]](image-url)
4. **Checking of critical chamber heat-transfer capabilities**: The amount of heat transferred to the turbine driving hydrogen, the achievable turbine efficiencies, and the requirement to reach supercritical hydrogen injection into the chamber are found to be critically interconnected. The actual quantity of transferred heat and the corresponding pressure loss in the cooling channels has to be assessed in a dedicated chamber design and analysis. This task is quite complex and not well suited for a preliminary design variation. In a pragmatic approach, earlier EADS-design-results serve as a reference for adapting the heat-transfer to the booster engine's requirements with an appropriate scaling law. Afterwards, the obtained heat flow values are returned to the cycle analysis to check their influence on the complete engine.

5. **Launcher integration issues of the engine**: To close the concurrent launcher engineering the investigated engine cycle is implemented into the reusable booster stage. It turns out that the low mixture ratio of 4.8 requires large liquid hydrogen tanks increasing stage length. However, it also shows that bleed cycle engines, although more severely restricted in chamber pressure than gas-generator types are able to lift nearly the same heavy payload to orbit.

4. **Conclusion**

The paper describes three representative cases of concurrent launcher engineering currently carried out at SART with emphasis on their multidisciplinary nature. The iterative design of a reusable booster stage with external partners is found to be the most complex. As long as the iterative process stays only within SART, the interfaces between the analysis programs of the different disciplines are well established and most of them are automated. A fully automatic design or vehicle optimization process has never been intended and its need was never felt during the studies. However, any possible automation of standard calculations and data exchange to facilitate sensitivity studies or parametrical variation should be used to support the selection of a promising vehicle configuration.

**References**

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*Further updated information concerning the SART concurrent engineering on space transportation concepts is available at: [http://www.dlr.de/SART](http://www.dlr.de/SART)*