70th International Astronautical Congress (IAC), Washington D.C., United States, 21-25 October 2019.

IAC-19-D2.3.10

A Systematic Assessment and Comparison of Reusable First Stage Return Options

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Abstract

Interest in the reusability of launch vehicle first stages has strongly increased since the successful landing, recovering and reflight of SpaceX and Blue Origin booster stages. However, different possibilities of recovering and reusing stages exist and each method has its specific advantages and disadvantages. This paper focuses on the comparison of different return options investigated within the DLR projects AKIRA and X-TRAS. Return options that are taken into account include vertical take-off, vertical landing (VTVL) stages and winged vertical take-off, horizontal landing (VTHL) stages. Among the respective methods various options are considered and compared: return-to-launch-site, downrange landing, In-Air-Capturing and flyback with turbine engines.

The characteristic flight conditions of the aforementioned return options considering ascent loads, atmospheric re-entry loads, dry mass increase, performance losses and launcher design are evaluated methodically. Since RLVs require additional operational equipment and measures compared to expendable launch vehicles, the required supplementary hardware, infrastructure and workload are identified. Furthermore, necessary modifications to existing hardware are evaluated and cost estimation methods are applied to obtain preliminary operational costs of landing ship operations, capturing aircraft operations and transportation operations. Further, preliminary production cost estimations with an adapted version of the cost model TRANSCOST are performed and the results are evaluated. Finally, the return options are compared with respect to their impact on performance, masses, return loads, operations and costs.

Keywords: RLV, VTVL, VTHL, Reusability, Costs, TRANSCOST

Acronyms/Abbreviations

AKIRA	Ausgewählte Kritische Technologien und Integrierte Systemuntersuchungen für RLV Anwendungen
C	Cost
DRL	Downrange Landing
ELV	Expendable Launch Vehicle
GTO	Geostationary Transfer Orbit
HL	Horizontal Landing
IMR	Inert Mass Ratio
Isp	Specific Impulse
LCH4	Liquid Methane
LFBB	Liquid Flyback Booster
LH2	Liquid Hydrogen
LOX	Liquid Oxygen
MECO	Main Engine Cutoff
RLV	Reusable Launch Vehicle
Ro-Ro	Roll On, Roll Of
RTLS	Return to Launch Site
TPS	Thermal Protection System
VL	Vertical Landing
VTHL	Vertical Take-off, Horizontal Landing
VTVL	Vertical Take-Off, Vertical Landing

1. Introduction

Whereas reusing a space transportation vehicle can have a strong impact on the costs and thus competitiveness of launchers, the historic Space Shuttle has also shown that this impact does not necessarily have to be positive if the refurbishment costs cannot be kept low. Nonetheless, recently the success of emerging private companies such as SpaceX (with Falcon 9 and Falcon Heavy) and Blue Origin (New Shephard) in landing, recovering and reusing their respective booster stages by means of retropropulsion have shown the possibility of developing, producing and operating reusable launchers at low launch service costs. This has led to a rearisen interest in studying reusable launch vehicles from a European perspective to pave the way for a possible future reusable launch vehicle (RLV) to stay competitive on the evolving launch market.

However, reusability for launch systems can be achieved through a broad range of different technologies and approaches. Understanding and evaluating the impact of the different possible return and reuse methods on a technological, operational and economic level is of essential importance for choosing a technology that is adaptable to a European launch system.

Fig. 1: SpaceX Falcon Heavy side booster using the VTVL method (upper; photo by SpaceX; CC0 1.0) and the LFBB representing the VTHL method (lower)

In order to assess the technological demands of reusable launch vehicles, DLR initiated several studies focusing on reusability and technologies linked to reusability. Among those studies, the X-TRAS, AKIRA and the FALCon project are especially relevant for this paper. The X-TRAS project focuses on investigating different launcher concepts with respect to performance, market servicing capability and system design [1], [2]. The AKIRA project is focused on raising the TRL of RLV technologies such as reusable thermal protection systems (TPS), cryoinsulation, health-monitoring systems and more [3]. Within this project, hardware on a subscale level is developed and tested. In the Horizon 2020 project FALCon, the In-Air-Capturing procedure, which is explained in detail in section 2.1, is demonstrated on subscale level with UAVs to further pave the way for a European RLV [4]. However, the development of required technologies is also linked to the demand of understanding and evaluating different return technologies to gain insight into the challenges and advantages of different return methods. Hence, a broad comparison of return methods suitable for first stage recovery is necessary.

In this context, two major return methods which can further be divided into subcategories were part of such a broad investigation of return methods: the vertical take-off, vertical landing method (VTVL or VL) and the vertical take-off, horizontal landing method (VTHL or HL) as shown in Fig. 1. These return methods are described in more detail in section 2.1. The goal is to allow a comparison of the aforementioned return technologies on different levels: first, the technological differences and the impacts on system level are evaluated. Thus, the RLV methods are compared with respect to their impact on the launcher design on a system level. Additionally, the re-entry trajectories are compared regarding reentry conditions and loads.

A very important and highly controversial question is the economic and operational profitability and viability of RLVs. Hence, another important aspect of comparing RLV methods lies in the estimation of the RLV's economics. However, the economics are difficult to assess especially considering refurbishment and maintenance costs. It is considered a fact that demonstrators are necessary to determine the impacts of different re-entry approaches on structures, TPS and the whole system. Currently, two different demonstrators are under development at DLR: ReFEx, incorporating the VTHL approach [5] and CALLISTO, representing a VTVL launcher [6].

Nevertheless, in this paper a comparison on operational and economic level is performed with the current knowledge available. For the recovery cost model a bottom-up approach was used which estimates the costs linked to RLV operations and recovery by using established cost models on subsystem level. The results of this operation and recovery cost model are presented and discussed herein. Furthermore, the costs of production are evaluated using the top-down cost model TRANSCOST [11], however, with simplified assumptions.

2. Methods and Assumptions

2.1. Return Methods

As explained in the introduction, two major methods were compared within this paper. Fig. 1 illustrates the differences in both methods. VTVL is today used by SpaceX to land the first stage, respectively the Falcon Heavy side boosters. This approach is based on the idea of reigniting the engines after the reusable first stage has separated from the second stage to perform several maneuvers. A final engine burn slows the vertically landing stage down to a safe touchdown velocity. As the engines are used in this method, additional propellant has to be carried by the stage that cannot be used to accelerate the payload. Furthermore, such a stage requires some kind of aerodynamic control surfaces and RCS to control the stage during ballistic flight, re-entry and descent as well as landing legs.

VL (vertical landing) systems can be further divided into return-to-launch-site (RTLS) or downrange landing (DLR). RTLS requires the stage to follow a trajectory bringing it back or close to the launch site. Thus, the stage lands on a landing pad somewhere on ground. In this case a so-called "boostback" burn has to alter the trajectory of the stage to bring it to the desired landing site. Further, burns to decrease re-entry loads (re-entry burn) and to safely land the stage are performed (landing burn). The RTLS method requires more propellant since the horizontal velocity has to be reversed after MECO. Contrary, the DRL method requires some kind of sea-going landing platform to safely land the first stage (see Fig. 2). In this case, there is no need for a boostback burn and thus propellant can be saved.

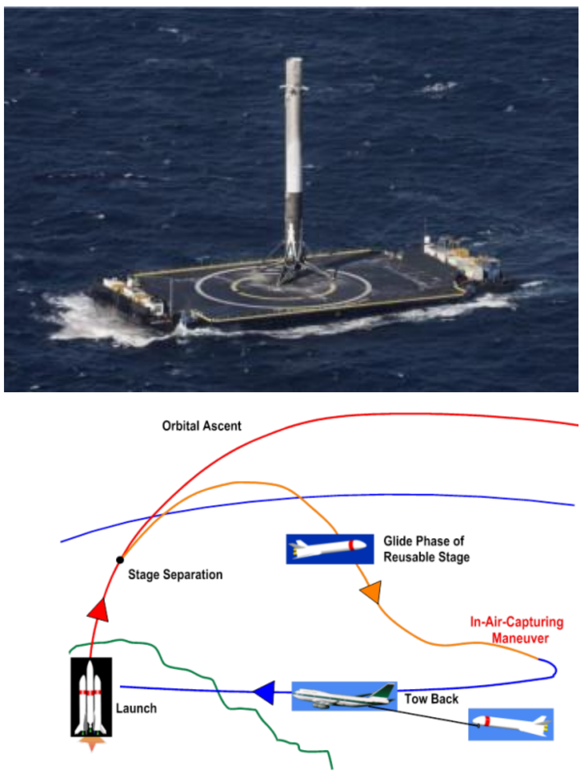

Fig. 2: SpaceX Falcon 9 landed stage on a ASDS (top, Photo by SpaceX; CC0 1.0) and the sketch of an In-Air-Capturing mission (bottom)

The VTHL method was used for the Space Shuttle and was studied extensively by DLR and others in the past. For example, the LFBB project was based on the idea to turn the Ariane 5 side boosters into winged reusable stages propelled by liquid propellants (respectively LOX/LH2) [7]. In general, a VTHL stage is equipped with lift-generating wings. Thus, the deceleration of the reusable stage occurs via the generation of aerodynamic forces. Consequently, reigniting the engines is not necessary and reduces the propellant need compared to the VTVL method. VTHL can be further divided into In-Air-Capturing (IAC) and Flyback HL stages. With In-Air-Capturing the first stage performs a re-entry maneuver decelerating the stage from hypersonic to subsonic velocity, where it enters a steady descent glide. In this gliding phase, the RLV stage shall be captured by an aircraft equipped with a capturing device and, after successful capture, be towed to its landing site (see Fig. 3). This method is comparable to a VTVL downrange landing for the reason that the RLV stage "lands" downrange in the air.

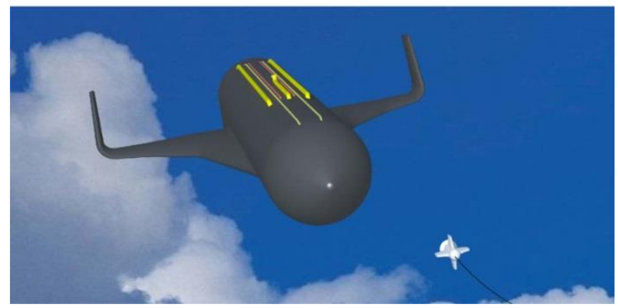

Fig. 3: SpaceLiner Booster stage approaching the capturing device during In-Air-Capturing [4]

Contrary to that approach the so-called Flyback (FB) method uses the same re-entry procedure,by generating lift and drag to slow down the vehicle while keeping the heat loads at a manageable level. Nevertheless, after transitioning to subsonic speed, the stage starts up turbine engines which allow it to travel by its own means to the landing site. By doing this additional propellant has to be carried by the stage. Several past studies or concept designs used this method of which the Baikal concept, the Phoenix concept and its demonstrator HOPPER [8], the LFBB study and the SpaceLiner concept [9] are worth mentioning.

A HL stage, apart from the wing structure, features further modifications compared to a conventional expendable stage. Aerodynamic control surfaces such as rudders or vertical fins, ailerons or flaps have to be installed. Furthermore, the stage has to be equipped with a landing gear comparable to that of the Space Shuttle and with additional propellant tanks for the turbine engines if flyback is chosen. In total, these hardware modifications generally lead to heavier stages compared to VL stages. In this paper, only fixed-wing stages were considered. Nevertheless, morphing or folding wings could be useful and are under investigation now at DLR [10].

Additionally, methods recovering only parts of the first stage are worth mentioning in the context of possible RLV return modes. Two concepts were proposed in the past years: the ADELINE concept by Arianegroup and the SMART concept by ULA. These concepts were based on the idea to only recover the engine and avionics bay and either do a flyback (ADELINE) or In-Air-Capturing approach with a helicopter (SMART). Due to the fact that the state of these concepts is unclear, no research in that direction is presented in this paper.

2.2. *Mission requirements and design assumptions*

Since the goal is a comparison of all aforementioned return methods it was decided to do conceptual designs of RLVs using those different return technologies based on equal mission requirements and design assumptions. Generic assumptions and design processes were used to allow for maximum comparability of the shown vehicles. Hence, all configurations considered within this paper use the same key mission requirements:

- 7000 kg + 500 kg margin payload to GTO of 250 km x 35786 km x 6° (standard Ariane 5 GTO) via a LEO parking orbit of 140 km x 330 km x 6°
- Launch from CSG, Kourou
- TSTO: Two Stage to Orbit
- Engine Cycles: Gas Generator (GG) and Staged Combustion (SC)
- Return modes:
    - VTVL with retropropulsion landing on downrange barge (DRL) or with return-to-launch-site (RTLS)
    - VTHL with In-Air-Capturing (IAC) or autonomous return to launch site (Flyback)
- 2nd stage Δv of 6.6 km/s, 7.0 km/s
- Propellant Combinations: LOX/LH2, LOX/LCH4, LOX/RP-1. LOX/LC3H8 (propane)

The design assumptions that were used to design the launchers which are presented herein are described in detail in [1]. It is important to mention that generic engines were used that were designed using the in-house tool *lrp* such as the commercial rocket engine analysis tool *RPA*. The structural layout was generated with the tool *lsap* which does a quasi-optimization of stringer/frame layout of tanks and skirts (see Fig. 4). Subsystem masses or masses of wings, fins, flaps and landing gear were estimated using the in-house tool *stsm* which uses empirical formula based on historical launchers. Considering the VTVL systems the masses of landing legs and grid fins were scaled according to the masses of the respective Falcon 9 hardware of SpaceX. For the HL systems, the wing, fin and landing gear masses were estimated with empirical formulas which are implemented in *stsm*.

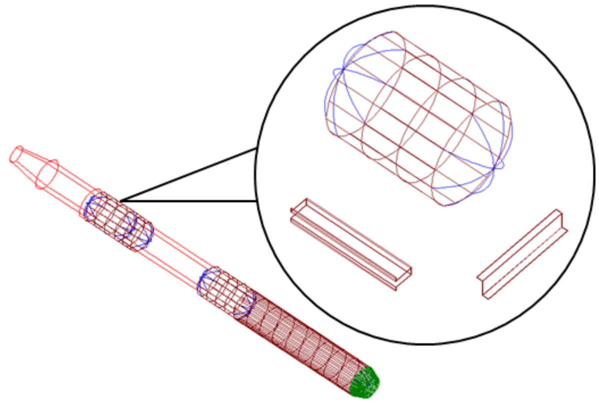

Fig. 4: Example of structural design for a VTVL launcher

2.3. *Recovery Operations*

The operation of an RLV and its cost take up a greater share of the total launch costs compared to an ELV due to the fact that recovery requires further hardware and personnel compared to an ELV [11]. Hence, understanding the operational measurements for the aforementioned return strategies is essential to derive a valid cost model. In this section, the requirements and assumed hardware and personnel costs of each recovery method are described.

<u>VTVL Downrange Landing/Return-to-Launch Site</u>

As described previously, the VL stages can either perform RTLS or do a downrange landing on either a ground pad on any piece of land downrange of the launch site or on a sea-going barge or ship. The downrange landing on a ship is most demanding from an infrastructural point of view. For downrange landings on a ship/barge two different approaches were considered in this paper. First, the approach which SpaceX is already using with several small ships and a stabilized but else passive landing barge is investigated (see Fig. 5). Second and contrary to the SpaceX method, the approach that Blue Origin has chosen to use is based on the idea to have a bigger and more agile vessel as landing ship (see Fig. 6).

Fig. 5: SpaceX Barge “Of Course I Still Love You” with landed first stage and crane in operation

For the recovery cost estimation of the SpaceX landing and recovering strategy, barges similar or close to the design of the SpaceX barges were assumed. These are mostly MARMAC typed barges which have to be modified to allow rocket stage landings on deck. In this model, all ships were assumed to be owned by the RLV launching and recovering agency/company. However, the vessels could also be chartered or leased. This will be evaluated in future work.

Fig. 6: SpaceX supply vessels GO Navigator (top) and Ro-Ro vessel bought by Blue Origin (bottom)

During a typical downrange landing mission the personnel responsible for post-processing, securing and transporting the barge with the landed stage are located on one to two supply vessels close by the landing barge (see Fig. 6, top). Additionally, tugboats for harbor operations are required. A mooring at the stage processing harbor is necessary which allows for handling of the respective RLV stage including crane operations and fixing the stage to a transportation vehicle. In this work the total crew size of recovery operations (barge, supply vessel personnel, tugboat personnel) was set to 30 plus 16 extra workers at the harbor for loading and transportation. This value assumes that the workers on the boat are not able to perform the tasks required in the harbor and consider a full occupancy of all accompanying boats. Advantages of the SpaceX approach are the comparable low acquisition costs (1.5 million to 3 million US$) and high flexibility due to redundancy in the fleet (see Table 1). Major disadvantages are the high travel time (travel speed of 12 knots) and the relatively high number of vessels for one mission.

Blue Origin’s approach to recovering the RLV stage differs slightly from the SpaceX approach. Recently, Blue Origin acquired a so-called RoRo ship (see Fig. 6, bottom). The idea is to land the stage on the modified ship’s deck. Therefore, there is no need for towing boats and the number and size of supply vessels can be reduced. Compared to the SpaceX approach, the acquisition costs are higher (30 million to 40 million US$) but the travel time can be reduced as summed up in Table 1.

Table 1: Comparison of SpaceX and Blue Origin recovery methods for VL stages

Method	**SpaceX**	**Blue Origin**
Vessels	1 x landing barge 1 – 2 x supply vessel Up to 3 tugboats per mission	1 x landing vessel 1x supply vessel (?)
Costs	1.5 million US$ - 3 million US$ (2nd hand)	30 million – 40 million US$ (2nd hand)
Travel Time	~ 12 knots	~22 knots
Crew	Barge: 0 Supply Vessel: 8 Tugboat: 8	RoRo: >18 Supply Vessel: 8
Vehicles/Facility	Harbor Crane/ Transport Vehicle/ Mooring	Harbor Crane/ Transport Vehicle/ Mooring

Considering an RTLS mission, the operational aspects are much less complex. The fact that the stage autonomously flies back to the launch site implies that no additional ships or vessels are needed. Instead, a simple landing platform which might consist of a concrete pad (compare with LZ-1 at Cape Canaveral) and communication devices can be sufficient.

VTHL In-Air-Capturing/Flyback

Similar to the VTVL downrange landing, the In-Air-Capturing method is considered a downrange "landing" method, where the landing occurs in-air with the successful capturing of the RLV stage. The following tow-back to the landing site is comparable to the transportation of the VTVL stage on the barge back to the harbor. In analogy to the VTVL downrange landing an airborne vessel with the possibility of capturing and towing the approaching stage is necessary.

Fig. 7: Commercial Aircraft that could be used for In-Air-Capturing: B747-400 (top) and A340-600 (bottom)

In this work, several second-hand commercial aircraft were deemed suitable for the task of catching and returning winged RLV stages, respectively the B747-400, the B747-8F, the A340-400, the A380-800 and the A330 NEO. Some of those suitable aircraft are shown in Fig. 7. Especially for the B747 aircraft a vast second-hand market exists and prices can vary depending on the aircraft's age and condition, the current market conditions and a range of other factors. The price ranges for the considered aircraft are shown in Table 2. Additional modifications to the aircraft are necessary such as structural reinforcement at the load transmission points where the stage is connected to the aircraft and the installation of the capturing system. Those modifications and the connected costs were based on estimations of upgrading a commercial aircraft with an in-air refueling system or converting a passenger aircraft into a transport aircraft. These costs were estimated to be as high as 43 million US$ [12]. Furthermore, the aircraft should be remotely controlled due to safety reasons. Hence, the pilots would be seated in the mission control center where they would be in command of the aircraft. In this study, 3 pilots and 3 flight engineers were assumed to be necessary for the control of the aircraft.

Table 2: Price of second hand commercial airliners suitable for IAC

Aircraft	**Listed Price**	**Secondhand price**
B747-400	306 M$	16 M$ - 32 M$ (age: 11 years)
A330-800	260 M$	27 M$ (age: 17 years)
A380	446 M$	205 M$
A340-600	307 M$	9 M$ (22 years) - 110 M$

The mission profile of an In-Air-Capturing mission for the aircraft consists of almost all typical phases of a commercial flight: engine start-up, taxiing, take-off, climb, cruise to the capturing site, waiting pattern until stage approach, IAC maneuver and stage capture, tow-back cruise, release, loiter, descent and landing and taxiing to parking position. Furthermore, and similar to commercial operations, additional fuel is reserved to allow pre-landing waiting or loitering patterns and a trip to an alternative landing site. These mission phases were used to estimate the performance of the IAC aircraft and calculate the required trip time and fuel consumption. The direct operating costs of aircrafts are then calculated by using well-known relations and cost models based on commercial aircraft operations [12].

Further hardware is required for post-landing procedures: the stage has to be depressurized and flushed of all remaining fuel/oxidizer residuals. Therefore, post-processing vehicles and personnel is needed at the stage's landing airport. The Space Shuttle for instance required around 150 of trained personnel and 25 vehicles to perform the required post-landing operations. However, this system was manned and returning from orbital velocities. For the herein used VTHL reference launchers a reduced vehicle fleet of 8 and a total team size of 46 was assumed which was based on values from the FESTIP studies [12].

Concerning facility costs the costs of building an adequate airstrip and hangar facilities were calculated. In reality, however, probably an already existing landing strip could be used or upgraded to allow the

RLV stages to land. Hence, in the cost model, the acquisition and maintenance costs of airstrip, ground and hangar is neglected. This can be compared to the VL barge approach where no new harbor or mooring has to be constructed especially for the barges.

In the case of a flyback with turbine engines, no capturing aircraft is required. Hence, in accordance with the RTLS landings of the VTVL stages, the recovery operations are reduced to post-processing of the stage. Thus, the same assumptions as for the IAC mission apply without consideration of any operational aspects linked to the capturing aircraft.

2.4. *Recovery, Refurbishment and Launch Cost Modeling*

The total cost of any launch system can be divided into recurring and non-recurring costs. Non-recurring costs are development costs, overhead costs and costs for tests, engine firings and further. Recurring costs include the production costs, operation cost, recovery and refurbishment costs. The total launch costs are then calculated according to equation (1).

$$\begin{aligned} Total\ Launch\ Costs \\ &= C_{production} \\ &+ C_{operations} + C_{recovery} \\ &+ C_{refurbishment} \\ &+ C_{fixed/overhead} \end{aligned} \tag{1}$$

The cost of stage recovery and transportation are based on the assumptions explained in the previous section. Hence, the cost model philosophy is a "bottom-up" approach, meaning that each subsystem's costs are estimated and the final costs are calculated by summing the individual expenses. The costs of recovery can be further broken down into the components as shown in equation (2). The DOC (direct operation costs) include fuel costs and docking, navigation, cargo handling and berthing fees for VL and fuel, crew, ground handling, navigation and landing fees for HL. The ownership costs include depreciation, interest and insurance rates, maintenance and repair. Facility costs include the costs for cranes, additional harbor facilities, the costs of supply vehicles and hangar facilities. An overhead for management and mission control costs is added.

$$\begin{aligned} Cost_{recovery} = {} & DOC_{Fleet,Aircraft} \\ &+ Costs_{Ownership} \\ &+ Costs_{Facilities} \\ &+ Costs_{Transportation} \end{aligned} \tag{2}$$

The further costs of production, overhead and ascent operations can be calculated with the TRANSCOST model [11]. This model is using a "top-down" approach, meaning that the calculation of costs is based on so-called CERs (Cost Estimation Relationships). These CERs are trends that are derived from costs of historical launch vehicle. This already reveals one of the major disadvantages of this approach; a sufficiently large database is required to use statistical methods to derive accurate trends. However, the database on operational or historic RLVs is much thinner compared to the data on ELVs, thus worsening the accuracy of a statistical "top-down" approach.

The production and operation costs in the TRANSCOST model scale with the mass and are calculated according to equation (3), where f_i are stage/launcher dependent factors that have to be selected according to the desired design. The factor *a* and the exponent *x* depend on propellant combination and type of stage.

$$Cost = f_i \cdot a \cdot M_{stage}^{x} \tag{3}$$

Another main driver, if not the one with the biggest influence on RLV costs, is the cost of refurbishment and maintenance. However, those costs are much more difficult to determine which was also experienced with the Space Shuttle. The difficulty arises from the fact that any valid refurbishment and maintenance has to be based on knowledge about required work processes, man-hours, materials and facility and management overhead costs added by refurbishment. However, this requires knowledge of the necessary refurbishment processes which can only be accurately determined once a RLV stage was actually flown and the impact of the re-entry loads on the stage has been evaluated. SpaceX constantly upgraded the Falcon 9 throughout the years based on the experience gained by examining the recovered stages. The DLR is currently following a roadmap of building subscale demonstrators of VTVL and VTHL launchers (respectively CALLISTO and ReFEx) and furthermore doing sophisticated analysis of re-entry loads and an estimation of their impact on the stage.

However, in this paper the problem of determining reasonable RLV launch costs was tackled with a different approach. The refurbishment costs were calculated as a fraction of the production costs of a new build first stage according to equation (4), where f_r (refurbishment factor) is any value between 0 and 1. With this highly simplified approach breakeven points can be identified where an RLV can be cost-effective compared to an ELV depending on factors as launch rate, number of reuses and refurbishment factor.

$$C_{refurbishment} = f_r \cdot C_{production} \tag{4}$$

3. Technical Comparison

3.1. *System Design, Mass Comparison*

The design assumptions and mission requirements described in section 2.2 were used to conduct a preliminary design of a vast range of different RLV using different return methods. These RLVs can be compared to each other with respect to lift-off masses, dry mass and structural index (SI), system design and impact on payload performance.

Some of those conceptual launchers are presented in Fig. 8. This figure also shows the internal layout of the respective stages. The launchers with VL stages consist of (from bottom to top) a rear skirt with a baseplate where the engines are attached to and parts of the propellant supply are covered by. Further, the landing legs are located there. In all first stages the fuel tank is positioned beneath the oxygen tank with a common bulkhead separating both stages. The interstage connects the first with the second stage and stays attached to the first stage after separation. The grid fins are connected to the interstage which also acts as a protection of the second stage engine and nozzle during ascent. The second stage tank order is reversed compared to the first stage. On top of the upper fuel tank a front skirt is attached which houses avionics and GNC of the 2nd stage and also acts as a connection to the fairing and the payload adapter.

The HL launchers follow the same principle except for the difference in first stage layout resulting from the wings and aerodynamic control surfaces. Also, the HL launchers re-enter nose first which requires the HL stage to be equipped with an ogival nose which is covered by the interstage during ascent. In that case, the interstage is not recovered and reused. Further, in case of flyback HL stages an additional fuel tank to drive the turbine engines is required.

Another aspect worth mentioning is the fact that a hybrid launcher is presented in Fig. 8 as well. This hybrid VL stage uses LOX/LCH4 in the first stage and LOX/LH2 in the upper stage, thus combining the high Isp upper stage propellant combination with a lower stage that is more in line with current engine development in Europe (e.g. Prometheus engine).

In general, the conceptual RLV stages are all bigger than the Ariane 5 or Falcon 9. This can be explained by the fact that the launchers are designed as RLVs with a different payload capability compared to Ariane 5 (13 t as ELV to GTO) or the Falcon 9 (5.5 tons to GTO as RLV). The relatively high volume of the LOX/LH2 launchers is due to the low bulk density of that propellant combination, for the hydrocarbons the low Isp leads to more propellant required.

These results are further highlighted in Fig. 9 and Fig. 10. Here, the mass breakdown of the conceptual launchers is shown. It is clearly visible that the LOX/LH2 launchers are lighter than their hydrocarbon counterparts for any upper stage Δv. The lowest GLOM, the HL launcher with LOX/LH2, In-Air-Capturing and stage combustion engines, is around 350 tons. The reason for the higher stage mass of the hydrocarbons, although generally having a better structural index, is lying in the lower Isp of that combination. The dependence of first stage GLOM on Isp is shown in Fig. 9. A low Isp has even more impact for vertical landings, since propellant is needed for the engine firings during descent. This descent propellant has to be accelerated during ascent, thus acting as “dead” or payload mass

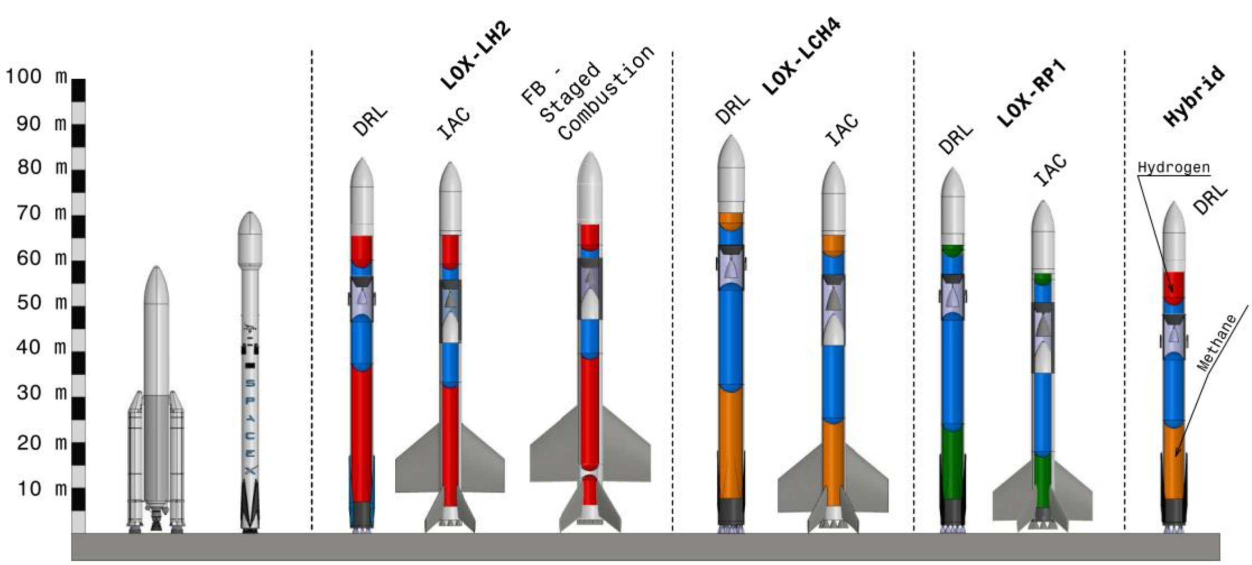

Fig. 8: Geometry and Layout of conceptual RLVs compared to Falcon 9 and Ariane 5

during ascent. According to the Tsiolkowski equation, the total propellant mass has to be increased in order to deliver the required Δv. In general, switching from hydrogen to hydrocarbons leads to a doubling in GLOM for HL systems and almost tripling in GLOM for VL systems.

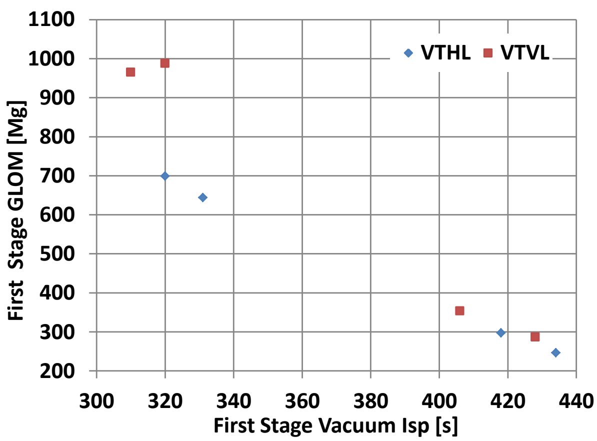

Fig. 9: First Stage GLOM over Isp for selected RLV launchers

These effects get clearer when taking a look at Fig. 11. Here, the structural index and the inert mass ratio are presented as defined according to equations (5) and (6). Here, inert mass is the mass of all components that are not contributing to accelerating the system during ascent. Hence, the IMR is, together with the Isp, a direct indicator of performance since it can be directly related to the mass fraction within the logarithm of the Tsiolkowski equation.

$$SI = \frac{m_{dry}}{m_{propellant}} \tag{5}$$

$$IMR = \frac{m_{inert}}{m_{GLOM,Stage}} \tag{6}$$

The SI of LOX/LH2 stages is higher compared to the hydrocarbons as it was expected. However, the figure also shows the impact of equipping the HL stages with wings and further equipment in a pronounced increase of dry mass, respectively SI. The SI is highest for flyback stages due to the added mass of engines and return propellant tanks. However, taking also inert mass ratio into account this effect diminishes in significance. Whereas VL stages have a lower dry mass, they carry a considerable amount of descent propellant with them, leading to a higher ratio of accelerated total "useless" mass. In general, the higher the required Δv for the return maneuvers, the higher the inert mass ratio and thus the decrease in performance.

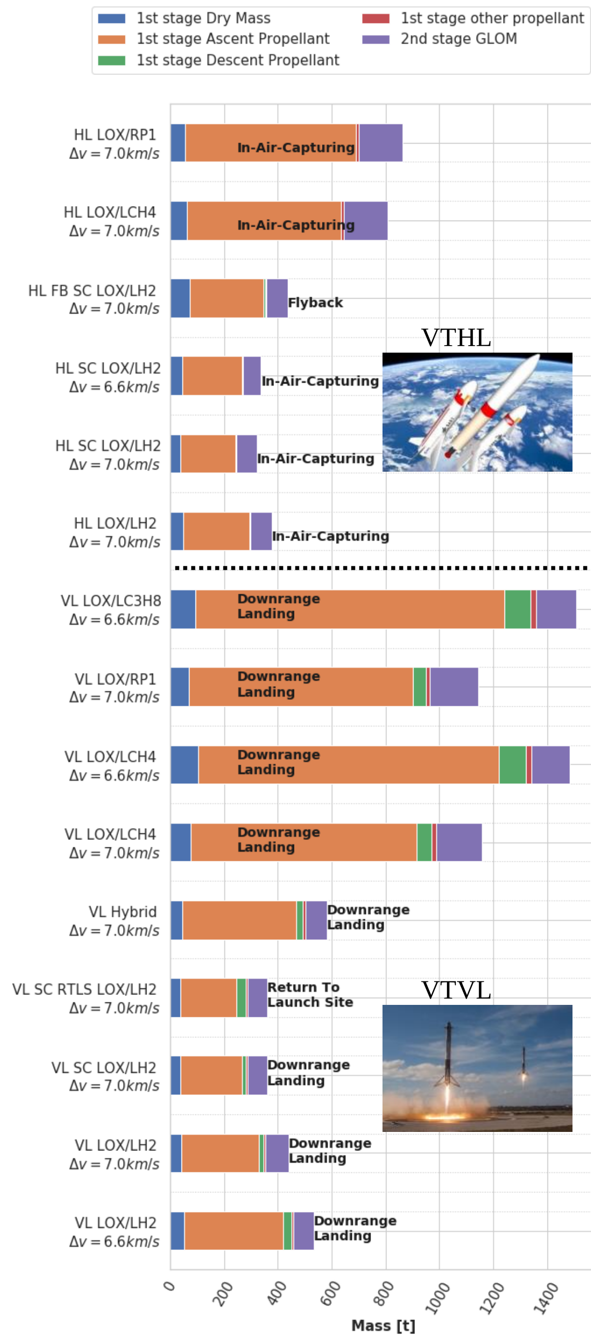

Fig. 10: Mass Breakdown of the Conceptual RLV Launcher

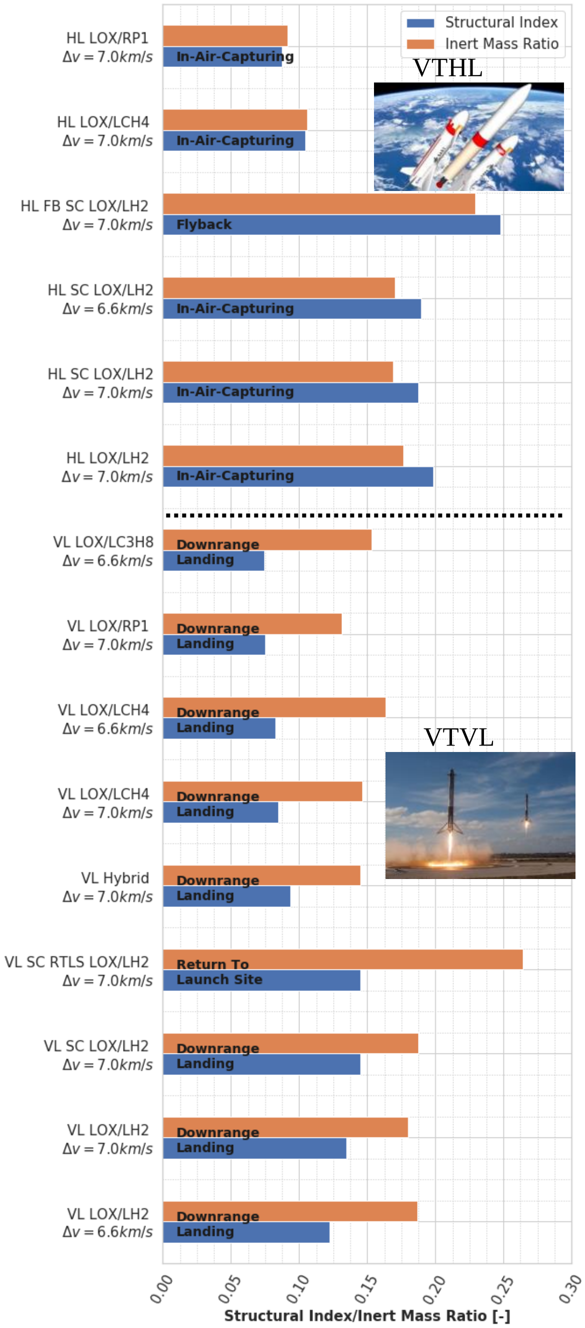

Fig. 11: Structural Index and Inert Mass Index of the conceptual RLV launcher

Comparing the inert mass ratio of RLVs using the same propellants can be directly related to the performance of those launchers. A high inert mass ratio indicates high performance losses and vice versa. Hence, comparing the LOX/LH2 VL to the HL launchers shows that whereas the dry mass of the VL stages is lower, the performance of the HL stages is slightly better due to the fact that no propellant for the re-entry is required. Comparing the IMRs for the hydrocarbons, the VL fare worse compared to the HL stages due to the fact that the low Isp has even worse impact on a VL system. The disadvantage of doing RTLS with a VL system is also pronounced in the high IMR which is the highest of all RLVs. It is important to note that the RTLS mission here was calculated with the VL SC LOX/LH2 launcher which leads to a decrease in GTO payload from 7.5 t to 3.5 t. The launcher was not resized to achieve the nominal 7.5 t GTO mission, thus the comparison has to be considered with care.

Finally, it is important to note that the upper stage Δv also has a considerable impact on the resulting lift off mass. Generally, the GLOMs are lower for RLVs with an upper stage Δv of 7.0 km/s than 6.6 km/s. This can be explained by the fact that the lower stage travels faster at MECO when the 2nd stage Δv is 6.6 km/s. This higher velocity has to be later reduced by engine firings or in case of HL systems higher TPS mass. Hence, the Δv required for descent gets higher or respectively the dry mass increases, leading to an overall increase in launcher mass in combination with a loss in performance.

3.2. *Re-entry Trajectories and Loads*

The re-entry trajectories and loads of the conceptual RLVs are shown in Fig. 12. The trajectory of the SpaceX Falcon 9 mission SES 10, which was launched in 2017, is added for comparison with an operational RLV. It is important to note that this trajectory was derived based on reverse-engineering the SpaceX mission and using in-house tools to reproduce a trajectory close to the actual one [13]. Isolines for heatflux and dynamic pressure are shown in the graph. The heatflux is calculated based on a modified Chapman equation as shown in equation (7). Here, ρ is the local density at the respective altitude according to the US standard atmosphere 1976, ρ_R is a reference density value of 1.225 kg/m³, $R_{N,r}$ is reference nose radius (here 1 m), R_N is the vehicle nose radius (here 0.5 m for all vehicles), v is the vehicle's velocity and v_R is a reference velocity of 10000 m/s.

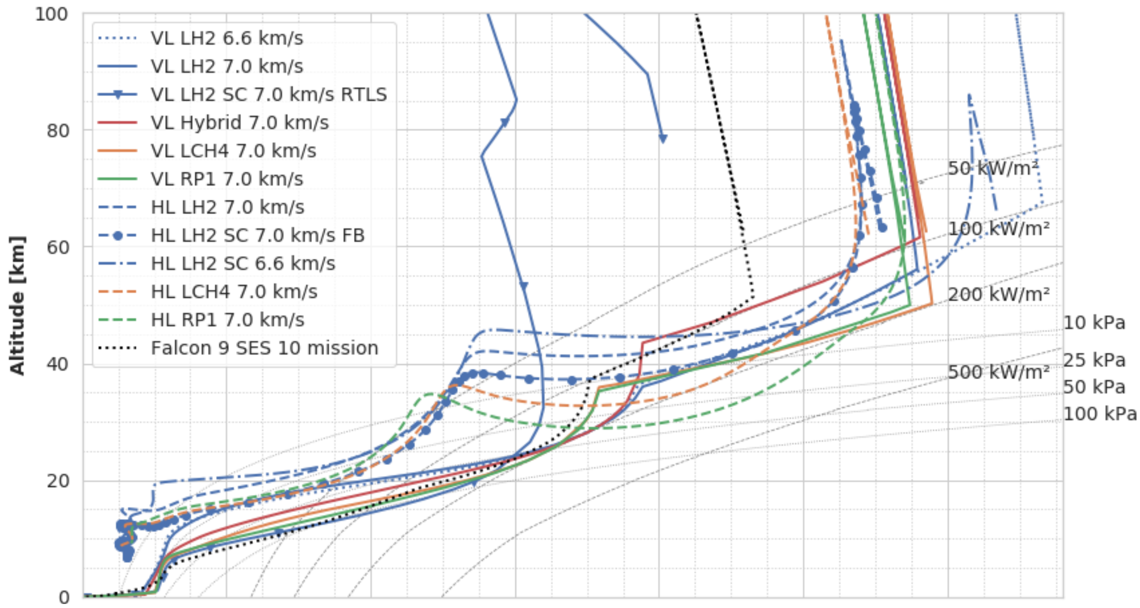

Fig. 12: Re-entry Trajectories of the conceptual RLVs

$$\dot{q} = 20254.4\ W/cm^2 \cdot \sqrt{\frac{\rho}{\rho_R}\frac{R_{N,r}}{R_{,N}}}\left(\frac{v}{v_r}\right)^{3.05} \qquad (7)$$

The altitude vs. velocity diagram shows the difference in re-entry strategy and load handling. The VL launchers are unable to control the heat flux via lift as the winged vehicles can do. Hence, a re-entry burn is required that occurs between 50 km and 67 km in altitude, marked by a sudden change in the velocity gradient. The VL launchers are limited to a maximum heat flux of 200 kW/m² which is based on the heat flux that was prevalent during the SES-10 mission. Due to this boundary, all VL launchers follow a similar re-entry profile. The ballistic coefficient, defined as the ratio between mass and drag, is of considerable importance for the aerodynamic phase of the VL's re-entry. The light, but voluminous LOX/LH2 launchers have a low ballistic coefficient and can thus reduce the burn time of the re-entry burn since more velocity can be shed by aerodynamic deceleration. The heat flux is the main driver of the re-entry burn since all other parameters, such as dynamic pressure, lateral and longitudinal loads and forces are well within reasonable limits.

Contrary to the VLs, the HL stages have a more gradual deceleration profile characterized by the generation of aerodynamic forces. In the upper layers of the atmosphere the air is too thin to decelerate the vehicle. Once the stage drops into the denser parts of the atmosphere significant aerodynamic forces are created, resulting in a deceleration of the vehicle. On the other hand, the lift generated by the wings and fuselage is used to maintain a certain altitude to reduce the maximum heat flux. Furthermore, the re-entry velocity and flight path angle such as the ballistic coefficient are the other main drivers of the HLs' re-entry loads. A shallow re-entry with a low flight path angle is advantageous since the gradient of aerodynamic forces is not as pronounced as with a steep re-entry. This can be seen comparing the hydrogen to the hydrocarbon HL stages. The HL stages are light and have a low ballistic coefficient and separate at slightly lower flight path angles. Hence, the heat flux during re-entry can be reduced which in turn results in a lighter TPS. Also, the lighter TPS for hydrogen launchers contributes to their performance advantage as explained in the previous section.

4. Economic Comparison

4.1. *Recovery Costs*

The recovery costs were calculated using the assumptions described in section 2.4. The costs of recovery per launch for different return methods for VL and HL stages are shown in Fig. 13. The costs are given in US$ with respect to the economic conditions of 2018. For In-Air-Capturing, the costs of the B-747, the A380 and the A330 NEO are presented. For VL recovery the SpaceX and Blue Origin barge/ship recovery methods and RTLS costs are added. The RTLS costs are also more or less valid for the HL flyback when assuming similar efforts in landing strip construction. The reference HL stage for the mission calculation is a ~50 ton landing mass stage and for VL a ~45 ton landing mass stage. However, the impact of landing mass on the mission is negligible due to the comparatively low direct launch costs in all cases, as will be explained in the following.

The recovery costs end up between 250 k$ (RTLS) to 670 k$ (SpaceX barge landing) to almost a million US$ for the Blue Origin method for VL related methods. Recovering the stage via IAC costs 650 k$ to 1.25 million US$ depending on the selected aircraft. The greatest share, regardless of VL or HL, is made up of indirect costs and overhead costs. This great share is due to the depreciation of the acquisition and modification costs over all launches assuming a remaining lifetime of 15 years. Hence, the recovery costs are highly dependent on the aircraft price which explains the high recovery costs for the A380.

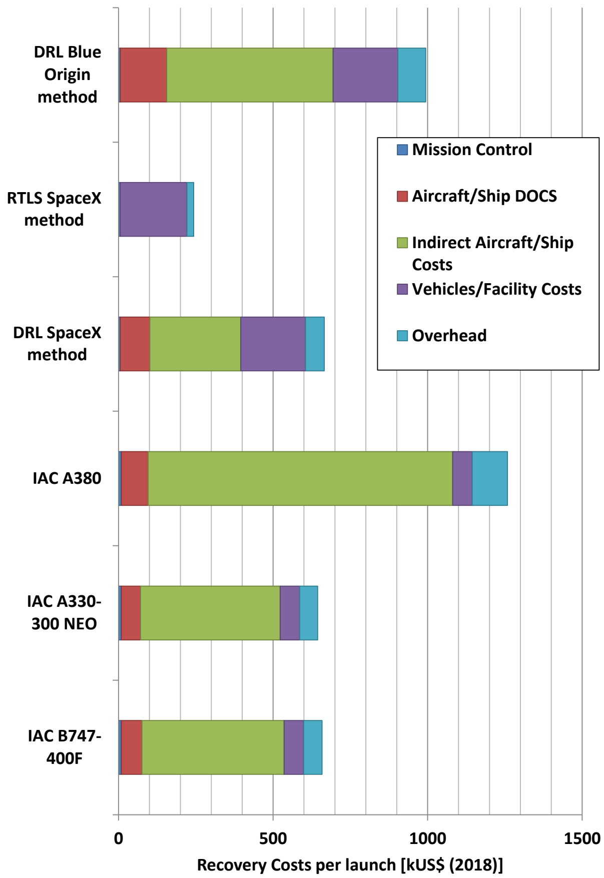

Fig. 13: Recovery Cost breakdown for different recovery strategies

Direct costs, including fuel and crew costs, landing fees, navigational fees or harbour fees and costs for extra services account for only roughly 100k$ per mission or 1.5 million – 2.5 million US$ per year depending on the recovery method. Of these direct costs 2/3 of costs are related to fuel for IAC. For VL methods, the greatest share of direct costs is due to crew costs. The facility and vehicles costs are higher for the VL recovery methods which can be explained by the fact that crane acquisition costs are increasing total costs. Contrary, the IAC costs don't include depreciation costs of the airstrip or hangar building. Including those costs would add additional 250 k$-400 k$ per launch.

$$WYr_{REC}^{TRANSCOST} = \frac{1.5}{L}(7 * L^{0.7} + m_{rec}^{0.83}) * f_i \tag{8}$$

As expected, the recovery costs are certainly dependent on the launch rate. Fig. 14 shows that dependency over launch rates from 5 to 45 launches per year. The same assumptions as described previously were used for this calculation. The recovery costs calculated with the top-down model TRANSCOST were added for comparison. In this model, the recovery costs are calculated according to equation (8) where L is the launch rate m_{rec} is the mass of the recovered stage/hardware and f_i are country- and business dependent factors.

The recovery costs depend exponentially on the launch costs with a negative exponent. Hence, the decrease of costs per launch in the comparable low launch rate regime is greater whereas the costs approach a boundary value when reaching very high launch rates. Nevertheless, doubling the launch rate from 15 to 30 launches per year would result in a decrease of -30% for the SpaceX method, -40% for the Blue Origin method and -35% for IAC. Using IAC as recovery method seems to be favourable for a launch rate greater than 15 launches per year. The recovery costs of using RTLS are negligible since they fall below 200 k$ per launch with a launch rate greater than 20 launches per year. The recovery costs calculated with TRANSCOST are considerably higher. This can be explained by the fact that the recovery CER is based on the recovery operations of the Space Shuttle solid boosters, which required a relative high effort due to the fact that it was the first time that rocket hardware was ever recovered.

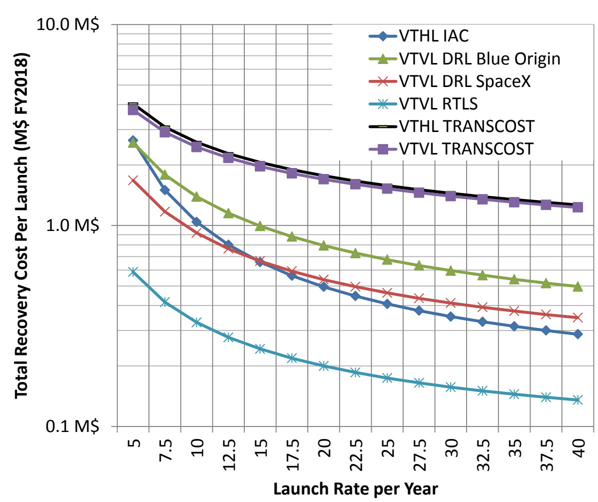

Fig. 14: Recovery Costs per launch in M$ (economic conditions: 2018) for VTVL and VTHL recovery methods

4.2. *Total Launch Costs*

The total launch costs herein were calculated by combining the TRANSCOST model with the in-house established recovery model. The production, ascent operations and overhead costs were calculated using the TRANSCOST model and the recovery costs explained in the previous section were simply added. Since the absolute values for TRANSCOST especially for RLV are still subject to high uncertainties, the relative comparison is of greater interest in the context of this paper. Hence, all costs presented herein are related to the respective costs of a comparable ELV system to identify breakeven points and determine ranges in which the RLVs might offer economic advantages over ELVs. However, at this stage the total launch costs are subject to very high uncertainties and should thus be taken as a preliminary glimpse at cost modelling of RLVs and not as a final and undeniable result.

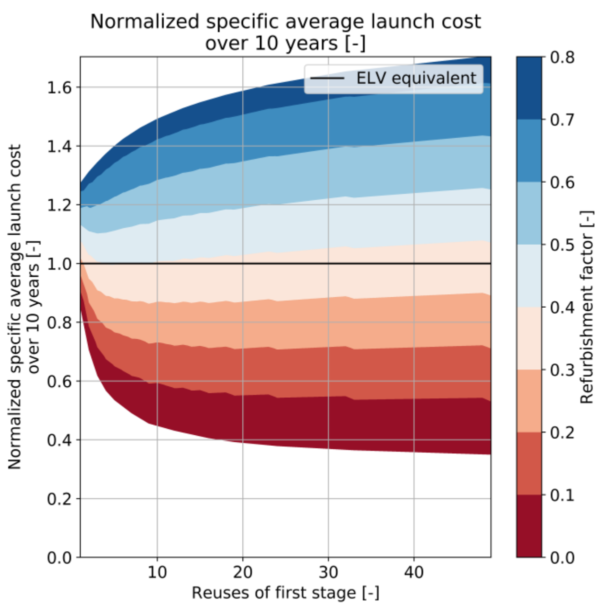

Fig. 15: Normalized average launch costs for the RLV hydrogen stages for different reusability factors at a launch rate of 10 launches/year

Fig. 15 shows the normalized average launch costs of the RLV hydrogen launchers over a period of 10 years. The costs are normalized with respect to the costs of the VL vehicle being operated as expendable vehicle, meaning that all recovery hardware is stripped off the vehicle and all propellant is used to accelerate the stage. The average is determined by calculating the cost of the launcher over 10 years and dividing the total costs by the number of launches. Furthermore, the costs are given for a launch rate of 10 launches/year and different refurbishment factors (see section 2.4 for the definition of the refurbishment factor). Any points below the 1.0 line are regions where the ELV would be cheaper than an ELV. It is visible that too high refurbishment costs of 0.4 (respectively 40% of first stage costs) or higher lead to increasing launch costs which lead to economically inviable solutions. If the refurbishment factor drops beneath 0.4, the RLV is cheaper than the respective ELV with greater advantage the lower the refurbishment costs are. Interestingly, while expecting a great cost decrease with an increase in reuses for less than 10 reuses, the averaged costs stagnate for more than 20 reuses for a refurbishment factor between 0 and 0.1. For higher refurbishment, a slight increase in costs for a high number of reuses can even be observed. This indicates that extensive number of reuses might not in all cases be of preference for a RLV.

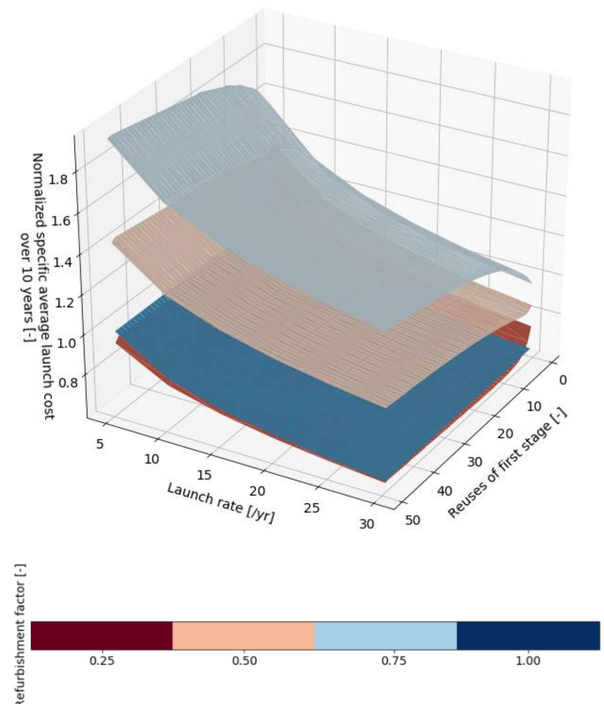

Fig. 16: Normalized average launch costs for the RLV hydrogen stages for different launch rates, number of reuses and reusability factors

The total launch costs of RLVs are also dependent on the launch rate. Fig. 16 shows that dependence for refurbishment factors of 0.25, 0.5, 0.75 and 1 which represents the ELV. An increase in launch rate leads to a reduction of launch costs in all cases. However, the reduction is comparable for ELV and RLV. The greatest driver for reducing the launch costs is decreasing the refurbishment factor, since only the RLV with a refurbishment factor of 0.25 is cheaper than the respective ELV launcher and that only for sufficiently high numbers of reuse.

In general, it should be noted that this model is a preliminary model. Hence, any cost values and relations presented depend highly on the assumptions that are input into the model. These assumptions depend on the business model, the country, team experience and further factors and the stage mass. An increase in stage mass leads to higher costs, which is why hydrogen seems also a good choice from an economic point of view. However, in the future course of economic studies of RLVs, the cost model shall be enhanced to include uncertainties and worst-cases to allow a more accurate determination of the overall costs.

5. Discussion & Conclusion

Currently, reusability for launch vehicles is once again being discussed in Europe due to the success of SpaceX and Blue Origin. From a European perspective it is important to ask and investigate how to stay competitive in the evolving launch market in this new markt. Whereas the Ariane 6 with its maiden flight scheduled for the year 2020 might be a viable interim solution to stay in business, a future possible launcher following the Ariane 6 has to already be discussed and prepared.

The use of reusability offers the potential to significantly lower the launch costs. In this context, DLR set up several projects in the past year that improve technologies that are necessary for reusable launch vehicles such as TPS, cryoinsulation, health-monitoring and the development of subscale flight demonstrators as CALLISTO and ReFEx. While the development of all these technologies is of high importance, simultaneously the question of how a full scale reusable future launch system could be designed has to be answered. This question was tackled in this work by investigating a broad range of different launcher options using various return methods such as vertical landing or horizontal landing. RLV systems using different return methods were conceptually designed using the same mission requirements and highly akin design assumptions. This approach shall allow an objective comparison of those launch systems from a technical, an economic and a recovery operations point of view.

Comparing the resulting launchers from a technical point of view leads to some interesting observations. First, RLVs with a reasonable payload capability of 7.5t to GTO don't necessarily have to be extensively heavy compared to ELV. Using hydrogen and VL leads to a GLOM of ~420 t whereas using HL can even reduce the GLOM to slightly below 400 t. These masses are even below the GLOM of Falcon 9 with 550 t and that of an Ariane 5 of roughly 800 t. However, the Falcon 9 has an even lower payload capability of 5.5t to GTO whereas the Ariane 5 can deliver up to 10 t to GTO as ELV. These low masses are only realized for LOX/LH2 as the propellant combination. Using any hydrocarbon results in significantly heavier launchers. Furthermore, major contributors to those low masses are the architecture as TSTO launchers without solid propellant boosters, the use of common bulkheads and the high specific impulse of the LOX/LH2 launchers. Even though the bulk density of this propellant combination is very low, leading to higher structural indices, the LOX/LH2 systems are lighter compared to their hydrocarbon counterparts. The GLOMs of the hydrocarbon vehicles are roughly three times higher than the GLOM of the respective hydrogen launchers with VL and twice as high with HL. The main driver for these higher masses is obviously the lower specific impulse. The lower specific impulse has a more severe impact on the VL stages: more propellant mass is needed for the return, re-entry and landing maneuvers and thus has to be accelerated additionally during launch. The two stage architecture also impacts the hydrocarbon stages more than the hydrogen-fueled stages: The Δv requirement for each stage is higher which can more easily be achieved with the higher specific impulse of hydrogen than with the lower inert mass ratio of the hydrocarbon launchers.

From a performance perspective, HL with In-Air-Capturing offers the possibility to build stages with the best performance to mass penalty ratio. This is reflected by the inert mass ratios shown in section 3.1. Any RLV is necessarily subject to mass and thus payload penalties compared to an ELV, additional mass is always needed to re-enter and land a RLV stage. The VL method with downrange landing offers a similar performance-to-mass-penalty. However, when doing VL in combination with RTLS the additional mass necessary to revert the trajectory to land at the launch site gets so large that the payload capability decreases by 50% or more compared to an ELV mission.

In this paper, the recovery and launch costs were considered with a preliminary cost assessment approach. Therefore, an in-house cost estimation model was derived that uses a bottom-up approach to estimate the recovery costs of VL and HL methods. Since in both cases hardware is used for which a vast database of cost data and models exist, e.g. aircraft or cargo ships, the estimation of said recovery costs can be determined within reasonable accuracy. For VL landings, the method foreseen by Blue Origin was compared to the SpaceX method. The Blue Origin method for downrange landings is based on the idea to use a big ship to land the RLV stage and thus decrease the number of supply or additional vessels needed while SpaceX uses multiple small boats and a barge with limited maneuvering capabilities for the RLV stage landing. RTLS was also considered but is seen as the less critical case since neither barge nor further vessels are required in this case. For HL, the In-Air-Capturing method was considered. Here, a commercial aircraft captures the RLV stage after re-entry and tows it back to the landing site where it lands on a conventional airstrip. In that case, different commercial airliners suitable for this task have been investigated, namely the B747, the A340 and the A380.

The recovery costs of either VL with downrange landing and HL with In-Air-Capturing are in a similar range. For a launch rate of 15 launches per year, the costs are between 600 kUS$ – 700 kUS$ (2018 economic conditions) per launch for SpaceX and IAC with either A330 or B747. Using the Blue Origin method leads to costs of 1 million US$ per launch and using an A380 for IAC leads to costs of 1.25 million US$. The higher cost of these methods lies in the high acquisition costs of the vessels which are depreciated along all launches. However, the Blue Origin method offers the advantage of reducing travel time and thus allowing for short turnaround times. Furthermore, the ship might not be as affected by sea swell as the small SpaceX landing barges. Two further points worth mentioning are the fact that the recovery costs are not that dependent of the recovered stage mass since the direct costs, especially fuel costs, are only a minor share of overall costs. Furthermore, the overall recovery costs are comparably small to total launch costs of existing launch systems.

Last but not least the production and launch costs were calculated using the TRANSCOST model in combination with the just explained recovery cost model. The costs were normalized with respect to the cost of the respective launcher operated as ELV since the absolute values are still subject to high uncertainties. Breakeven points could be identified that pointed into the direction that RLV system in general can offer economic advantages if the refurbishment can be kept low. The refurbishment costs with the herein used assumptions have to be below 0.25 for the hydrogen launchers to be economically viable. However, the cost model shall be improved in the further course of the study.

In summary, a feasible future RLV could be imagined that offers high payload capability, high flexibility and reasonable mass and thus costs. Feasible designs with either VL or HL return methods or various propellant combinations were identified. For the general launcher mass and size the use of LOX/LH2 as propellant combination is very advantageous. Nevertheless, at this point of preliminary RLV investigation it is still difficult to determine the impact of reusability on all aspects with certainty. A study was launched at DLR last year that looks into much more detail into several questions related to RLV design such as thermal protection, re-entry loads, structural design and control and dynamics [14]. Further work at DLR will focus on gaining insight from the RLV demonstrators and projects and thus improving respective RLV design and cost modelling.

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