Evaluation of Parametric Cost Estimation in the Preliminary Design Phase of Reusable Launch Vehicles

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Abstract

Reusability for space transportation vehicles offers the potential to lower launch costs, thus enabling low-cost and frequent access to space. Nevertheless, estimating the costs of such an RLV, although being the main driver for the economic success of such a vehicle, is a highly uncertain and unreliable task. For this paper, the well-known cost estimation tool Transcost was critically investigated in terms of its applicability to determine development costs of RLVs. In the course of this investigation new cost estimation relationships for ELV and RLV stages were determined. This analysis was complemented by an estimation of the development cost for the Falcon 9 by reverse-engineering methods. Furthermore, a statistical approach using uncertainties to determine probabilities for final costs is examined. Finally, a cost estimation method for recovery costs was established. The purpose of this investigation is to pave the way for a more thorough understanding of potential and limits of cost estimation in the preliminary design phase of RLVs.

CER	Cost Estimation Relationship
ELV	Expendable Launch Vehicle
RLV	Reusable Launch Vehicle
VTHL	Vertical Takeoff, Horizontal Landing
VTVL	Vertical Takeoff, Vertical Landing
WYr	WorkYear

1. Introduction

Reusability in space travel has already been a topic since the earliest spacefaring years in the 20th century. The idea of recovering and reusing launch systems or particular stages however was not turned into reality until the Space Transportation System, the renowned Space Shuttle, was first launched in 1981. The Space Shuttle orbiter returned from space and landed horizontally on a runway, using wings to create sufficient lift and drag for a controlled, atmospheric re-entry. Initially sought to lower the costs of space transportation significantly, the Space Shuttle program turned out not to be the economic success that was hoped for. Instead, launch costs were even higher than comparable expendable launch vehicles (ELV) costs. The reasons for this are manifold, but can partly be related to its design as reusable launch system: the cost and time to overhaul the system (refurbishment) after every launch was much higher than expected. The Space Shuttle program thus proved a very important point: the technologies for reusable launch vehicles (RLVs) are challenging, but feasible. In order to allow for cheap and frequent transportation to space, reusable launchers however have to have very low refurbishment costs and turnover times in order to compete against conventional, expendable launchers.

Nonetheless, in the 21st century the idea of reusable launch vehicles experienced a renewed boost. The successes of SpaceX (with Falcon 9 and Falcon Heavy) and Blue Origin (New Shephard) in landing, recovering and reusing the first stages of their respective launch vehicles by means of retropropulsion have shown the possibility of developing, producing and operating reusable launchers at low launch service costs and high reliability. This has raised the interest to investigate the impact of developing reusable European launchers as a way to lower the launch costs and stay competitive on the evolving launch market. However, reusability for launch systems can be achieved through a broad range of different approaches, each offering unique advantages, but also technical challenges. Understanding and evaluating the impact of those different recover and reuse methods on a technological, operational and economic level is of essential importance to choose a technology that is adaptable to a European launch system.

The technical and operational challenges have been investigated thoroughly in past studies at DLR [1] - [4]. However, the final goal is to determine whether RLVs are able to lower the total launch costs compared to conventional ELV. A suitable tool that was used in the past to determine ELV costs is parametric cost estimation by the Transcost model [5]. This model is a so-called top-down approach deriving cost estimation formula from historical launcher cost data. Thus, intrinsically, higher accuracy in launcher cost prediction requires rather many data points. This leads to a huge challenge in predicting RLV costs: due to the fact that as of 2022, only two reusable space transportation systems have been in operational use (the Space Shuttle and the Falcon 9), the data on RLV costs is very limited. Furthermore, those systems differ greatly in the recovery options they apply and in the final production and operational costs for both systems. Hence, using those systems as baseline to calculate RLV costs renders highly uncertain and unreliable cost estimations.

Thus, in this paper, the Transcost approach is critically re-evaluated and extended with more data on ELV and on winged reusable stage costs. Further, an in-house estimation of actual Falcon 9 costs was performed in order to determine a more accurate understanding of the costs of an operational, commercial RLV. From the analysis of Transcost, a statistical approach to modelling launcher development costs is investigated. Furthermore, a cost model to determine the costs of recovery is presented, which is based on a rather bottom-up approach focusing on determining the costs of additional infrastructure, vehicles and further more. The thus derived cost estimation relationships were used to evaluate different RLVs that were designed in the framework of the DLR studies ENTRAIN [4] and AKIRA [1]. Those considerations shall be evaluated and discussed to determine the applicability of current cost estimation methods to RLVs.

1.1 Recovery and Reusability Methods

In the following, the main methods to recover first stages are explained. A breakdown of the methods considered is shown in Figure 1. The methods can be divided into vertical take-off, vertical landing methods (VTVL), vertical take-off, horizontal landing methods (VTHL) and parachute/ballute recovery. The latter is only considered herein for smaller launchers of the microlauncher class, since the experience in the past with the parachute recovery of the Space Shuttle boosters have shown that a controlled landing is essential.

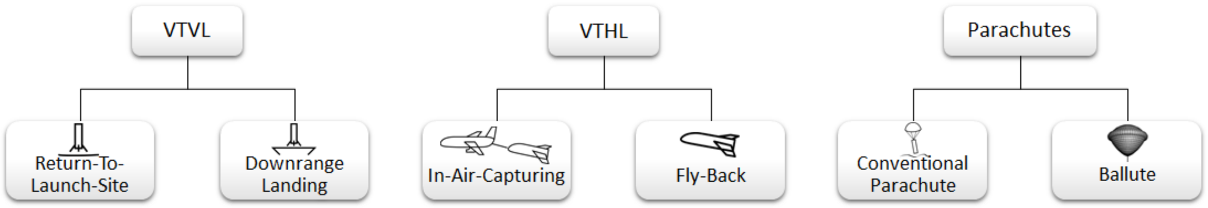

Figure 1: Return Methods for First Stage Recovery

Here, for the launcher class with a payload capability similar to Ariane 5 and Ariane 6, only VTVL and VTHL methods are considered. The VTVL method features deceleration and landing by reignition of the engines and requires additional fuel for the maneuvers during the return part of the mission. Further, we distinguish between downrange landings (DRL) and Return-to-launch-site (RTLS). For horizontally landing stages, the vehicle is decelerated by aerobraking only. For this purpose, the stages are equipped with a wing and further aerodynamic control surfaces. Within VTHL methods we distinguish additionally between Fly-Back methods, where the RLV stage returns to the landing site by igniting an airbreathing engine, and In-Air-Capturing, which is a highly innovative approach that is based on the idea to capture the RLV stage with a towing aircraft in-flight and tow it back to the landing site. This method is currently studied in the frame of the EC-funded FALCon project [6]. For further details about the RLV methods refer to [4].

2. Launcher Development Cost Estimation

Generally, the total costs of any launch vehicle are composed of the four major components shown in Figure 2. Those can be classified as either recurring or non-recurring costs. Recurring costs are costs that occur repeatedly over the vehicle's life cycle whereas non-recurring costs are costs that only occur once in the vehicle's lifetime (e.g. development costs). In Figure 2 the overhead costs are specially treated since they actually occur regularly (recurring costs) but are rather fixed to a timeframe and are determined by a range of external factors.

For an RLV the cost breakdown is different to an ELV, since it features recovery, refurbishment and re-launch operations while having a significantly different production approach than conventional ELV. While the production rate of ELVs is equal to the launch rate (one unit produced per launch), the RLV production costs are amortized between all launches it is used for. This is considered to be the great benefit of RLVs if all other additional costs can be kept low. Additional recurring costs related to reusability are refurbishment, maintenance and recovery costs. The major difference between refurbishment and maintenance is the fact that refurbishment are regular, minor activities performed after each launch and maintenance are major activities performed when necessary (comparable to regular maintenance checks for aircraft, e.g. replacing an engine). The goal for any RLV is to keep the amount of refurbishment and maintenance as low as possible while still achieving high reliability and safety. The recovery costs are also recurring costs and are comprised of the costs for recovery infrastructure and vessels, personnel, fuel costs, fees for harbor moorings and much more (see section 4 for details).

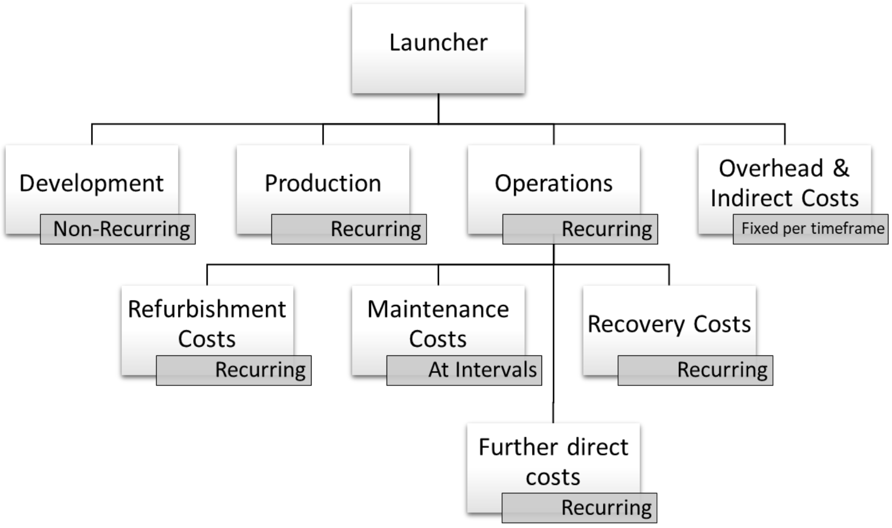

Figure 2: Cost Breakdown of a reusable launcher

In this paper, the development, production and operations costs linked to all ascent operations are evaluated with the Transcost model. For recovery costs, an in-house model was established that uses rather straight-forward estimations based on established bottom-up models. Refurbishment and Maintenance costs cannot be estimated yet since they are highly dependent on the specific RLV system and require actual flight testing in order to be understood well enough. Nevertheless, a parametric approach was investigated where the influence of different values of refurbishment and maintenance, based on the Transcost model, was used to determine the effect of those values.

2.1 Transcost Model

The Transcost model was developed by D. Kölle and is based on a top-down approach, meaning that costs are estimated on system rather than on subsystem level. The Transcost approach uses Workyear as unit for costs. Here all costs are expressed in terms of full-time employee workyears. The advantage of this approach is that costs of different time periods are comparable since inflation is neglected. To calculate launch vehicle costs, cost estimation relationships (CERs) are determined by using cost data of historical launchers. By applying an exponential regression of the basic form as shown in (1) through available data points, the CER of said system can be determined. Here, a and x are coefficients specific to the launcher component considered, whereas M is the mass of the component. Component categories in TRANCOST are for example, liquid stages, solid stages, pressure-fed engines, turbo-fed engines, and much more.

$$CER = a \cdot M^x \tag{1}$$

In order to consider different levels of system complexity and further external factors, such as team experience, TRL of the technology of the component and productivity, further factors are introduced into equation (1) depending on the type of cost considered (development, production…). For development costs, the component cost is then calculated as shown in equation (2). Here, f_1 is a factor reflecting the technological readiness and complexity of the component compared to state-of-the-art, f_2 is a technical factor dependent on the component and f_3 is representing team experience.

The Transcost documentation recommends certain ranges depending on the conditions [5]. In order to “normalize” or calibrate known component’s costs, one would have to divide the costs by the chosen factors f_1, f_2 and f_3 (compare equation (3)) so that the CER can be derived.

$$C_{Dev,Component} = f_1 \cdot f_2 \cdot f_3 \cdot a \cdot M^x \tag{2}$$

$$C_{Dev,Normalized} = \frac{C_{Dev,Component}}{f_1 \cdot f_2 \cdot f_3} = a \cdot M^x \tag{3}$$

This approach already shows one of the main drawbacks of this top-down approach: the selection of those factors is subjective and different individuals would select different factors. Figure 3 shows this approach exemplary for the development costs of expendable ballistic stages. The data shown is extracted directly from the Transcost manual. Black represents the original data as Kölle collected it from various sources whereas the blue data shows the normalized, respectively calibrated, data. It is clearly visible that the original data shows a much higher variance compared to the data that was normalized according to equation (3), as shown in Table 1. R^2 here is the coefficient of determination, which is 60.4% before and 96.3% after calibration.

However, the Transcost manual does not describe how the normalization was performed and which factors were used. In fact, when trying to reproduce the data from Transcost in-house, the correlation derived was much different than the one from Transcost. Hence, we decided to establish a new and updated CER with more up-to-date data points, including also recent data from Ariane 6 developments and from past Ariane 5 developments to improve the accuracy of the top-down approach.

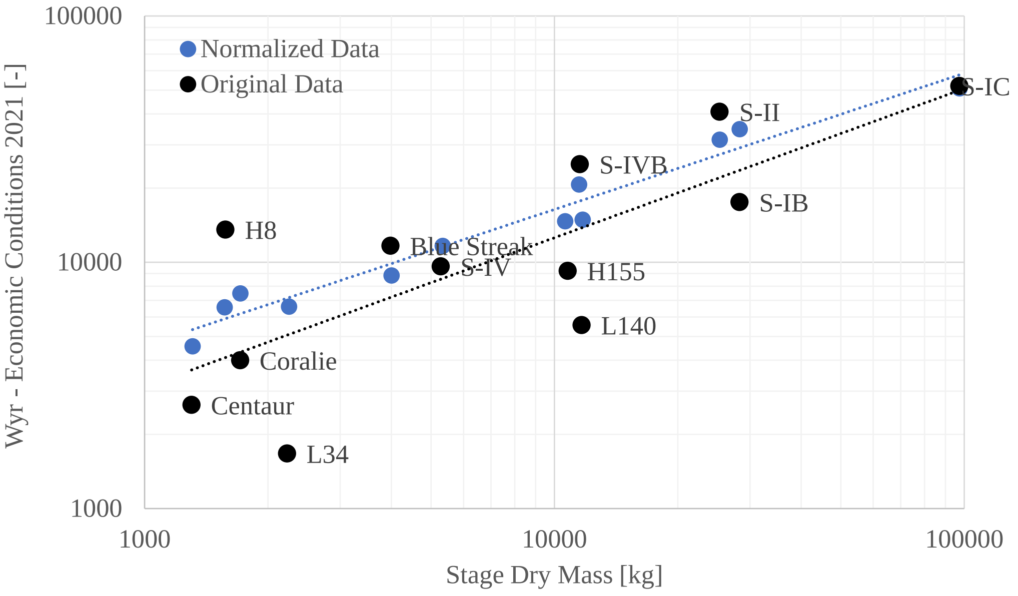

Figure 3: Development Costs for expendable first stages according to Transcost [5]

2.2 In-House ELV Development Costs

Using the same procedure as Kölle for the Transcost model, an in-house CER for expendable, ballistic first stages was derived. Therefore, some more cost data was added to the database, including data on Ariane 5 H170 and H-155 stages, Ariane 6 upper and central stage and updates on the L-34 and S-I stage [7], [8]. The calibration, respectively setting of the f_1, f_2 and f_3 factors, was performed to the best knowledge by the authors. Of course, the same problem as for the Transcost model arises, namely the dependency on subjective decisions. This problem is intrinsically linked to the methodical approach of the top-down Transcost model.

The thus established data points, including original data and calibrated data, are shown in Table 1. Two different regressions were established, namely a potential regression of the standard Transcost form shown in equation (1) and a linear regression of the form Cost = a*M+b to compare the validity of the potential approach. The in-house CER is named SART CER. It can be seen that same level of determination accuracy cannot be achieved and the CER from

Transcost can’t be reproduced properly. In fact, the linear regression features a higher R² value of 0.67 compared to the R² of the potential regression with an R² of 0.3.

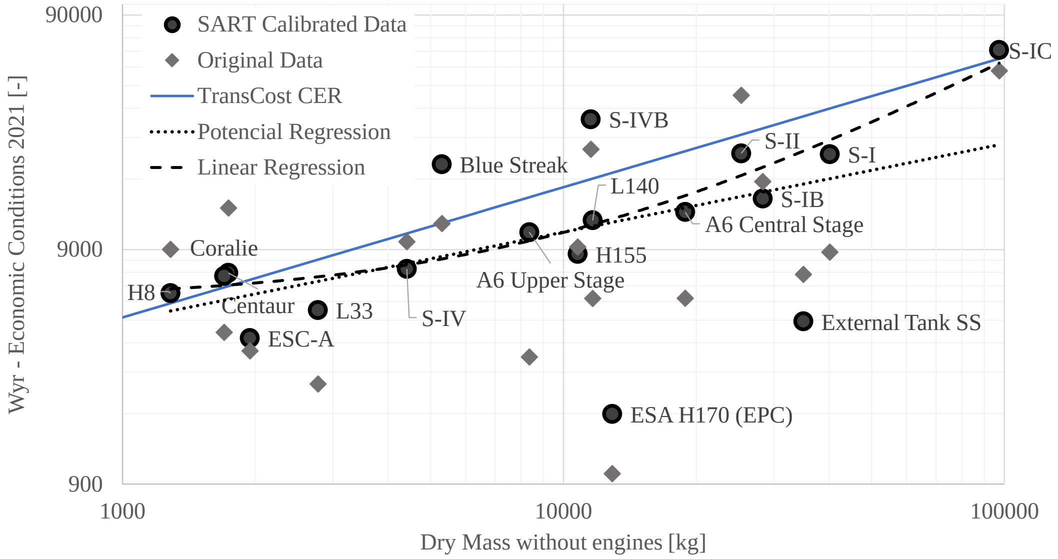

Figure 4: Development Costs for different expendable stages with in-house calibrated data

Nevertheless, the variance of the in-house derived data is too high and the R² value too low to yield accurate results using this model. The reason for that behaviour is that certain datapoints differ vastly from the regression, for example the H170 stage, the External Tank of the Space Shuttle and the S-IV B stage of the Saturn V. Furthermore, the predicted cost by the potential in-house regression is lower than the cost by the standard Transcost CER, due to the low launch costs of the European stages and the difference in calibration.

The high variance and coefficient of determination R² leads to the question if such top-down parametric models using highly differing launch systems and few data points are suitable for cost estimation purposes for future launch vehicles, where reusability and the impact of commercialization plays a growing role. The overall bad coefficient of determination leads to the question if either further factors shall be introduced while keeping the general approach of using dry mass as scaling metric for costs, or if rather a more statistically based approach would be suitable for cost estimation in the future. Thus, the uncertainties and vast variance in the cost data could be accounted for. This statistical approach is explained in more detail in section 4. Nevertheless, this method to calculate costs could not be thoroughly analysed in this paper, hence remaining focus for future work.

In general, Kölle recommends to use the ELV CER also for the calculation of ballistic RLV first stages using retropropulsion. Hence, this formula was also considered for the calculation of VTVL stages comparable to the Falcon 9.

Table 1: Coefficients a, x and R² for original and calibrated data and for linear and potential regression for expandable first stages CER

	Original Data	**Transcost CER**	**SART Potential Regression**	**SART Linear Regression**
a	47.4	100	331	0.5209
x	0.606	0.555	0.377	-
b	-	-	-	5443.2
R²	0.6043	0.9625	0.30	0.67

2.3 In-House Winged RLV CER

For winged suborbital stages TRANCOST provides a CER to calculate respective development costs. The CER is mainly based on cost estimations for study concepts of winged stages from the FESTIP study from 1985 [9]. For the cost estimation the commercial tool PRICE-H was used. It is important to note that none of those concepts was ever developed and built in reality, thus the costs remain unconfirmed as of today. Comparable to the ELV CER analysis, first the data points from Transcost were used to try to reproduce the respective CER. Then, additional data points were added from in-house cost analysis dating back to 2012 [10]. The database was extended by further FESTIP RLV stages and by a cost estimation of the SpaceLiner Booster, a hypersonic passenger transporter [10].

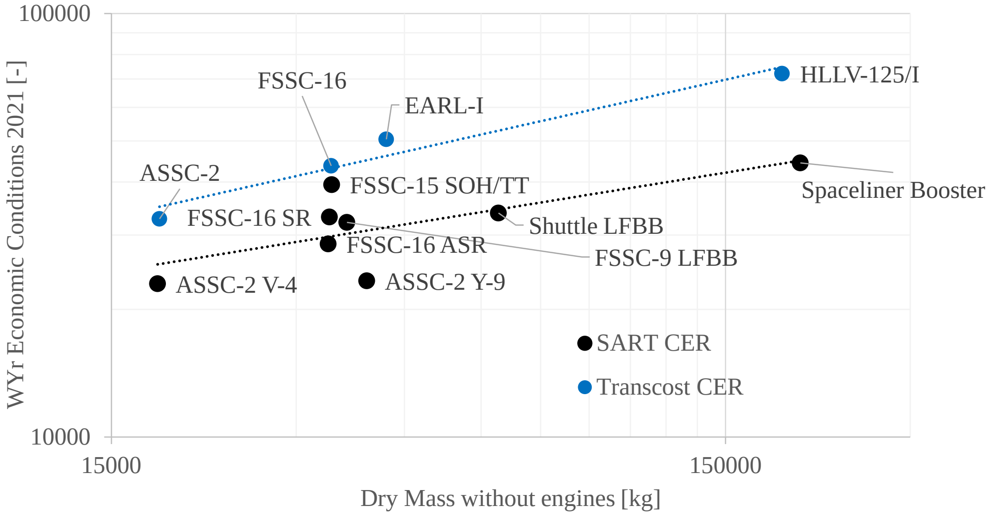

Figure 5: Development Costs for winged reusable stages with in-house calibrated data

Figure 5 shows the respective datapoints and the CER that was derived from it. The respective values for a, x and the R² coefficient of determination are presented in Table 2. Once again, the variance of the in-house SART CER is higher compared to the Transcost CER and the SART CER estimates generally lower development costs than the original trend. The overall bad R² value and high variance once again state the uncertainty in data points which directly translates to very uncertain estimations for potential future RLV. It is hence recommended to seek for alternative approaches or introduce more data points to the Transcost model in order to allow for certainty in cost estimations.

Table 2: Coefficients a, x and R² for the Transcost and in-house CER for winged reusable first stages

	Transcost CER	**SART Regression**
a	1442.3	2580
x	0.3255	0.2343
R²	0.957	0.512

2.4 SpaceX Development Cost Estimation

The commercial success of SpaceX has proven the economic viability of reusable launchers. As of today, launches with the Falcon 9 are sold for 67 million US$. Using the Transcost model to calculate the development and production costs of the Falcon 9 yields costs that are much higher than they could realistically be. For example, using the Transcost model to estimate the Falcon 9 development costs renders costs of 25.9 billion € (2019 economic conditions), respectively 10 billion € using commercial factors that Kölle introduced into the Transcost model by adapting the CERs to SpaceX cost data. However, SpaceX CEO Elon Musk once stated that the costs to add reusability to the Falcon 9 were totaling up to 1 billion US$, which was more than it cost SpaceX to develop the Falcon 9 itself (360 million US$ according to Musk).

The mismatch between the cost estimation on Falcon 9 by Transcost and by roughly estimated cost figures based on statements, tweets and the launch prices of the Falcon 9 and Falcon Heavy leads to the necessity to thoroughly understand the cost breakdown of a commercial launch service provider such as SpaceX. Thus, a datapoint could be created which can be added to the respective CER estimation database, similar to what Kölle proposed by the introduction of a commercial factor for Transcost. Also, it allows to better understand the added cost of developing a reusable system compared to a conventional ELV.

For this task, a rather detailed analysis and estimation of SpaceX' cost structure was performed. The detailed process is described in [11], but the basic idea is to estimate all expenses of SpaceX by collecting available data on cost, personnel, salaries and job positions at SpaceX and estimate the income based on the one hand publicly available data, such as NASA funding through the CRS program, and estimated income through satellite launches on the other hand. Therefore, the number of employed personnel SpaceX was collected from 2002 until today and combined with the number of people occupying different job positions and the typical salary in that respective sector to calculate personnel costs. For further overhead costs, the costs for fixed costs such as leasing or rental costs, for water, electricity, hardware, IT infrastructure and further more was estimated by collecting information on standard values for the respective costs for the region SpaceX is situated. Then, a best guess of which SpaceX program (Falcon 9 development, Merlin development, Dragon development, Falcon 9 operations, etc.) accounted for which internal share of resources for each year was done, based on information available online through platforms such as reddit or statements (either official or unofficial) by SpaceX employees.

Using this approach, the development costs of the Falcon 9 were calculated as shown in Figure 6. The development costs of the first and second stage combined add up to a total of around 750 million US$ which is quite close to the 650 million US$ communicated by Elon Musk. Also, the engine development of Merlin 1D according to this cost breakdown is around 500 million US$. Nevertheless, it is important to note that SpaceX has developed Merlin 1D based on the Merlin 1A to Merlin 1C which were used for the Falcon 1. Also, following its maiden flight in 2013, the engine was every now and then updated, so further development occurred while the Merlin 1D was already in operation.

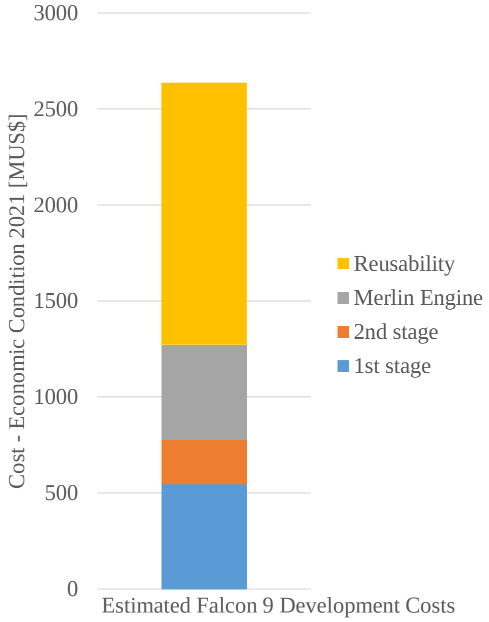

Figure 6: Development Cost breakdown of SpaceX Falcon 9 launcher based on in-house cost estimation

The estimated development costs to add reusability to the system, respectively introduce landing hardware, GNC, engine control and deep throttling and structural changes such as TPS integration and stage enhancement, account for 1.3 billion US$. This is a bit higher than the 1 billion US$ stated by Elon Musk but, considering the approach this cost breakdown was based on, surprisingly close. Hence, the summed-up development costs of the Falcon 9 of 2.6 billion US$ were used as additional datapoint in the Transcost CER model (see following section for details). Nevertheless, it is important to mention that the cost breakdown is based on a range of assumptions that were selected to the best knowledge of the authors. However, as for most cost models, a change in assumptions can lead to varying results, indicating high uncertainties in the estimation process. As such, the SpaceX cost breakdown should not be considered a definitive and completely certain result.

2.5 Comparison of CERs

The final comparison of all CERs from the previous sections is shown in Figure 7. Furthermore, the datapoint of the SpaceX estimation was added and the SART CER trendline was moved to fit the point, meaning the gradient is equal to the SART CER and only the coefficient a is adapted. However, this procedure can be considered a pure academic exercise at this point, since it is based on only one datapoint by a commercial company known for its highly competitive pricing.

Once again, the comparison clearly shows that the original Transcost CERs tend to estimate higher development costs, but with a higher R² value. For smaller masses below 800 kg dry mass, the Transcost CER is estimating lower costs compared to the SART CER. Nevertheless, stages that light are not in the realistic region for RLV first stages. Another interesting observation is the fact that the Transcost ELV CER has a breakeven point with the winged SART CER at around 18000 kg dry mass and further a breakeven point with the Transcost winged CER at around 100000 kg dry mass. Even though the dry masses are quite high, it is not expected that an ELV would cost more than a RLV stage with the same mass. Once again, the necessity to critically evaluate the Transcost model and establish alternative approaches gets highlighted by this observation.

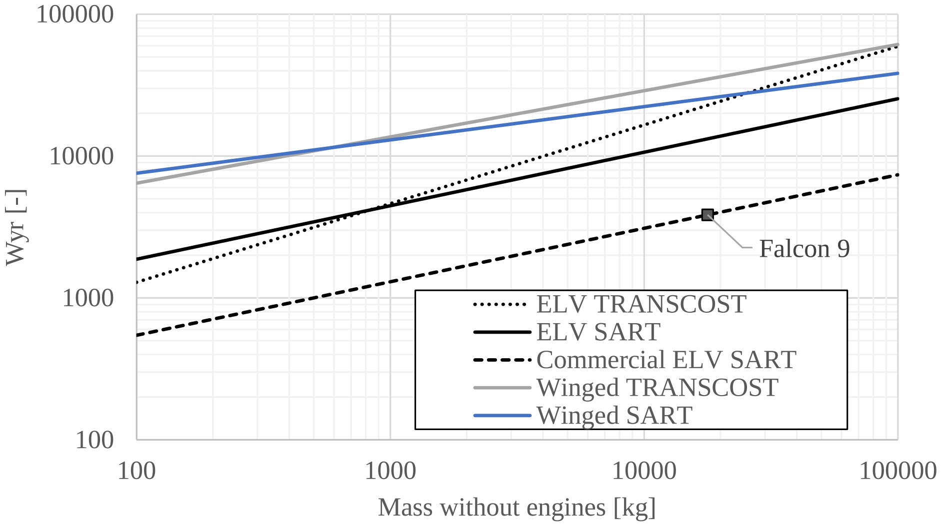

Figure 7: Comparison of TRANCOST ELV and winged stage CER to in-house SART ELV, commercial ELV and winged stage CER

3. Cost Estimation with Uncertainties

The previous critical analysis of the Transcost top-down cost estimation model has revealed some critical points of the model. First, the CER derived in Transcost could not be reproduced by in-house calibration of the data. Second, the newly derived SART CER features high uncertainties and the R² value of the regression is rather bad. This led to the conclusion that a top-down estimation approach to calculate launcher development costs might not be suitable considering the highly unreliable and quite variant database the model relies on. Further, for unconventional vehicles, like RLVs, the top-down approach might not be suitable.

Those problems about the Transcost approach led to the question if another approach considering the uncertainties in the cost data might be applicable to launcher cost estimation. In a paper presented at IAC 2018, the Transcost model was used in combination with probability distributions to determine probabilities of final development costs within certain confidence intervals [13]. A similar approach could be suitable for launcher cost estimation using the results from the previous section to determine the upper and lower boundaries for the CERs derived herein. Figure 8 shows the prediction intervals with a 95% confidence interval for the Transcost CER and the SART CER for ELVs. It is clearly visible, that the SART CER has a much higher range of possible upper and lower boundaries of the CER, due to the higher variance in data and the worse R² value of the regression (compare Figure 4). Contrary, the Transcost CER has much tighter boundaries as its calibrated datapoints feature a lower variance (compare also Figure 3).

Although the prediction interval curves are not exactly of potential nature (respectively linear in the double-log plot), the basic approach to model the uncertainty was to take the exponent value of the CERs and only change the coefficient a to fit the upper and lower boundaries. This procedure can also be applied to the CERs for winged stages. Table 3 shows the values that were derived for the upper (a_{upper}) and lower (a_{lower}) boundaries for the respective CERs.

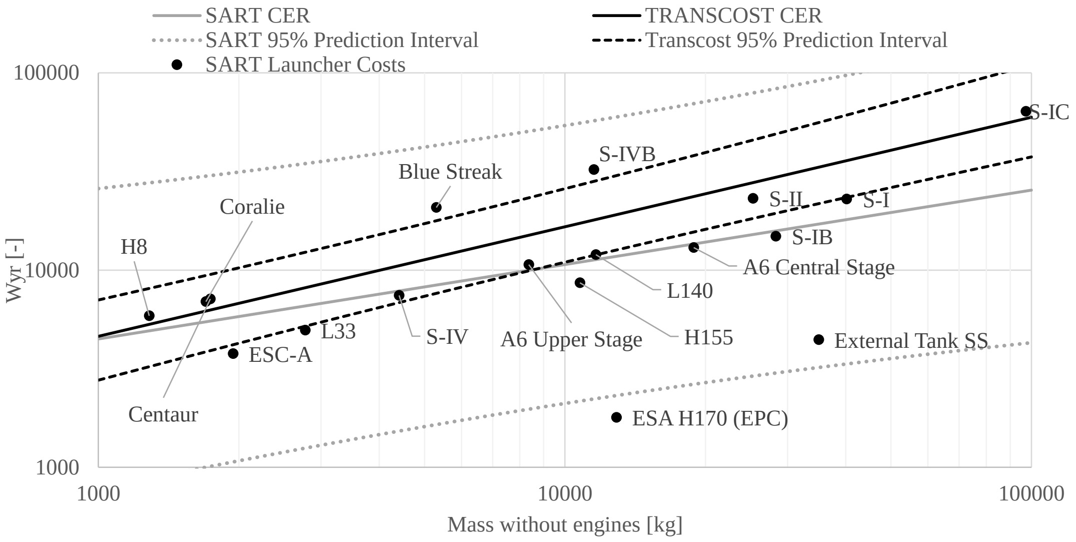

Figure 8: 95% Prediction Intervals for Transcost and SART ELV CER

The values shown in Table 3 are then used to assume a triangular distribution of the respective values for the coefficient a for each CER. This probability distribution is then applied to two different launch vehicles, keeping all other factors equal to 1, to show only the difference in final cost estimation due to the uncertainty in the CER itself. The two launch vehicles are from RLV system studies performed at DLR in the past [1], [2], [4]. For this purpose, only the development costs of the first RLV stage were considered. The mass of the VTVL first stage, which is loaded with LOX-LH2, is 33.7 t, the mass of the winged LOX-LH2 stage is 41.7 t.

Table 3: CER Coefficients for upper and lower boundary CERs

	a_{mean}	a_{upper}	a_{lower}	x
ELV Transcost	100	109	58.3	0.555
ELV SART	331	1675	65.4	0.377
Winged Transcost	1442	3338	623	0.3255
Winged SART	2580	11131	598	0.2343

The results from this exercise should be understood purely academic as for now. The calculated development costs do not contain any information about the other factors which influence the development costs, thought they could also be added with uncertainties in future work. As such, the development costs will not be in realistic ranges, but serve as a means of comparing the influence of the uncertainty distribution in the CERs on the cost calculation. The distribution could change when assuming a different distribution of the CER a and x coefficients, for example using a normal distribution instead of a triangular one.

With this knowledge in mind, Figure 9 presents the results from the development cost estimation using uncertainty distributions in the CER for 2500 launch cost calculations for each vehicle. The boxplots show the median of all values, the upper and lower quartile (50% of all values are in between those lines) and the upper and lower extreme values. As expected, the higher the uncertainty, the greater the expected spread of costs. The VTVL calculated with Transcost uncertainties has a very low variance between 20000 to 40000 in WYr costs. Interestingly, although the SART CER calculates generally lower costs, the median value in this case is higher than the Transcost CER. On the other hand, there are more lower points in the SART CER than for the Transcost CER. 50% of development costs end up between 22000 WYrs to 50000 WYrs for the SART CER and between 30000 WYrs to 35000 WYrs for the Transcost CER.

The VTHL development costs generally feature a greater variance due to lesser datapoints the CER is based on. Again, the greater variance for the SART CER leads to a greater spread of development costs which lie between very low values of around 10000 WYr to above 140000 WYrs. Nevertheless, the median value is almost the same for the Transcost and SART VTHL. 50% of all launcher development costs are between ~40000 WYrs to ~80000 WYrs for the SART winged CER and between 45000 WYrs to 75000 WYrs for the Transcost winged CER.

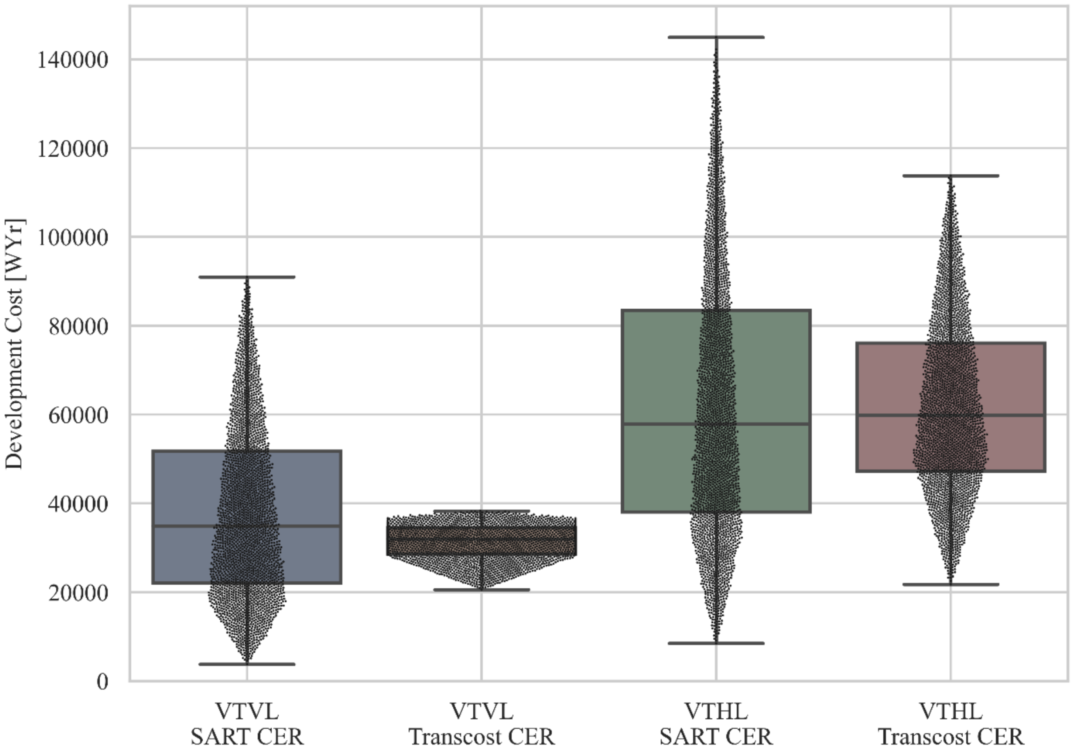

Figure 9: Development Cost Estimation with uncertainties of the CER for VTVL and VTHL vehicle

The analysis of development costs with a statistical background while taking the uncertainties in the CER estimation into account, has shown the great influence the accuracy of the regression behind the CER has onto the cost calculation. As of now, the Transcost model focuses on calculating costs based on CERs derived from a database with a very high variance and uncertainty. To improve the accuracy of the regression, those datapoints are calibrated by a method that, at times, seems like a more random calibration of the datapoints. Nevertheless, the approach of taking uncertainties in the datapoints into account to rather determine ranges of probable launch costs could offer the potential benefit of allowing to better capture the highly uncertain nature of cost estimation. The herein presented results shall be further evaluated and updated in future work to also accommodate other uncertainties and to allow for the calculation of production and, potentially, refurbishment costs.

4. Recovery Cost Estimation

Contrary to an expendable launch vehicle, any reusable launch vehicle requires hardware, additional infrastructure and personnel to recover or land the stage. Contrary to the problems encountered for estimating RLV costs with conventional approaches, such as Transcost (compare section 2), the costs for recovery operations can be estimated by a rather straightforward bottom-up approach. Established cost models for the calculation of aircraft costs, ground personnel, costs for barges and ships and further are rather well-known compared to launch vehicle costs. Thus, an in-house cost mode was established. This model is explained in detail in [12].

In the following, the recovery costs for three different recovery methods, RTLS, DRL and IAC is calculated. The Fly-back strategy was neglected, since recovery costs would expected to be in the range of RTLS as not much additional infrastructure would be needed. This model used for the calculation of the respective costs was established in-house and the in-depth explanation of all and assumptions can be found in. Details about the cost modelling of the remaining methods (Downrange Landing, LFBB, RTLS) can be also found in that report.

The costs of recovery per launch for different return methods for VL and HL stages are shown in for heavy class launchers. The costs are given in US$ with respect to the economic conditions of 2021. For In-Air-Capturing, the costs of the B-747, the A380 and the A330 NEO are presented in Figure 10. For VL recovery the SpaceX and Blue Origin barge/ship recovery methods as well as RTLS costs are considered. The difference between the SpaceX and Blue Origin approach is the fact that SpaceX uses numerous rather small vessels while Blue Origin aims to use one big vessel for recovery operations. The cost of DRL recovery are expected to not change significantly when reducing the size of the launcher. 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.

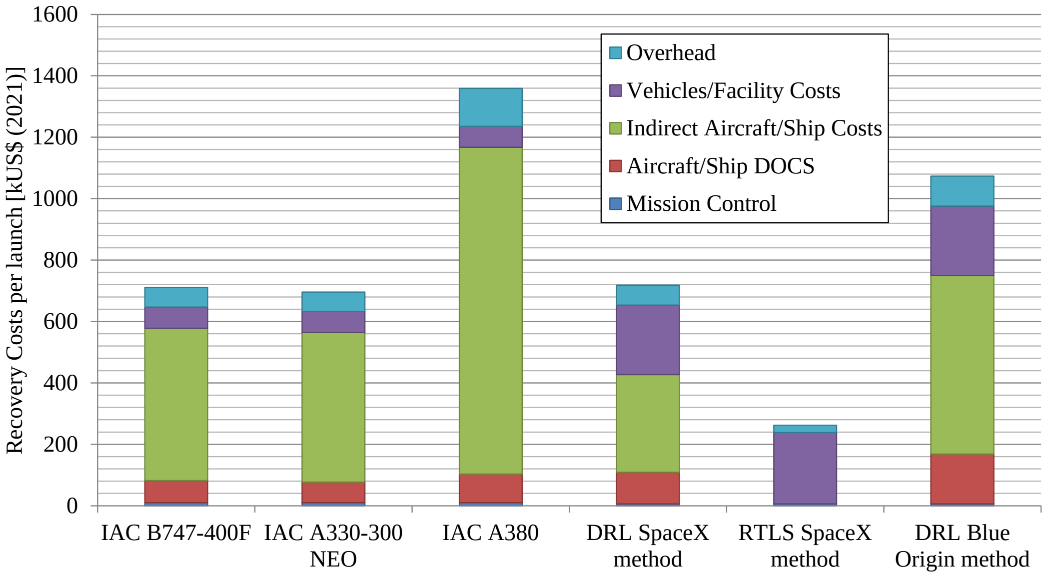

Figure 10: Recovery Cost breakdown for different return strategies for RLVs with a launch rate of 15 launches per year

The recovery costs end up between 250 k$ (RTLS) to 700 k$ (SpaceX barge landing) to almost 1.1 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 of the recovery vessel 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. In case of In-Air-Capturing, relying on flight-proven second-hand aircraft, which are usually available for much lower prices on the market compared to a completely new vehicle, is crucial.

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. In case a new airstrip and airport would have to be constructed, those costs would add an additional 250 k$-400 k$ per launch.

5. Summary & Outlook

In this paper different estimation methods to investigate RLV and ELV costs were analysed. For the determination of RLV development costs, the Transcost top-down method was critically evaluated to assess its applicability to cost estimation. The evaluation of the Transcost CERs led to the conclusion, that the cost estimation formulas are based on datapoints with a very high variance, thus relying on quite uncertain data. Within Transcost, this problem is solved by calibrating the datapoints so that they allow for a more accurate regression. However, the calibration that Transcost uses could not be reproduced, using even a range of extreme combinations of factors. Thus, it was decided to derive a new in-house CER for ELV, which is equivalent to VTVL ballistic stages in Transcost, and for winged RLV stages. Furthermore, by reverse-engineering the cost structure of SpaceX, a cost estimation for the development costs of the Falcon 9 was derived, which served to derive a “commercial RLV” CER.

For this purpose, more recent data on launcher development costs were collected and added to the Transcost database. Thus, new in-house SART CERs could be derived. Nevertheless, the accuracy of the regression turned out to be rather low, ranging between R^2 values of 0.3 – 0.5, even with calibration of the data. Hence, the SART CERs revealed a further problem of the top-down Transcost approach: the calibration of the datapoints is highly subjective and has a big influence on the outcome of the cost estimation. In general, it is questionable if such a deterministic model is suitable for the cost estimation of rather unconventional vehicles, like RLV.

In order to deal with intrinsic uncertainties of cost estimation, a statistical approach was investigated. This model is based on the idea to include the high variance of the datapoints to determine ranges of probable launch costs compared to trying to pinpoint the exact final value of development costs. Therefore, a cost model initially developed by experts at the MIT [13] and further developed in-house was used to include uncertainties for the coefficient a of each CER in the development cost estimation of a VTVL and a VTHL vehicle. This approach showed some potential to be used for future launch vehicle cost estimation. Nevertheless, it would have to be improved by investigating the uncertainties in more detail, potentially including sensitivity analyses and the influence of all other factors of the Transcost model in the cost calculation. Also, this approach could potentially be applied to production and refurbishment costs to include the fact that refurbishment costs are very difficult to determine.

Finally, an estimation of the RLV recovery method costs was established based on a bottom-up approach by estimating the costs of single elements involved in the recovery operations. This analysis gives potentially more accurate results than the Transcost approach since it is based on established and proven cost models for the elements involved, e.g. aircraft or ships. The results show that the recovery costs generally account for only a marginal increase in total launch costs. Further, the costs between vertical landing and horizontal landing methods are in the same range. Nevertheless, the biggest cost driver here is the acquisition cost of the main vehicles involved in the recovery which has to be depreciated along all launches.

The considerations herein are not supposed to present a new cost model for launcher cost estimation, especially for RLVs. Instead, several different approaches, be it conventional and frequently used in launch cost estimation (Transcost) or newly developed in-house (recovery costs) are presented to highlight the pros and cons and determine their level of accuracy for launch cost estimation. This analysis has shown that further work should be put into modelling the launch costs by the conventional top-down approach used by Transcost. For future work, innovative approaches should be investigated, such as using the uncertainty model for cost calculation. The final goal should be to a link all cost estimation tools, so either Transcost top-down or statistical top-down and recovery cost model to establish an RLV cost model that could help in investigating the economic potential of future European RLV.

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