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Analysis of cost-efficient launcher family composition under consideration of uncertain launch market scenarios

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Abstract
A modular family of launch vehicles based on the Prometheus engine, currently in development, is among the concepts being explored for future European launch systems. This modular approach enables the sharing of major components across different configurations, potentially reducing development costs and lowering recurring launch expenses through increased production efficiency. However, the optimal composition and sizing of such modular launch families remain insufficiently addressed in existing literature. This study provides an initial investigation into the recurring and non-recurring costs associated with two modular launch vehicle families employing reusable Vertical Takeoff and Vertical Landing first stages. It examines how the number and selection of family members influence overall costs and evaluates the sensitivity of these outcomes to uncertainties in the future launch market. The analysis reveals that the largest family is not the most cost-effective composition for partially reusable launch vehicle systems. Thanks to the recurring cost reduction enabled by reusing the first stage, the additional cost of developing the entire family is not amortized across a broad spectrum of future possible launch markets. Instead, a streamlined family consisting of two members with significant component overlap minimizes total costs. In contrast, for a launch vehicle family utilizing expendable first stages, the larger family compositions amortize the additional development costs, resulting in lower total costs compared to family compositions with fewer members. As an additional observation, the cost-optimal family composition with reusable first stages costs approximately one-third less than its expendable counterpart.

Keywords Launch vehicle family · Cost estimation · Reusability trade-off · Modular · Monte Carlo simulation

Abbreviations

CER	Cost estimation relationship
VTVL	Vertical take-off, vertical landing
VTHL	Vertical take-off, horizontal landing
TFU	Theoretical first unit
ELV	Expendable launch vehicle
RLV	Reusable launch vehicle
SLME	SpaceLiner main engine
DRL	Downrange landing
DLR	German Aerospace Center
ESA	European Space Agency
RTLS	Return to launch site
LOX	Liquid oxygen
LH2	Liquid hydrogen
LCH4	Liquid methane
LEO	Low earth orbit
SSO	Sun synchronous orbit
GTO	Geostationary transfer orbit
WYr	Work-year
IAC	In-air-capturing
TSTO	Two-stage-to-orbit
3STO	Three-stage-to-orbit
FF	First-fit
FFD	First-fit-decreasing
SSTO	Single-stage-to-orbit
GLOW	Gross-lift-off-weight
MDO	Multidisciplinary optimization process

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1 Introduction

One of the options currently being discussed for future European launch vehicles is a modular family of launch vehicles based on the Prometheus engines currently in development.

This approach allows for the sharing of major components among multiple launch vehicle configurations, thus sharing development costs and potentially reducing recurring costs per launch through higher production cadence [1].

For the optimal staging and sizing of the individual launch vehicles themselves, a range of literature exists. Ranging from the purely analytical [2], to semi-analytical solutions (for example [3] for Expendable Launch Vehicles (ELVs) or [4] for Reusable Launch Vehicles (RLVs)), to fully numerical approaches such as presented in [5]. In contrast, significantly less research has been published on launch vehicle families, particularly in the context of cost optimization. In [6] a Multidisciplinary Optimization Process (MDO) approach is applied to a family of launch vehicles consisting of an ELV and an RLV that share several components, including engines, the second stage, and most of the first stage components (apart from a "reusability kit"). The goal of this analysis was to minimize the Gross-Lift-Off-Weight (GLOW of these configurations, with the payload mass requirements predetermined. In [7], a method is proposed to optimize the staging of multiple launch vehicles sharing major components for optimal cost. However, this approach assumes fixed family composition and a predetermined number of launches for each configuration.

In practice, the number of launches for a given vehicle in the family depends on several factors. These include the vehicle's payload performance, the dynamics of the launch market, and how payloads are distributed across the available family options.

Another gap in the literature lies in addressing the optimal size and composition of a launch vehicle family. How many family members and shared components are necessary to achieve cost-optimality? With multiple modular components, numerous combinations of potential launch vehicles become feasible. Having more launcher options can indeed reduce recurring costs by allowing payloads to be distributed more efficiently. However, each additional component comes with its own development cost, and every new family member adds complexity and extra engineering effort to the overall system.

This study takes an initial step in addressing these interdependencies by evaluating and comparing various possible launch vehicle family compositions in terms of their non-recurring and recurring costs.

To understand the recurring costs of a launch vehicle family, the entire market scenario must be considered, including how payloads are assigned to different family members. Since launch vehicles take many years to develop and are expected to stay in service for decades, predicting the future launch market is required. These long-term forecasts involve significant uncertainties, which need to be accounted for in the analysis.

In [8], a method was developed to estimate the recurring and non-recurring costs of launch vehicles and families under uncertain market conditions. This paper builds on that work by analyzing the composition of launch vehicle families with reusable Vertical Take-off, Vertical Landing (VTVL) first stages. Two families are studied: one using Liquid Hydrogen (LH2) and the other using Liquid Methane (LCH4). Each family combines five components (three stages and two engines) into up to five launch vehicles with varying sizes and payload capacities. It is unclear if all these combinations are needed to meet future market demands or if a smaller set of launchers would be more economical. To explore this, the costs of different family compositions, including fully expendable options, are evaluated.

The method used to assess the cost of the potential launch vehicle families is described in Sect. 2, including a description of the underlying cost models in Sect. 2.3. The technical data of the reference launch vehicle families is given in Sect. 3. The results for the various different launch vehicle family compositions (nine total for two different reference cases) are shown and discussed in Sect. 4.

2 Evaluation of launch market scenarios

To evaluate the recurring costs associated with serving a specific launch market scenario with a particular launch vehicle family, this study combines three components from previous research. The overall process and the corresponding literature references are shown in Fig. 1.

First, the relevant technical data must be available. The required level of detail depends on the cost model used. In this study, a parametric cost model is applied, which requires the mass of the major vehicle components. Additionally, the maximum payload capacity to each relevant orbit is needed to properly assign payloads to the available launch options.

Next, the payloads are optimally assigned to the suitable launch options, determining the number of launches required for each member of the launch vehicle family. Once the number of launches is established, the cost model can be used to estimate both recurring and non-recurring costs, resulting in the total cost.

The technical specifications of the launch vehicle families are presented and discussed in Sect. 3. The following sections summarize the payload assignment algorithm from [8] and the cost model adapted from [9], which together form the basis of the methodology used in this study. For a more detailed description and discussion of these methods, the reader is referred to the original sources.

To consider the substantial uncertainties associated with predicting the future launch service market, a Monte Carlo Analysis is done for randomly generated market scenarios.

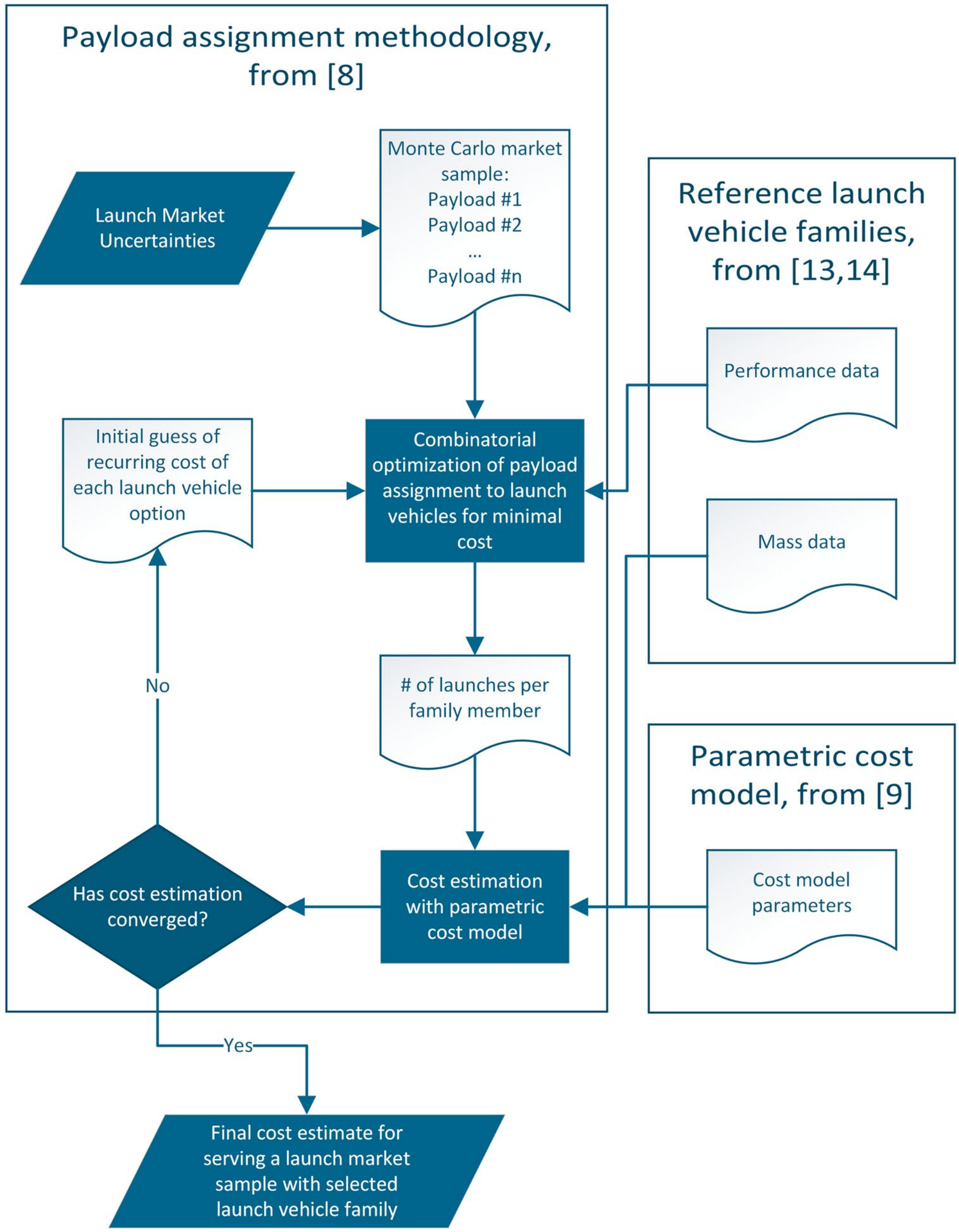


Fig. 1 Overview of workflow used to assess recurring and non-recurring costs for a selected launch vehicle family, including references for more information

The parameter space for this analysis is discussed in Sect. 2.2.1.

2.1 Payload assignment optimization

In [8], a methodology was introduced to handle uncertain market scenarios and optimize the assignment of payloads to available launch options for minimal costs. This optimization problem is a variation of the bin packing problem, complicated by the fact that the production/refurbishment cost of the launch options depends on the number of components previously produced/refurbished. The overall process is structured as follows:

1. Define launcher and market data
   - Establish the mass, performance, and staging configurations of the launch vehicle family, including variations such as reusable and expendable stages.
   - Define a probabilistic launch market scenario, incorporating parameters such as payload mass distribution, orbital destinations (e.g., SSO, GTO), market share, dedicated versus rideshare missions, and expected payload numbers.
2. Optimization of payload assignment
   - Payloads are grouped by destination orbit and launch timeframe (epochs).

- A combinatorial optimization (bin-packing problem) is performed for each group, assigning payloads to the most cost-effective launcher configurations while considering payload performance constraints. These subproblems are solved using Google's OR-Tools library [10] with the CP-SAT solver.

3. Dedicated and constellation launch handling

- Payloads requiring dedicated launches (e.g., sensitive government payloads or those with strict timing/orbital constraints) are assigned to the least expensive feasible launcher configuration.
- Constellation payloads, which often require frequent and bulk launches, are handled separately. They can either be integrated into general payload assignments or launched in dedicated missions.
- To efficiently process large numbers of constellation payloads, a bin-packing heuristic (e.g., First-Fit-Decreasing algorithm) is applied to minimize the number of required launches while ensuring full utilization of vehicle capacity.

4. Iterative refinement

- An initial estimate of recurring launch costs is made using predefined launch rates for each vehicle configuration.
- The optimized launch numbers from the payload assignment process are used to update cost estimates iteratively

5. Monte Carlo analysis for uncertainty modeling
- The entire process is repeated across multiple randomized launch market scenarios to quantify the effects of the future launch market uncertainties

More information, such as an analysis of the sensitivity to the initial launch rates, and a discussion of the method itself can be found in [8].

2.2 Definition of launch market scenarios

For the following cost assessments, the launch market scenario describes the demand for payload launches in a given timeframe and their relevant properties. Only payloads accessible to the operator of the launch vehicle family are considered. As in [8], herein a launch market scenario is defined by the following characteristics:

Duration of scenario: Reflecting the long lifespan of launch systems due to significant initial investments, the timeframe for assessing future launch needs is extensive. Longer durations introduce greater market uncertainties.

Probability of dedicated launch: This factor considers the likelihood that a payload requires a dedicated launch due to specific needs such as security concerns, unique orbital requirements, or a strict schedule.

Market share: This denotes the percentage of payloads an organization successfully acquires in the competitive launch market. Herein, the market share for single payloads and for constellation payloads are varied separately.

Number of launch epochs: Launch epochs model the intervals between launches to determine payload grouping for rideshare opportunities. Payloads are assigned to epochs randomly, affecting the feasibility of combining them in shared launches based on their time sensitivity.

Number of payloads and mass distribution: Payloads are categorized by their intended orbits, such as Sun Synchronous Orbit (SSO) and Geostationary Transfer Orbit (GTO). This classification influences the launcher's performance and the potential for rideshare missions, dictated by the compatibility of destination orbits.

Herein, only GTO and SSO are considered as orbital destinations. Historically, these have been primary targets for non-constellation payloads and are likely to remain important due to their unique characteristics. The probability for dedicated launch can be interpreted as a partial substitute for the fraction of single payloads not going into these orbits and thus unable to share launchers.

For constellation payloads, which are anticipated to form a large part of the future launch market, the specific orbital destination is often not fixed, and parameters can vary across the constellation. Due to the lack of comprehensive launcher performance data for all possible inclinations, SSO performance metrics are applied when assigning constellation payloads to launchers.

If a single launch market scenario is to be evaluated, the values for all of these parameters are known in advance. Herein, we assume uncertain market scenarios where a distribution is sampled. Based on the abovementioned properties, a random selection of payloads is generated to represent one scenario. Each payload is defined by the following properties:

- Mass
- Destination orbit
- Launch epoch
- Dedicated launch necessity

2.2.1 Uncertainties in launch market scenarios

For the case studies presented in Sect. 4, the parameter space is defined using the intervals from Table 1, from which individual scenario samples are drawn. The mean values for payload mass and numbers are based on recent ESA forecasts [11]. Other values, such as the probability for dedicated launches or the willingness of satellite operators to wait for rideshare missions (modeled via the number of launch epochs) are highly speculative. In these cases, the range in values is selected to represent a broad range of plausible future market demands. Thus, when comparing the results of two different launch vehicle families, as done in Sect. 4, the sensitivity of the comparison to the values can be considered, not only the average results. The scenarios considered in this study span 20 years, divided into multiple launch epochs. The chosen parameter boundaries result in a minimum launch epoch duration of 3 months and a maximum of 2 years.

As noted above, a Monte Carlo Analysis is used to assess the effect of these uncertainties. For each sample, values are drawn randomly and uniformly from the parameter space defined in Table 1. For the main results shown in Sect. 4, 1000 market samples were evaluated for each composition analyzed. This cutoff value is based on previous experience with regard to the convergence and the need to have enough samples to meaningfully evaluate individual uncertainties. For the sensitivity studies in Sect. 4.4 only 200 samples each were used. An example of the convergence behavior for the full LH2 fueled family is shown in Fig. 2.

2.3 Cost model

The same cost model as in [9] is used to estimate the recurring and non-recurring costs of each launch vehicle and its major components. This model is based on the TRANSCOST methodology [12], which estimates the cost of major launch vehicle components using Cost Estimation Relationships (CERs) derived from historical data. Hereafter, the aspects regarding the modeling of launch vehicle families are summarized.

By applying regression to the basic exponential equation in Eq. (1), the CER for a component type can be determined. Here, a and x are coefficients specific to the component, and M represents the component's mass. The TRANSCOST model includes categories such as liquid stages, solid stages, pressure-fed engines, and turbo-fed engines. The resulting effort E is expressed in work-years (WYr), allowing for an inflation-adjusted comparison to historical cost data.

Table 1 Uncertainty parameters of launch scenarios, all sampled uniformly

Parameter	Interval	Unit
No. of payloads for GTO per year	[7, 13]	–
No. of payloads for SSO per year	[11, 20]	–
No. of constellation payloads	[3000, 5000]	–
No. of epochs	[10, 80]	–
Dedicated launch probability	[0, 0.8]	–
Market share	[0.1, 1.0]	–
Payload mass GTO payload	[2500, 8000]	kg
Payload mass SSO payload	[300, 6500]	kg
Payload mass of constellation payloads	[400, 600]	kg

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

To consider different levels of system complexity and further external factors, such as team experience or TRL of the technology, additional factors are introduced into Eq. 1 depending on the type of cost considered.

In addition to the development effort associated with each component, TRANSCOST also considers project system engineering and integration effort E_{sys} as a factor of the sum of the development costs of the i components. This factor depends on the number of stages N:

$$E_{sys} = (1.04^N - 1) * \sum_1^i E_{dev,i} \tag{2}$$

Within this study, when calculating the cost of developing an entire launcher family, the development cost of each element is only considered once, however the system engineering costs associated with a particular launcher are still considered and added to the total sum. Considering a launcher family consisting of i components and j launch vehicles, the total development effort can be described as:

$$E_{dev,fam} = \sum_1^i E_{dev,i} + \sum_1^j E_{sys,j} \tag{3}$$

Vehicles with different possible missions, e.g., ELV vs RLV modes for VTVL vehicles, are considered separate options from a perspective of the payload assignment but are not considered separate vehicles from a development cost perspective. When a family includes components with both reusable and expendable versions (for example, the first stage engines), for the development cost only the reusable version is considered.

The recurring cost for a given number of launches is calculated similarly to that of a single launch vehicle. However, in the case of a launch vehicle family, components are shared among different family members, increasing the total production volume n. This results in a lower learning factor f_4:

$$f_4(n) = n^{\frac{\ln p}{\ln 2}} \tag{4}$$

which consequently reduces the estimated production effort E_{prod}:

$$E_{prod} = f_4 \cdot a_{prod} \cdot M^{x_{prod}} \tag{5}$$

The same parameter values for the e CERs as in [9] are used for the following analysis. They are listed for each component in Tables 5 and 6. A discussion of this cost model and a comparison to the limited, real-world data currently

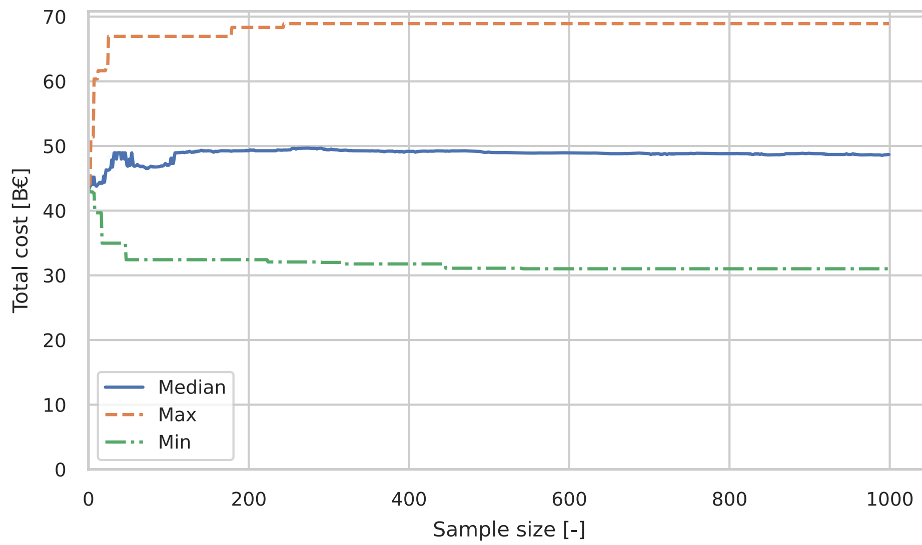


Fig. 2 Convergence of median, maximum and minimum values of the total cost of the full LH2 fueled family up to 1000 samples

available can be found in [9]. Compared to the original TRANSCOST values, the adaptations include updated databases and dedicated CERs for components specific to reusable first stages, such as grid fins and landing legs.

Hereafter, a work-year cost of 370 k€ is assumed. This results from extrapolating the Work-Year (WYr) cost data for Europe from TRANSCOST to the year 2022.

3 Reference launcher families

The families used in this case study were previously presented in more detail in [13, 14]. The following sections provide only a brief overview of their general architecture. Two launch vehicle families are considered, both featuring the ability for VTVL-type reuse of the first stage. The main difference between the two families is the choice of fuel-one uses hydrogen, the other one methane. The launchers were not sized for identical payload performance but instead sized to best accommodate ongoing European engine developments. Nonetheless, the payload performances, as shown in Table 2, are similar, and both families are able to serve the entire launch market, as described in Sect. 2.2. For this initial analysis and comparison, the full development effort is included for every component, even though in reality some of the engines already are operational or in development.

3.1 LH2 fueled family

Based on a possible Prometheus-H engine, a family of launchers was assessed by the German Aerospace Center (DLR), using the VTVL return modes. Configurations were identified where three stages and two engines (Prometheus-H and Vinci) could be combined into five launchers, covering a wide range of payload performances. These launchers, named S, M, L, XL, and XXL, form the full LH2 VTVL launcher family. A sketch of these configurations is shown in Fig. 3a. The major components of each launcher are listed in Table 8, and the masses of the modular components are provided in Table 5. The stages are referred to by their fuel name and propellant loading. For example, the H240 is a hydrogen fueled stage with a total propellant loading of approximately 240 metric tons.

3.2 LCH4 fueled family

Similar to the LH2-fueled family, the LCH4 VTVL launcher family is based on the Prometheus-M engine, with LCH4 as the fuel. The smaller engine option is assumed to be the Mira engine. Three stages were sized, which can be combined into several launchers. However, the S configuration was found to be infeasible because a single Prometheus-M engine's thrust is insufficient to launch the M110 stage. A sketch of the remaining M, L, XL, and XXL launchers is shown in Fig. 3b. The major components of each launcher are listed in Table 7, and the masses of the modular components are provided in Table 6.

3.3 Performance data

While the LH2 VTVL family consists of five launchers, due to the flexibility of the VTVL recovery approach a total number of ten missions can be considered:

- S Launcher as ELV

- M Launcher as RLV
- M Launcher as ELV
- L Launcher as RLV
- L Launcher as ELV
- XL Launcher as RLV
- XL Launcher as ELV
- XXL Launcher as RLV, recovering the core stage as well as the booster stages
- XXL Launcher as RLV, recovering only the booster stages
- XXL Launcher as ELV

As the LCH4 fueled family does not contain an S launcher, the number of different missions is consequently reduced to nine. The performance data for all the herein considered missions is given in Table 2. The so-called RLV missions include the reuse of the first stage. The upper stages are expended in all cases.

4 Family composition analysis

The methods described in the previous chapters are applied to the two reference launch vehicle families to assess the costs associated with different family compositions. In the following section the results are discussed in detail for the LH2 VTVL family, the results for the LCH4 family are shown in Sect. 4.3.

4.1 Composition of the LH2 VTVL family

The following compositions with reusable first stages were analyzed:

A: S, M, L, XL and XXL

B: M, L, XL and XXL

C: L, XL and XXL

D: L and XXL

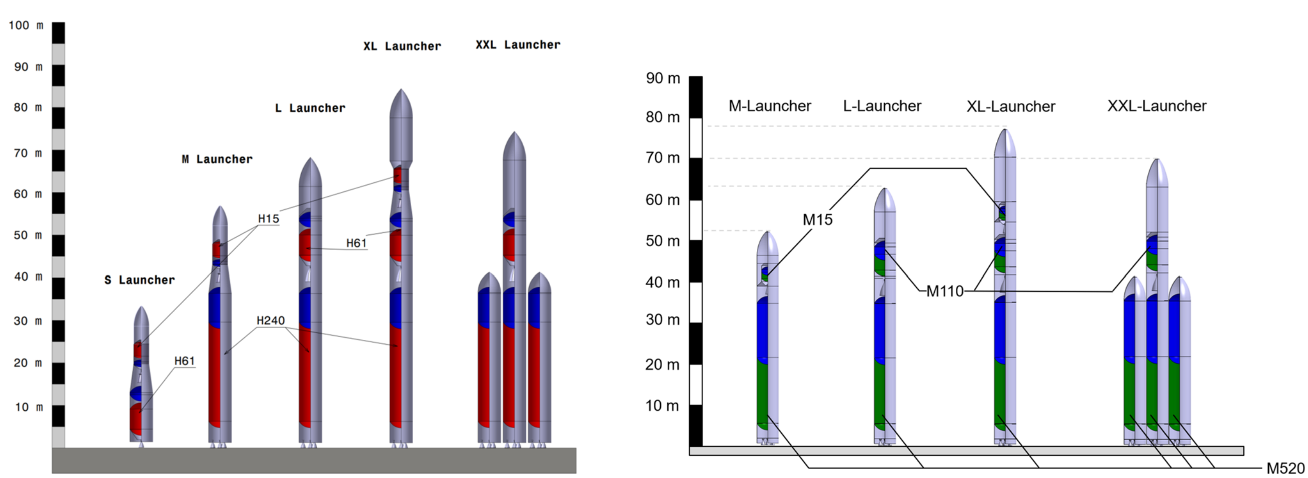
E: XXL

Composition D results in a launcher family similar to the Falcon 9/Falcon Heavy family, with the XXL launcher being

Table 2 Payload performance of VTVL families

	LH2 VTVL family		LCH4 VTVL family	
	Payload [t]		Payload [t]	
	GTO	SSO	GTO	SSO
S ELV	–	1.5	–	–
M RLV	–	4.5	–	2.5
M ELV	–	10.6	–	8.2
L RLV	2.3	10.0	–	8.6
L ELV	4.7	13.4	2.4	13.0
XL ELV	8.4	–	8.1	–
XL RLV	7.2	–	6.3	–
XXL booster and core reuse	8.3	19.7[a]	6.3	18.9[a]
XXL booster reuse	14.8	19.7[a]	14.1	18.9[a]
XXL ELV	19.7	19.7[a]	18.9	18.9[a]

[a]Theoretical performance is higher, limited for structural reasons



(a) LH2 VTVL launchers family

(b) LCH4 VTVL launchers family

Fig. 3 Sketches of the launch vehicle families used for case studies, from [13, 14] a variant of the L launcher, featuring three first-stage copies burning in parallel.

Additionally, the same configurations, but limited to expendable mission modes, are evaluated in Sect. 4.2.1.

4.2 Results for LH2 VTVL family

The average recurring and non-recurring costs for the five family configurations are shown in Fig. 4. Since the uncertainties in the launch scenario affect only the recurring costs, the non-recurring cost remains constant across all samples for a given composition. The 1000 scenarios considered cover a wide range of launch numbers, from 2.5 to ca. 32 launches per year over a 20-year period.

As expected, family compositions with fewer vehicles and/or components are significantly less costly in terms of development. Reducing the number of vehicles does decrease the system development effort. However, the most significant difference is between designs that include the H15 stage with the Vinci engine (cases A, B, and C) and those that use only the H240 and H61 stages with the Prometheus-H engine (cases D and E). In the latter cases, development costs are reduced not only by lower system engineering effort but also by saving the costs associated with unneeded components.

For recurring costs, a lower number of launch options leads to an increase, as payload assignment is constrained to fewer options. However, the change in recurring cost between options A, B, C, and D is limited. The reason for this is visible in Fig. 5, which shows the distribution of launch numbers for each vehicle option in the different family compositions.

Even for the full family, the smaller launchers (S, M, and even L) are used much less frequently than the larger ones. In fact, within composition A, the payload assignment algorithm never selects the S launcher. This is partly due to its inability to reuse the first stage, as the H61 engine relies on a single engine and cannot achieve a low enough thrust-to-weight ratio to perform a VTVL mission.

It is important to note that the launch scenarios, as shown in Table 1, include payloads as small as 300 kg. Even when these small payloads require a dedicated launch, it is more cost-effective to use the larger launchers with the reusable first stage, despite their dry mass being four times greater. Thus, the recurring cost is unaffected by the exclusion of the S launcher.

The impact of eliminating the M launcher from the family is evident but still results in a lower total cost. This occurs even though the payloads are shifted to the larger L launcher, which has to launch more frequently with suboptimal payload loading.

In families that include the XL launcher, it is often selected due to the Three-Stage-To-Orbit (3STO) architecture, which enables a high payload-to-dry mass ratio and, consequently, a low cost per kilogram of payload. In cases where the XL launcher is not available (e.g., in compositions D and E), the payloads tend to be shifted towards the XXL launcher.

As the optimization considered both ELV and RLV configurations, it is noteworthy that the ELV configurations are rarely selected by the assignment algorithm. Under the current assumptions for refurbishment and recovery, the cost advantage of the RLV configuration outweighs the higher payload performance of the ELV versions. The exclusive use of reusable options is possible because the performance of the RLV versions is sufficiently high to launch any payload in the scenario using the XXL launcher while reusing at least its two outer boosters.

To assess the trade-off between recurring and non-recurring costs for the different family compositions, the total cost, as shown in Fig. 4, must be considered. The A, B, and C families have higher development costs, which are not fully offset by their lower recurring costs, resulting in a higher total cost compared to the D and E families. Family

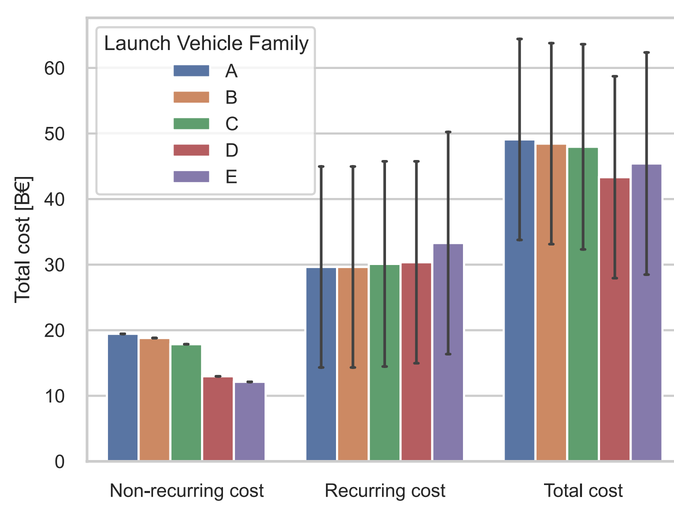


Fig. 4 Costs for various LH2 RLV launcher family compositions for uncertain market scenarios, error bars show two standard deviations, based on 1000 samples

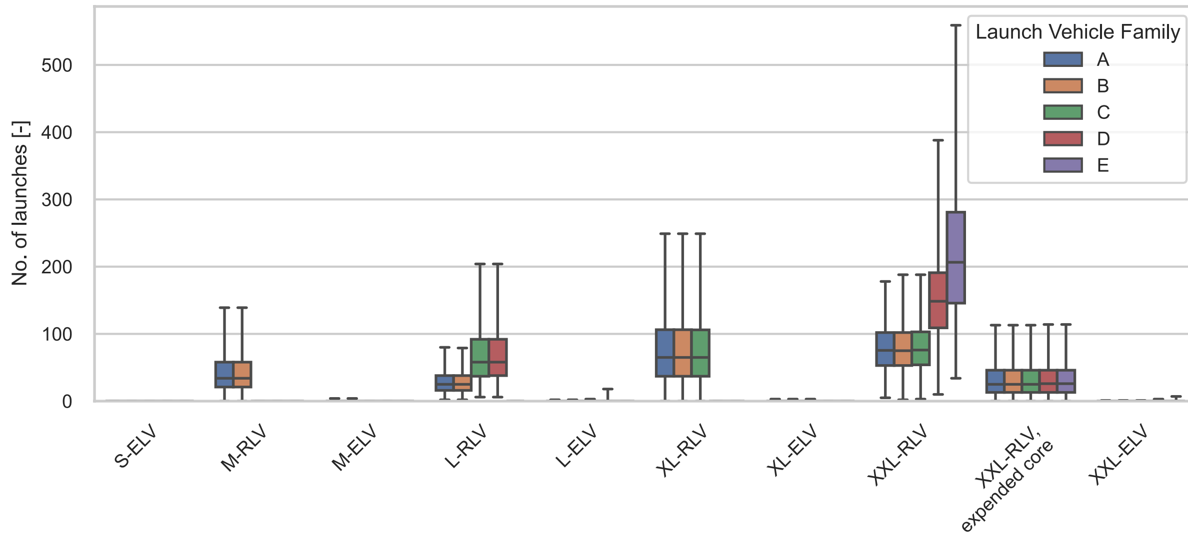


Fig. 5 Optimized launch numbers for various compositions of the LH2 RLV family for uncertain market scenarios. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

E, consisting only of the XXL launcher, represents the opposite extreme: lower development costs but higher recurring costs. The D family, which includes the L and XXL launchers, strikes a favorable balance. The savings from excluding the H15 stage and its engine more than compensate for the slight increase in recurring costs, leading to the lowest total cost among all compositions. This is particularly notable because the launch scenarios involve smaller payloads that could be assigned to dedicated launches on the L launcher. However, with the assumed recovery and refurbishment costs, the recurring cost of using the L launcher remains low enough to avoid a significant increase in overall costs.

Figure 6 illustrates the effect of four uncertainties in the launch market scenario on the total cost. The near-identical results for the A and B families across all uncertainties highlight the minimal impact of the S launcher, with the only difference being the fixed system development cost associated with the S launcher.

Regarding market shares, all five compositions with reusable stages follow a similar trend, with the E family exhibiting a slightly steeper slope due to its reliance on a single launch vehicle.

The uncertainties in dedicated launches and the number of launch epochs, as shown in Fig. 6, both limit the degree to which payloads can be combined in rideshare missions. For all families, this results in an increase in total launch costs, although the effect is much less pronounced than the impact of market share. Overall, the trends across the various family compositions are consistent. The impact of uncertainties in rideshare opportunities is small. However, composition E, with its exclusive reliance on the XXL launcher, shows a more noticeable increase in cost, while the other compositions remain robust.

These results indicate that, even in scenarios with a high percentage of dedicated launches, the full launcher family (composition A) does not offer a cost advantage over the D composition. Although the cost difference decreases in such cases, the D composition consistently remains the lowest in total cost.

4.2.1 Results for purely expendable launcher family

To investigate whether the observations made above also apply to a purely expendable launch vehicle family, the same analysis was conducted while excluding all reusable mission modes. As a result, the development CER applicable to expendable stages was applied to the H240 stage as well. The results for recurring, non-recurring, and total costs are presented in Fig. 7. Compared to the family compositions with a reusable first stage, the development costs are significantly lower. However, the recurring costs are higher, leading to overall higher total costs for the fully expendable family configurations.

The general trends for recurring and non-recurring costs are similar to those observed for the families with reusable first stages: more family members lead to lower recurring costs but higher development costs. However, a much larger fraction of the total cost comes from recurring costs, as no stages or engines are reused. This drives up the recurring launch costs, even as development costs remain comparatively low. As a result, the cost trend for fully expendable launch families differs from that of partially reusable configurations. In the expendable case, larger families achieve the lower total

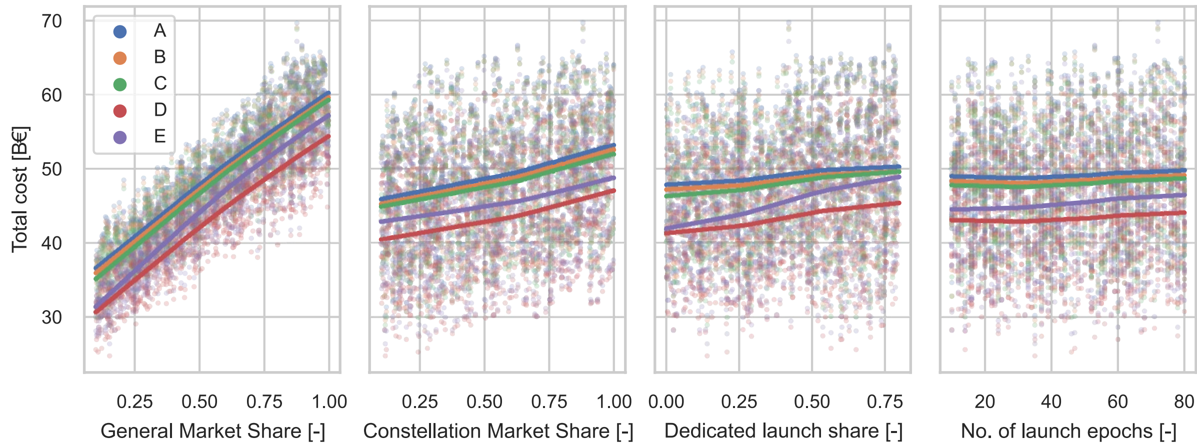


Fig. 6 Effect of selected uncertain parameters on total cost for various compositions of LH2 RLV family shown for 1000 samples. The solid line is a locally weighted linear regression as shown in [15]

cost because the savings from reduced recurring costs more than compensate for the added development effort. Notably, the total cost differences between compositions A, B, and C are minimal, indicating that additional vehicle variants provide diminishing returns in terms of cost savings.

Another notable consequence is seen in the launch numbers resulting from the payload assignment optimization, shown in Fig. 8. The S and M launchers are selected noticeably more often than in the cases with reusable stages. Their increased usage has an impact on the total cost, offsetting their additional development effort, which results in the B composition achieving the lowest total cost (though with a marginal difference to the A and C compositions).

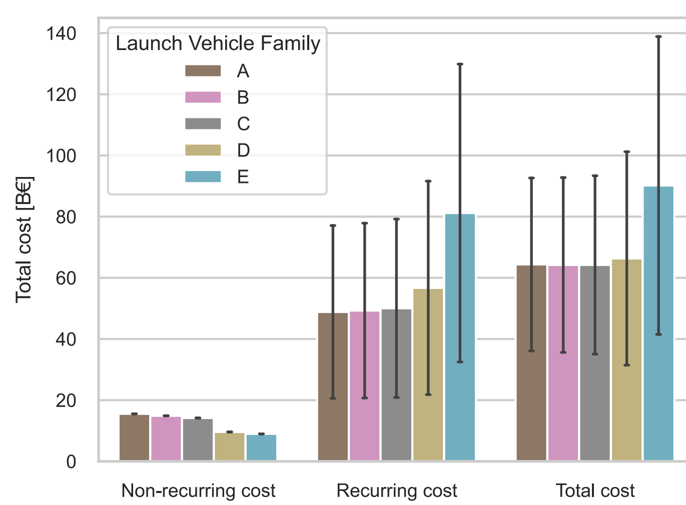
Figure 9 illustrates the effect of the four uncertainties on the total cost of the expendable compositions. The single-launcher composition E stands out as an outlier, being highly sensitive to any limitations on rideshare options. This outcome is expected, as the composition relies entirely on the XXL launcher.

The A, B and C composition show virtually the same behavior with regard to all uncertainties, with the D composition showing very similar behavior. It appears that the compositions with more members fare better with higher market shares, while the compositions with fewer members have a slight edge for lower market share or at very low dedicated launch shares. A high number of dedicated launches leads to a large increase in cost for the D composition, while the full family composition can accommodate these scenarios with less additional cost. This is due to its ability to efficiently accommodate the dedicated launches to fitting launchers. Generally, the full five-member family performs well over the range of all shown uncertainties.

4.2.2 Comparison of RLV and ELV cases

In this section, the results for four cases will be compared and discussed: the compositions A (S, M, L, XL, XXL) and

Fig. 7 Costs for LH2 ELV launcher family compositions for uncertain market scenarios, error bars show two standard deviations, based on 1000 samples



D (L, XXL) each for a fully expendable case and a case with partial reuse. This comparison highlights the most extreme compositions shown above, excluding the single-launcher E variant, which was found to be more expensive for both ELV and RLV cases. The recurring, non-recurring, and total costs for these cases are shown in Fig. 10. Table 3 contains the median total cost of each case. As expected, the families with reusable first stages are consistently less costly. Compared to their reusable counterparts, the fully expendable A composition is 33% more expensive, and the expendable D composition is 55% more expensive. When comparing the cost-optimal cases, partially reusable D versus fully expendable A, the latter is 50% more expensive.

The contrasting trends regarding family composition are evident: for the RLV case, the reduced D family, consisting only of the L and XXL launchers, results in the lowest cost. In contrast, for the ELV case, the full family composition achieves the lower cost.

Regarding the launch numbers, as shown in Fig. 11, the differing distributions of payloads across the various family members are clearly visible. In the cases with the full family, the expendable families make more use of the S, M, and L launchers. In contrast, for the full family with reusable first stages, the payload assignments are noticeably shifted toward the larger XL and XXL launchers. A similar trend is observed in the comparison of the D families, which consist of only the L and XXL launchers.

Figure 12 shows the launch numbers divided into the two target orbits SSO and GTO. It should be noted that the SSO launch numbers include the launches with constellation payloads, as the payload performance from the SSO mission is used to determine the number of launches necessary for the constellation satellites, as described in Sect. 2.2. As expected, the larger launchers are predominantly used to service GTO missions. A clear difference between the cases with and without reusable first stages is the use of the XXL launchers for SSO missions. In the cases where it is available, the 3STO XL Launcher is the preferred option for GTO missions, in both RLV and ELV families.

The differing properties of these four options can also be seen in their reaction to the uncertainties in the launch market as shown in Fig. 13. Due to the higher average launch cost, the ELV families are more sensitive to any change in the launch market that increases the number of launches, the full expendable family has a slightly lower slope since it can better adapt to dedicated or time sensitive launches by relying on the smaller family members. With the assumptions for the cost of reuses described in Sect. 2.3 the families with reusable first stages are always less costly than the ELV families, even at the lowest market shares considered herein.

4.3 Results for LCH4 VTVL family

The same analysis described above for the LH2-fueled families was also conducted for the LCH4-fueled versions outlined in Sect. 3. Since most results are similar, the discussion here focuses on the comparison of the B and D families, both with and without reusable first stages. As noted previously, the LCH4-fueled family does not include an S launcher, and therefore lacks an A composition. Consequently, the B composition represents the full family.

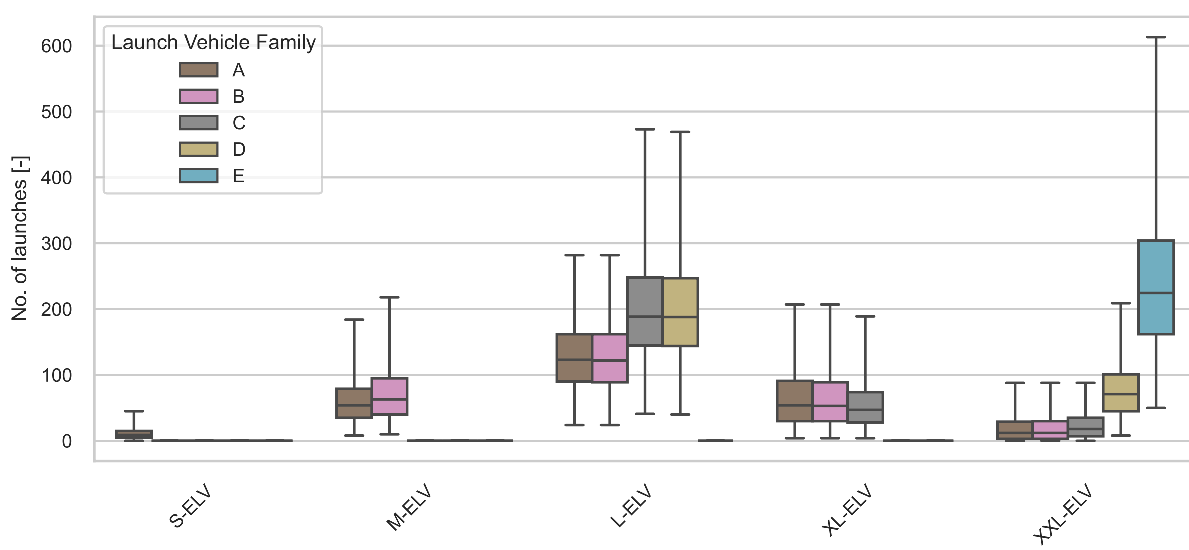


Fig. 8 Optimized launch numbers for various compositions of the LH2 ELV family for uncertain market scenarios. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

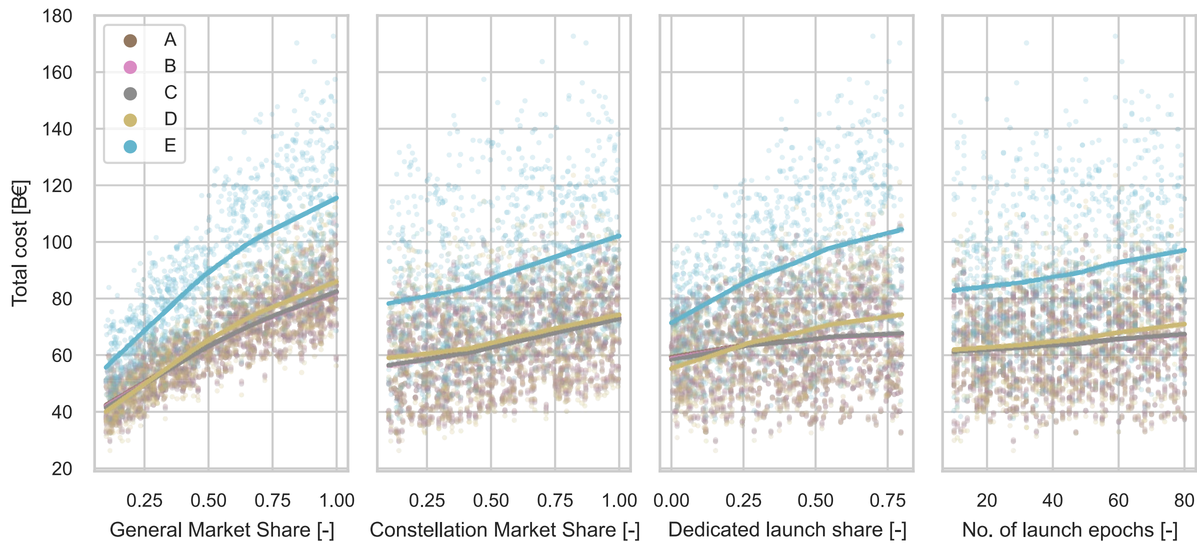


Fig. 9 Effect of selected uncertain parameters on total cost for various compositions of LH2 ELV family shown for 1000 samples. The solid line is a locally weighted linear regression as shown in [15]

Fig. 10 Costs for the A (S, M, L, XL, XXL) and D (L, XXL) compositions of the LH2 fueled launcher family with both reusable and expendable first stages for uncertain market scenarios. Error bars show two standard deviations, based on 1000 samples

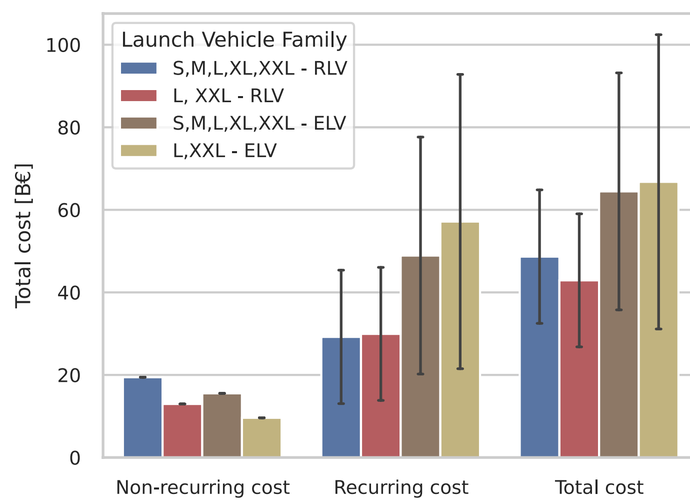


Table 3 Median total costs for selected LH2 fueled launcher family configurations

Configuration	Median total cost [Be]	Relative difference
A: RLV (S, M, L, XL, XXL)	48.7	+14%
D: RLV (L, XXL)	42.9	0% (best)
A: ELV (S, M, L, XL, XXL)	64.5	+50%
D: ELV (L, XXL)	66.7	+55%

With regard to costs, the same trends observed for the LH2-fueled families are evident in Fig. 14. For the ELV case, the full family is the more cost-effective choice, whereas for the RLV family, the reduced configuration with only the L and XXL launchers offers lower total costs. The median values are given in Table 4.

The cost difference between the full and reduced expendable families is more pronounced for the LCH4-fueled cases, as the L launcher has a much smaller GTO performance. Consequently, more launches of the costlier XXL launcher are required. This is evident when comparing the launch numbers of the LCH4 cases shown in Fig. 15 to those of the hydrogen-fueled cases in Fig. 11. Interestingly, the cost ratio between the expendable and partially reusable families closely mirrors that of the hydrogen-fueled counterparts. Compared to the configurations with reusable first stages, the expendable B and D compositions are 37% and 58% more expensive, respectively. The expendable B

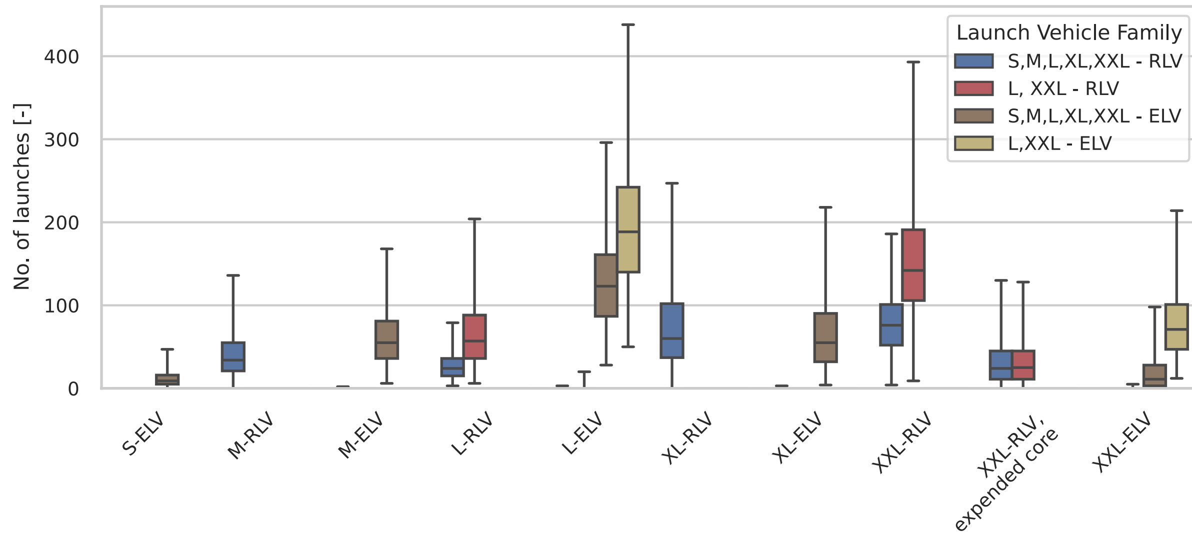


Fig. 11 Launch numbers for the A (S, M, L, XL, XXL) and D (L, XXL) compositions of the LH2 fueled launcher family with both reusable and expendable first stages for 1000 samples of uncertain market scenarios. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

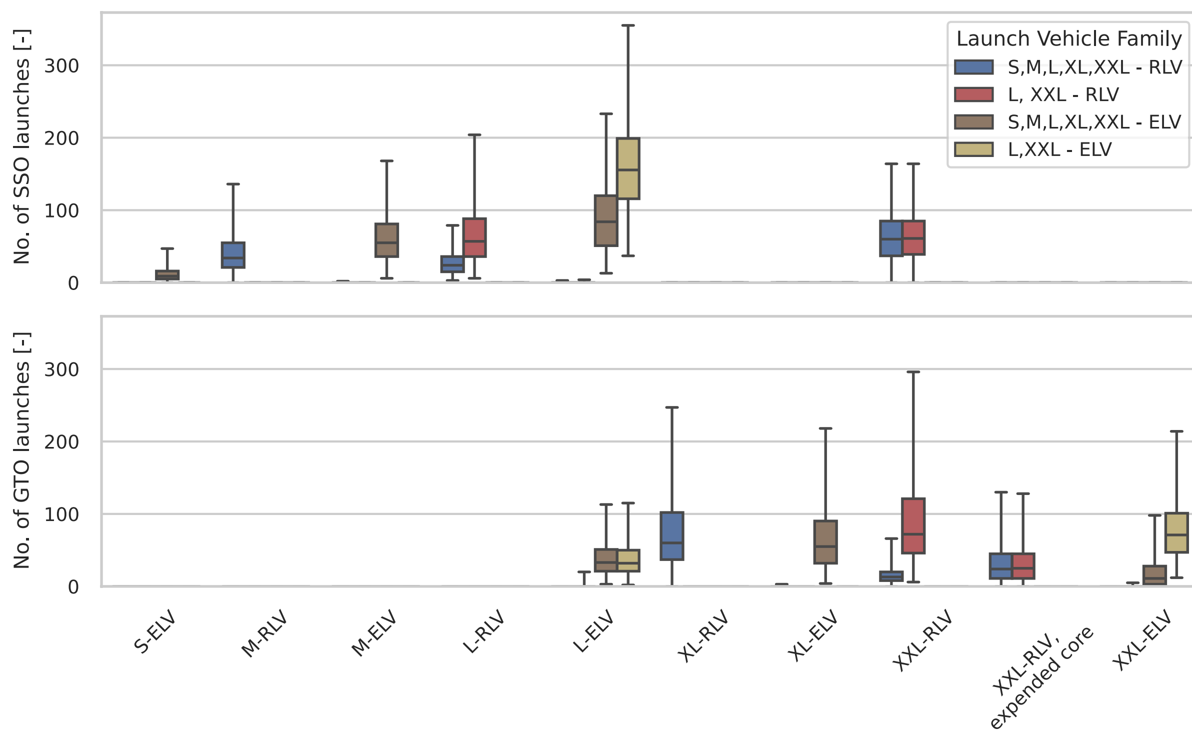


Fig. 12 Launch numbers for the A (S, M, L, XL, XXL) and D (L, XXL) compositions of the LH2 fueled launcher family with both reusable and expendable first stages for 1000 samples of uncertain market scenarios by destination orbit. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

composition is also 30% more expensive than the partially reusable D configuration.

Although not the primary focus of this study, the partially reusable methane-fueled D composition has, on average, a total cost that is 16% higher than its hydrogen-fueled equivalent.

Overall, the slightly lower payload performance of the LCH4-fueled family results in higher launch numbers. Notably, the three-stage layout of the XL launcher is less affected

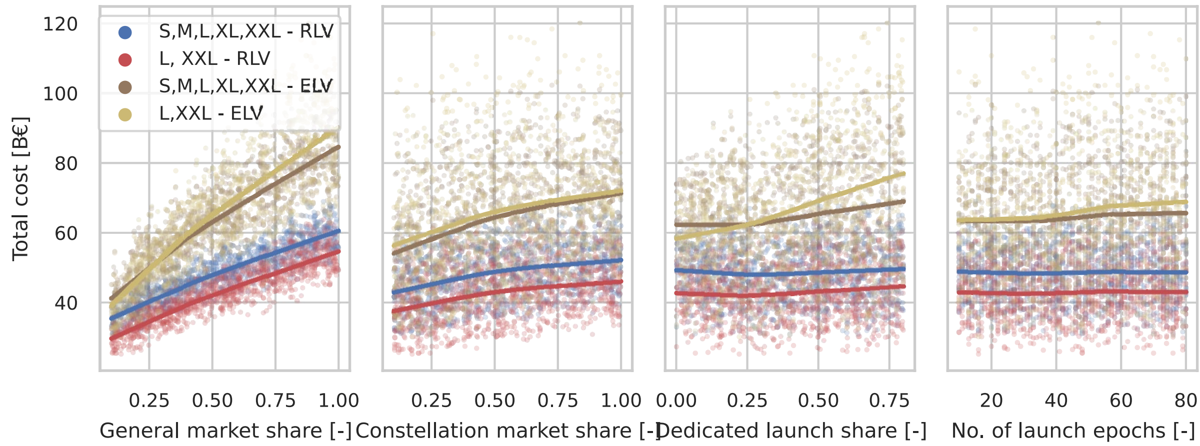
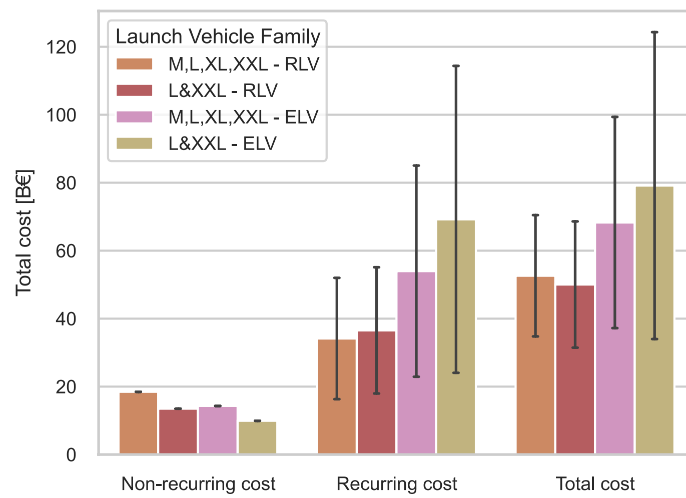


Fig. 13 Effect of selected uncertain parameters on total cost for A (S, M, L, XL, XXL) and D (L, XXL) compositions of the LH2 fueled launcher family shown for 1000 samples. The solid line is a locally weighted linear regression as shown in [15]

Fig. 14 Costs for the B (M, L, XL, XXL) and D (L, XXL) compositions of the LCH4 fueled launcher family with both reusable and expendable first stages for uncertain market scenarios. Error bars show two standard deviations, based on 1000 samples



by the reduced specific impulse compared to the two-stage variants, leading to its more frequent selection in these cases. Interestingly, the LCH4-fueled XL-ELV launcher is the only expendable variant chosen by the payload assignment optimization in significant numbers when reusable launch options are available.

Additional differences emerge when comparing the target orbit-specific launch numbers in Fig. 16 for methane-fueled vehicles to their hydrogen-fueled counterparts in Fig. 12. Notably, the methane-fueled L launcher is never selected for GTO missions due to its lower payload capacity for that orbit, resulting in a greater reliance on the XL and XXL variants.

Another key distinction is the distribution of mission types for the XXL launcher, specifically the choice between a reusable or expendable center core. In the methane-fueled cases, the expendable center core is selected more frequently. This suggests a different trade-off dynamic between cost and performance: while reusability is favored in the hydrogen-fueled family, the expendable-core configuration is chosen more often in the methane-fueled cases for its higher performance, even with its higher cost.

In general, the methane-fueled families exhibit similar reactions to their hydrogen-fueled counterparts when exposed to uncertainties in the launch scenarios, as shown in

Table 4 Median total costs for selected LCH4 fueled launcher family configurations

Configuration	Median total cost [Be]	Relative difference
B: RLV (M, L, XL, XXL)	52.6	+5%
D: RLV (L, XXL)	50.0	0% (best)
B: ELV (M, L, XL, XXL)	68.3	+37%
D: ELV (L, XXL)	79.1	+58%

Fig. 17. Since the full family configuration does not include an S launcher, the two RLV cases are more closely aligned in terms of cost performance.

However, the cost difference between the two ELV families is more pronounced, primarily due to the high recurring costs associated with the expendable LCH4 L&XXL family, as discussed earlier. Unlike the results for the LH2-fueled families, the full LCH4 fueled ELV family (B) remains more cost-effective than the equivalent D composition, even when the dedicated launch share is reduced to zero.

4.4 Sensitivity studies

Beyond the market uncertainties discussed above, the cost model parameters are the main sources of uncertainty in this analysis. Since the study is comparative, factors that affect the relative costs between configurations are especially important. The following sections explore how variations in two key cost model parameters influence the results, providing insight into the sensitivity of the core findings.

4.5 Sensitivity to recurring and non-recurring cost balance

The trade-off between different family compositions and the number of family members largely hinges on the balance between recurring and non-recurring costs. Consequently, if the cost model systematically over- or underestimates the contribution of one of these components, the resulting comparisons would be skewed.

To evaluate this sensitivity, the recurring costs of selected family configurations were incrementally increased, and the effect on the comparative outcome was assessed. Two specific cases were selected to test core conclusions: first, that smaller family compositions are preferable for RLVs, and second, that larger family compositions are preferable for ELVs.

Figure 18 illustrates how the share of Monte Carlo samples in which the full family configuration (A) incurs higher total cost than the reduced configuration (D) evolves as the recurring cost increases. Since the initial difference in recurring costs between the two configurations is small (as shown in Fig. 10), a substantial increase in recurring cost is necessary to reverse the original conclusion and make the full family more favorable. This is expected, given the limited recurring cost difference discussed in Sect. 4.2.

Figure 19 presents the same sensitivity analysis for the fully expendable family configurations. In this case, the original recurring cost differences (Fig. 13) are more pronounced, while the difference in total cost was smaller and as a result, the comparative outcome is more sensitive to changes in the recurring cost assumptions. A moderate reduction in recurring cost is sufficient to tip the scale towards the D composition. However, the comparison is never entirely on sided. Even at the edge of the considered parameter space at least 20% of the samples are lower cost for the non-dominant solution. This indicates that this result is fairly dependent on the future launch market dynamics.

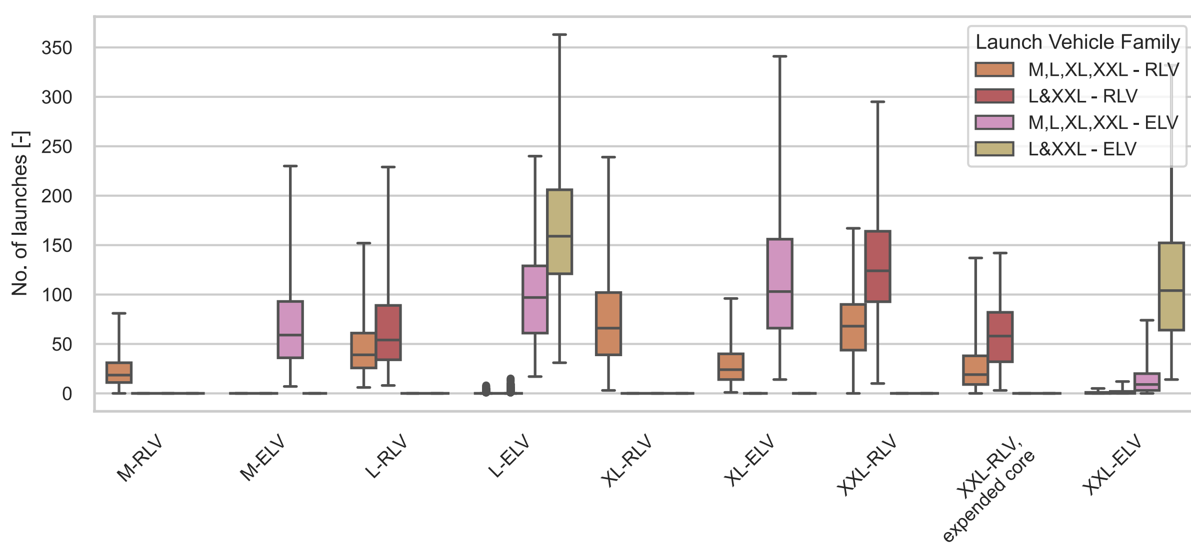


Fig. 15 Launch numbers for the B (M, L, XL, XXL) and D (L, XXL) compositions of the LCH4 fueled launcher family with both reusable and expendable first stages for 1000 samples of uncertain market scenarios. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

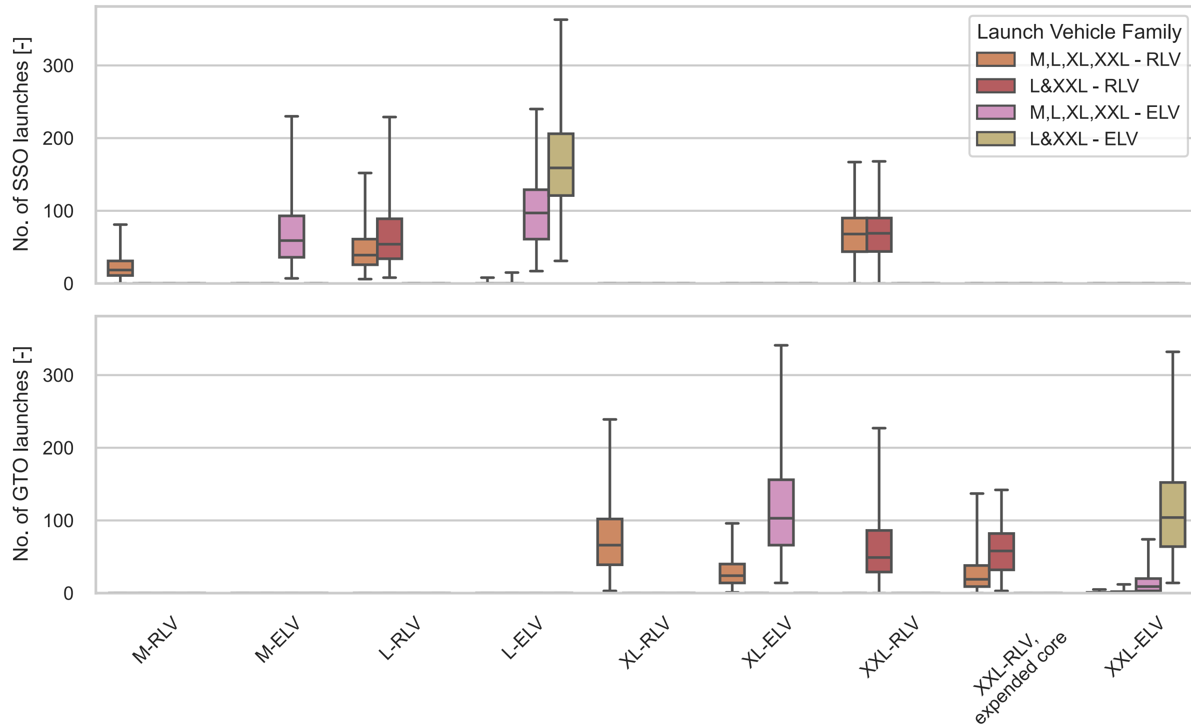


Fig. 16 Launch numbers for the B (M, L, XL, XXL) and D (L, XXL) compositions of the LCH4 fueled launcher family with both reusable and expendable first stages for 1000 samples of uncertain market scenarios by destination orbit. Boxes range from 25th to 75th percentile, with the median indicated in between. Whiskers indicate maximum and minimum values

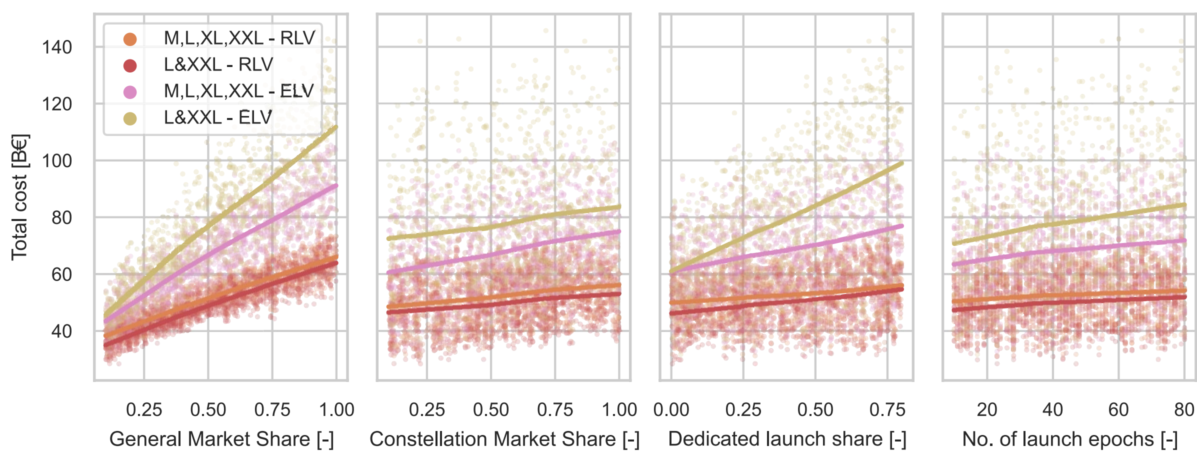


Fig. 17 Effect of selected uncertain parameters on total cost for B (M, L, XL, XXL) and D (L, XXL) compositions of the LCH4 fueled launcher family shown for 1000 samples. The solid line is a locally weighted linear regression as shown in [15]

4.5.1 Sensitivity to reusability cost assumptions

Given the limited experience, outside of SpaceX, with the refurbishment and recovery of rocket stages and engines, the cost assumptions associated with reusability are especially uncertain. In the cost model employed herein, refurbishment costs are represented by the refurbishment factor f_5, as introduced in Sect. 2.3. This factor directly influences recurring costs and indirectly affects optimal payload assignment, as higher reuse costs make expendable options within a family more attractive.

To evaluate the impact of this uncertainty, a smaller Monte Carlo study with 200 samples was performed across a range of f_5 values. Results are shown in Fig. 20.

In the baseline model, f_5 is set to 0.06 for VTVL stages and 0.07 for rocket engines. For simplicity in this sensitivity study, the same value is used for both components.

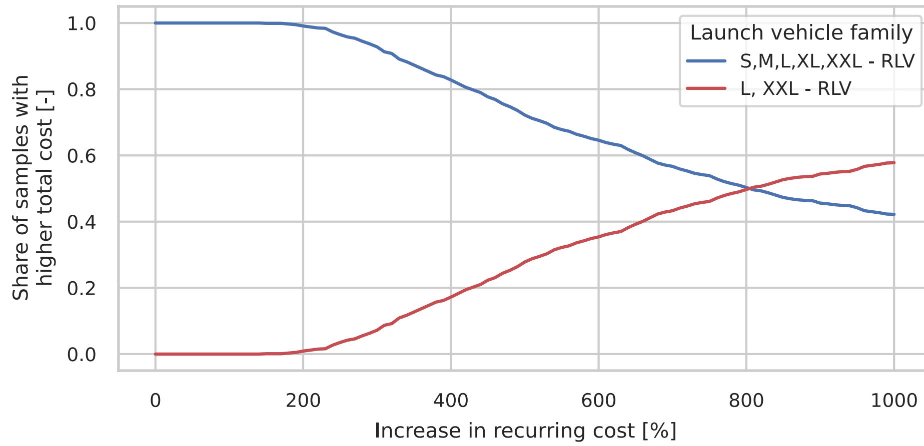


Fig. 18 Effect of increased recurring cost on the comparison of the LH2 fueled RLV composition A (S, M, L, XL, XXL) to the reduced composition D (L, XXL)

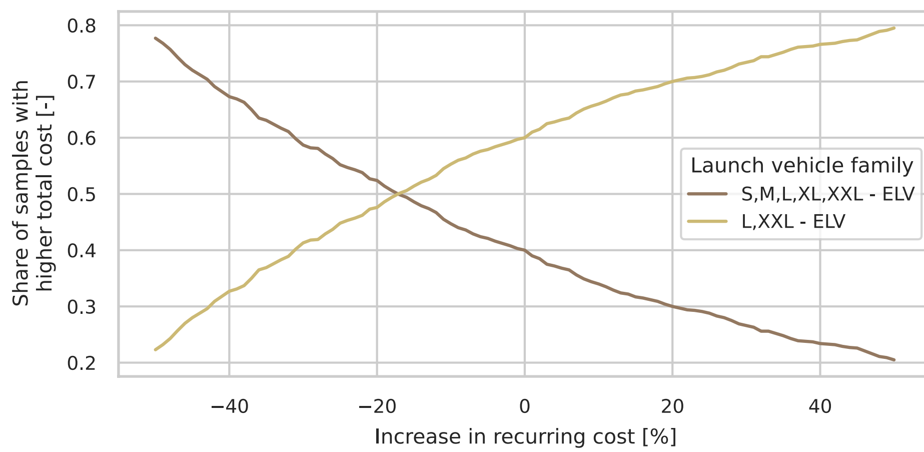


Fig. 19 Effect of increased recurring cost on the comparison of the LH2 fueled ELV composition A (S, M, L, XL, XXL) to the reduced composition D (L, XXL)

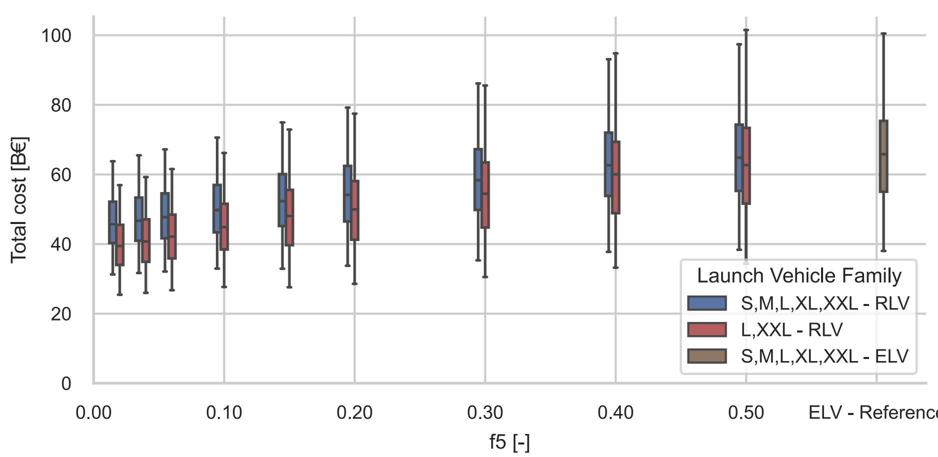


Fig. 20 Results of parametric study with regard to the impact of the f_5 factor, representing the fraction of cost of reusing a component compared to producing a new on, on the total costs of the LH2 fueled compositions A (S, M, L, XL, XXL) and D (L, XXL). The fully expendable composition A is shown for comparison

As refurbishment costs increase, the advantage of the reduced configuration D diminishes. Rising recurring costs lead to higher penalties for launching small payloads with large, underutilized vehicles. Nevertheless, for realistic values of f_5, the composition D remains the lower-cost option. Even when f_5 reaches 0.5, more than eight times the baseline assumption, the median cost of configuration D remains below that of the full composition A. At this level of refurbishment cost, reusable configurations no longer provide a meaningful cost advantage over fully expendable designs.

4.6 Limitations

As an initial exploration of the research questions discussed in the introduction, simplifications were made to arrive at the results discussed above.

With regard to the cost model, the same caveats as discussed at the source of the cost model [9] apply here: This study employs a parametric cost modeling approach to estimate the recurring and non-recurring costs of launch vehicles, which inherently includes simplifications due to the lack of detailed data at the conceptual design stage. While the methodology effectively identifies general cost drivers, it does not account for all complexities and nuances involved in real-world development and operations. Additionally, the absence of cost details for modern launch vehicles and the limited availability of data for the proposed configurations-such as the VTVL stages-reduce the accuracy of the estimates. The modeling relies on historical data and results from prior studies, which, while valuable, may not fully reflect the current state of the industry. Assumptions made in selecting specific cost parameters and scenarios may introduce biases, particularly regarding the cost of reusable stages. Furthermore, the analysis of future launch markets, even while covering a broad range of scenarios, is inherently uncertain.

On the technical side, the reference family configurations used in this study represent realistic options but cannot be considered fully representative of all possible launch vehicle families. The propellant loading of the stages in these configurations is primarily determined by the thrust levels of the chosen engines. A more holistic optimization of both propellant loadings and engine thrust levels for each potential composition could likely result in lower costs. However, such an optimization would be less relevant to the ongoing development programs in Europe, as it would diverge from the components currently in focus. For the payload assignment, only the allowable mass of the payloads is considered. In theory, the maximal loading of the various launch vehicles could also be constrained by the fairing volume. Such a constraint is not considered herein.

5 Summary and conclusion

While the idea of modular launch vehicle families with shared components has become increasingly popular, there is little literature addressing how many launchers such a family should include. With the advent of partially reusable systems, assumptions based on earlier expendable designs may no longer hold and need to be reevaluated.

To explore this gap, this study applies a methodology that combines parametric cost estimation, future market scenarios and optimal payload assignment to identify cost-optimal launcher family compositions under uncertain demand. By accounting for recurring and non-recurring costs across randomized market scenarios, the approach supports a realistic, data-driven evaluation of architecture choices, capturing trade-offs that would be missed in a static or deterministic analysis.

The methodology was applied to two representative launcher families based on PROMETHEUS-H and PROMETHEUS-M engines, representing hydrogen- and methane-fueled systems. The families included up to five modular configurations (S, M, L, XL, XXL), evaluated in both partially reusable (with VTVL boosters) and fully expendable variants. Rather than assigning fixed roles to each launcher, the optimization assigned payloads across family members to minimize recurring costs for each market scenario.

The results showed clear trends depending on reusability. For partial RLVs, a reduced family containing only the L and XXL launchers achieved an 11% lower total lifecycle cost than the full five-vehicle setup. Although this came with slightly higher recurring costs due to less optimal payload matching, the development savings more than compensated this. In contrast, expendable families benefited from having more family members, which allowed better alignment between payload and capacity, reducing recurring cost enough to outweigh the added development effort. This difference is driven by the lower recurring costs enabled by reusability.

The explicit modeling of market uncertainties helps distinguish between insights that hold across a wide range of market scenarios and those that depend on specific market conditions. While the findings related to partially reusable families are robust to variations in critical cost parameters and market properties, the comparative results for purely expendable families are more sensitive to changes in these underlying factors.

The results underline that lessons from designing expendable systems may not directly apply to reusable ones. With partial reusability, familiar trade-offs can behave differently and should be reexamined in that context.

While not the main focus, the study also found that hydrogen-fueled families consistently outperformed methane-fueled ones in terms of total lifecycle cost. The lowest cost methane configuration was about 16% more expensive than its hydrogen equivalent. Partial reusability offered significant lifecycle cost reductions: approximately 33% for hydrogen and 27% for methane fueled launch vehicle families.

6 Outlook

This manuscript focused on evaluating different compositions within a fixed launch vehicle family. A logical next step would be to examine the sizing of individual stages and engines and optimize them for minimal total cost. The optimal size of these components are likely to vary depending on the overall family configuration and the degree of reusability involved.

In addition, designing for flexibility to serve a projected future launch market, rather than targeting a specific payload capacity, presents an interesting research pathway. This approach could also be valuable when applied to single launch vehicles, as most previous studies have focused on optimizing for fixed payloads rather than broader market adaptability.

7 LLM-assisted text revision

During the preparation of this work, the author used ChatGPT 4o to revise the text. After using this tool/service, the author reviewed and edited the content as needed and takes full responsibility for the content of the publication.

Appendix 1: Reference data

See Tables 5, 6, 7 and 8

Table 5 Major components of the LH2 launch vehicle family members and the CER parameters used to assess their recurring and non-recurring costs. Mass of GNC component is symbolic to include it as a component

Element	Mass [t]	a_{dev}	x_{dev}	a_{prod}	x_{prod}	f_1	f_2	f_3	f_5	p	p_{reuse}	No. of reuses
H240 core stage, reusable	21.6	331.00	0.38	1.84	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
H240 reentry GNC	1e-3	2500.00	1.00	0.00	1.00	1.00	1.00	1.00	–	–	–	–
H240 reentry hardware	1.0	0.90	0.97	1.90	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
H240 landing hardware	4×0.8	1.12	0.92	0.84	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
Prometheus-H, reusable	1.6	277.00	0.48	1.67	0.54	1.00	0.85	1.00	0.07	0.85	0.85	20
H240 core stage, expendable	21.6	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
Prometheus-H, expendable	1.6	277.00	0.48	1.67	0.54	1.00	0.85	1.00	–	0.85	–	–
H61	6.1	331.00	0.38	1.84	0.59	0.70	1.00	1.00	-	0.85	–	–
H61, incl. interstage	7.3	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
Prometheus H, vac	2.4	277.00	0.48	1.67	0.54	1.00	0.85	1.00	–	0.85	–	–
H15	2.1	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
Vinci	0.8	277.00	0.48	1.67	0.54	1.00	0.85	1.00	–	0.85	–	–

Table 6 Major components of the LH2 launch vehicle family members and the CER parameters used to assess their recurring and non-recurring costs. Mass of GNC component is symbolic to include it as a component

Element	Mass [t]	a_{dev}	x_{dev}	a_{prod}	x_{prod}	f_1	f_2	f_3	f_5	p	p_{reuse}	No. of reuses
M520 core stage, reusable	25.4	331.00	0.38	1.84	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
M520 reentry GNC	1e-3	2500.00	1.00	0.00	1.00	1.00	1.00	1.00	–	–	–	–
M520 reentry hardware	1.2	0.90	0.97	1.90	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
M520 landing hardware	4×1.0	1.12	0.92	0.84	0.59	1.00	1.00	1.00	0.06	0.85	0.85	25
Prometheus - M, reusable	1.3	277.00	0.48	1.20	0.54	1.10	0.85	1.00	0.07	0.85	0.85	20
M520 core stage, expendable	25.4	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
Prometheus M, expendable	1.3	277.00	0.48	1.20	0.54	1.10	0.85	1.00	–	0.85	–	–
M110	6.3	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
M110, incl. interstage	7.7	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
M15	1.5	331.00	0.38	1.84	0.59	0.70	1.00	1.00	–	0.85	–	–
Mira	0.3	277.00	0.48	1.20	0.54	1.10	0.85	1.00	–	0.85	–	–

Table 7 Major components of each of the LCH4 launch vehicle family members

	LCH4 Launch vehicles			
Stage	M	L	XL	XXL
1	M520	M520	M520	3 x M520
	7 Prom-M	7 Prom-M	7 Prom-M	21 Prom-M
2	M15	M110, w/o IS	M110, with IS	M110 w/o IS
	Mira	Prom-M, vac	Prom-M, vac	Prom-M, vac
3	–	–	M15	–
	–	–	Mira	–

Prom-M Prometheus-M, *IS* interstage

Table 8 Major components of each of the LH2 launch vehicle family members

	LH2 Launch vehicles				
Stage	S	M	L	XL	XXL
1	H61, with IS	H240	H240	H240	3 x H240
	Prom-H	4 Prom-H	4 Prom-H	4 Prom-H	12 Prom-H
2	H15	H15	H61, w/o IS	H61, with IS	H61 w/o IS
	Vinci	Vinci	Prom-H, vac	Prom-H, vac	Prom-H, vac
3	–	–	–	H15	–
	-	–	–	Vinci	–

Prom-H Prometheus-H, *IS* interstage

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Data availability All data generated or analyzed during this study are included in this published article, with the exception of the individual sample results from the Monte Carlo analyses. These results are available from the corresponding author upon reasonable request.

Conflict of interest The author declares that they have no conflict of interest.

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