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Cost Estimating of Commercial Smallsat Launch Vehicles

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Abstract

Commercial launch service providers' low-priced offerings have been a hotly debated topic. However, the strategies with which these firms reduce costs have seen little incorporation into the hardware Cost Estimating Methods (CEMs) and tools prevalent in the aerospace industry. This research changes this, by providing adaptations to agency-focused CEMs that befit a new commercial paradigm, with an emphasis on smallsat launch vehicles.

A parametric model for estimating costs in an early phase of development was synthesized, with which it is possible to approximate the full life-cycle costs of small commercial liquid and solid propellant rockets, as well as their cost-based price per flight. Key elements included were reductions in cost achieved by commercial launch operators, by modeling reduced subcontractor management effort and profit retention experienced at lower subcontracting rates.

Along with the newly developed methodologies, novel insights such as required launch rates have shone a light on small commercial launch systems' cost feasibility in the age of public-private spaceflight partnerships.

1. Introduction

The spaceflight environment is changing rapidly, with new commercial companies establishing themselves in all segments of the industry [1]. Currently, there is a dynamic that did not exist under the traditional approach to technology development that has pervaded government agencies so far. The launch market is a particularly interesting example. Companies established by Silicon Valley entrepreneurs are offering launches to orbit at significantly lower prices than traditional state-sponsored aerospace giants have for so long [2].

Commercial companies have changed their way of doing business compared to traditional aerospace hardware manufacturers. Costs are for example lowered by restricting the amount of work contracted out and producing most, if not all, vehicle parts in-house [3]. In this way profit is retained, and subcontractor management effort is reduced [1].

1.1 Small Launch Vehicles

In tandem, other developments have taken place. Miniaturization of technologies has led to the development and rise in popularity of small satellites [4] and the emergence of small satellite manufacturers starting in the 80's [5]. The market for small satellites is expected to exhibit an increase in demand [6], which in Europe is now mainly institutional [5]. Performance increases will enable more applications in civil and earth observation fields with these satellites, mainly for land monitoring and energy resource discovery [5]. A requirement for a viable program involving small satellites is low-cost and frequent access to space [4]. Dedicated launch options that are able to reach a tailored orbit height and inclination are lacking. Currently operating launch vehicles are seen as far too expensive to support the business plans of the emerging smallsat market [7]. There is an identified need for a dedicated launch system to loft 100-700 kg satellites into orbit [1]. The FAA forecasts that although the relatively high cost of dedicated launches on small launch vehicles has kept this demand low as of yet, this dynamic will change as more new small launch vehicles become available, resulting in a demand increase [8].

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A number of commercial, partially-government-funded firms and governments are vying to compete for the small rocket market and provide this dedicated launch opportunity. These efforts have been collected by Niederstrasser and Frick from ATK in a 2015 smallsat launcher market study [7].

Companies listed there quote prices-per-kilogram to orbit that are often significantly lower than current launch options. Given the fact that these companies have no demonstrated flight hardware, the question arises whether these prices are realistic with respect to their costs, considering their new development. Up until now, there has been no purpose-built methodology yet available to estimate in an early phase of development the costs and cost-based price per flight of these small rockets [1]. This research developed such a methodology in partnership with the TU Delft and the European Space Agency, with the aim of being able to estimate within 20% of reported costs, while accounting for a 1 σ standard deviation of the input data.

1.2 Cost Estimates

Establishing accurate cost estimates for space missions is important, and has recently become more important still.

First of all, this is because traditionally, space agencies strove to design their systems to optimize performance. When recently the COTS and CRS programs were introduced by NASA [9], aerospace companies entered into direct competition with each other based on cost. Cost has become a variable to be optimized throughout the design process and life-cycle [3, 10] in order to maximize competitiveness and profitability. This way, cost estimates have become an important design tool for space systems.

Secondly, decisions on project feasibility are often made based on early-phase preliminary cost estimates. If an estimate is high in the initial phases, a project might not be able to secure the funding it requires to continue development. If the costs of a project are overestimated initially by a competitive bidder, the project might not pass a go/no-go decision point based on its high costs, or another bidder might be awarded the contract. On the other hand, underestimation could result in the project making a loss. Inaccurate estimates are therefore a risk. [10, 11]

Finally, this aforementioned selection pressure could, in an agency environment, result in projects' costs being underestimated deliberately in order to increase chances of selection. This influences the project manager's decision-making. [10, 11, 12]

1.3 Previous Cost Estimating Work

The perceived high cost of space transportation is viewed as one of the biggest obstacles to space commercialization and exploration [13]. Unsurprisingly then, there have been countless studies into ways to characterize and subsequently reduce these costs. The problem was addressed both by academics such as Koelle [3, 14, 15, 16] and space agencies such as NASA and ESA alike.

In the process, various estimating tools were developed. There are 8 estimating tools commonly used in the industry that can be used to cost launch vehicles. These are the *TRANSCOST* tool by Koelle [3], the Unmanned Space Vehicle Cost Model (USCM), Small Satellite Cost Model (SSCM), *TruePlanner* by PRICE Systems Solutions, *aces* by 4cost, *SEER-H*, the NASA Air Force Cost Model (NAFCOM) and the restricted Aerospace Launch Vehicle Cost Model (LVCM). An important characteristic [1] of these tools is their availability to be used and the openness of their Cost Estimating Relationships (CERs) for modification purposes; some are restricted to government use, or are paid-for commercial tools that provide little insight into the CERs behind them. The only publicly available tool with open CERs is the dedicated rocket costing tool TRANSCOST. [1, 10]

2. Methodology

In order to estimate costs for small, commercially developed rockets, a Cost Estimating Method (CEM) was selected. Usable tools were subsequently evaluated, and knowledge to incorporate into a hybrid estimate was gathered. This hybrid approach involved combining the *Theoretical First Unit* method of estimating [17], with Koelle's TRANSCOST [3].

2.1 Cost Estimating Methodology Selection

In the selection of an estimating methodology, advanced cost estimating methods treated by for example Curran [18] were not considered, as these have not matured enough to perform estimates on these novel systems with. Reviewing traditional estimating methods, the *parametric* approach was chosen instead of an *engineering build-up* or *analogy* estimate, as this is an often used method of costing for systems in early phases of development [10]. There is too

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little detail known about often secretive launcher designs for the former, and the latter would require similar systems as a reference, which currently do not exist because of the novel nature of smallsat launch vehicles. A choice for the *parametric* approach also facilitates the use of the readily available TRANSCOST as a backbone to construct a more detailed estimate on.

2.1.1 Cost Estimate Hybrid Approach

Because of TRANSCOST's availability and open-naturedness, the three-phase approach, namely *Development*, *Manufacturing* and *Operations,* taken by Koelle [3] in his seminal work was chosen as a basis of the estimate. A choice was made to embed within that framework the important lessons learnt from a broad array of projects at the European Space Agency.

To achieve this, the three-phase approach championed by Koelle was augmented with a deeper understanding of the CERs that apply broadly to subsystem costs (whereas TRANSCOST merely estimates at a system level), and was accompanied by publicly available data necessary for the construction of these CERs. These formed the basis of a concept called the *Flight Unit* (FU, NASA), or *Theoretical First Unit* (T1, ESA/NASA), a parametric approach to cost modeling proposed by Mandell [17] to estimate costs in early phases.

It is common practice to use a subsystem or system T1 as a basis within estimating tools such as NAFCOM [19] and *TruePlanning*, and it is also a way of estimating applied extensively at the European Space Agency and NASA [20]. The Space Systems Cost Analysis Group (SSCAG), a professional organization for cost engineers founded with the goal of encouraging effective knowledge management and resource pooling, has also helped develop this way of estimating space systems' costs with the T1 [21, 22].

The T1 approach first involved establishing the cost of a first theoretical production unit, the T1/FU costs, which was derived by costing individual hardware elements with data-driven CERs, and combining these for the entire rocket. This process was detailed in Section 2.2. Then, the non-recurring costs of developing the rocket were approximated using the T1/FU. To achieve this, typical expenditures on System Test Hardware (STH) and Design and Development (DD) engineering work in the development phase were described as a function of the T1. It was also possible to do the same for the manufacturing phase, where cost improvements dictate how recurring unit production costs decrease over time compared to the T1.

In such a way, the *Development* (DEV) and *Manufacturing* (MAN) life-cycle phase costs were estimated in Section 2.3 and Section 2.4. For the third, the *Operations* (OPS) cost, direct application of the TRANSCOST methododology's system-level CERs were necessary. Section 2.6 will detail this estimating approach.

Figure 1 shows the developed estimate's Cost per Flight (CpF) buildup in its entirety.

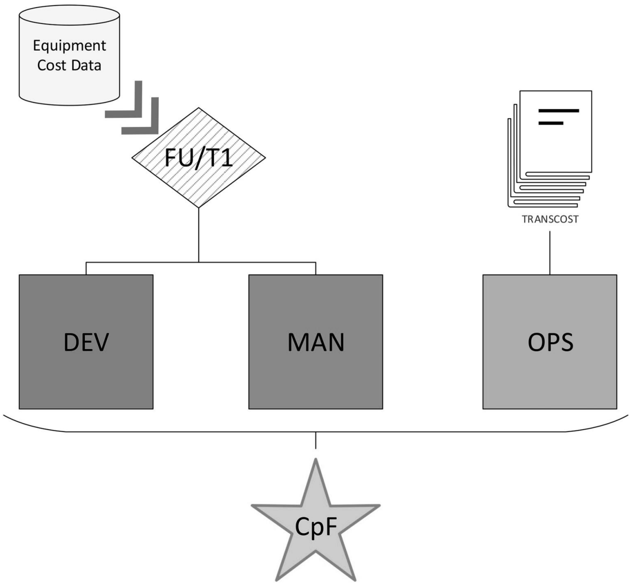

Figure 1: Cost per Flight (CpF) estimating process developed for this research, which uses data-driven CERs converted into T1 Equivalents [17, 19, 21] to approximate development (DEV) and manufacturing (MAN) costs, and TRANSCOST [3] to establish a baseline operations (OPS) effort

Both the T1 method and TRANSCOST tool chosen for estimating use system/subsystem mass as a parameter.

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It was a logical choice for a free variable cost driver, because mass is a parameter that is available and worked with throughout the entire design process [23].

2.2 Flight Unit T1 Estimate

The Flight Unit costs formed the basis for the *Development* and *Manufacturing* costs. Therefore, it warranted special attention.

To arrive at a Flight Unit (T1/FU) estimate a choice was made to deconstruct the launch vehicle into equipment-level elements to cost individually with mass-cost CERs. Which level of depth can be chosen depends on the quality and amount of data available to the estimator. In this research particularly, a liquid propellant stage was deconstructed into 24 elements, while in a solid propellant stage 12 elements were identified. These are listed in Table 2.2.

The key difference in the two types of stages is that an entire solid stage including thrust vector control units, all structural elements and propellant can be costed at once, while the liquid propellant stage has more individual propulsion-related equipment to be costed.

Table 1: Equipment cost elements for solid and liquid propelled stages

Equipment Name	
Pressurizant Tank^a	Pipes^a
Fuel Tank^a	Valves^a
Oxidizer Tank^a	Stage Harness
Thrust Cone^a	Interstage Structure
Skirt^a	Payload Adapter
Thermal Control^a	Payload Fairing
Engine(s)^a	Comms
Thrust Vector Control	Power
Fuel^a	Data Handling
Oxidizer^a	GNC
Pressurizant^a	Avionics Harness
Pressurization System^a	Attitude Control Module
Solid Rocket Casing, including Propellant^b	

^{a} Liquid propellant stage only
^{b} Solid propellant stage only

In this estimating methodology, the development and manufacturing costs are approximated for each equipment element individually from the equipment-specific T1/FU. This allows cost theories like the learning curve [3, 24, 25] to be applied at a a greater level of depth than Koelle does, as detailed in Section 2.4.

A power curve relationship between cost and mass was assumed in the form of Equation 1. This power assumption is widely used as a way of representing costs versus system mass [3, 21].

$$C = a \cdot M^b \tag{1}$$

In Equation 1 C is cost in k€, M is mass in kilogram and a and b are regression coefficients derived from linear regression of Equation 1 in logarithmic space, in the form of Equation 2, of the normalized [1] historic mass-cost data per equipment element.

$$\ln C = \ln a + b \cdot \ln M \tag{2}$$

Regression curves lacking enough data to show significant relationships for a and b coefficients, tested through the t-statistic on the student's distribution [12], were replaced by those with a and b coefficients derived from the NASA Air Force Cost Model (NAFCOM) reference for b values, in a similar way as proposed by Smart [26]. Table 2 shows the data-derived a and b regression coefficients and their Relative Standard Error (RSE), otherwise called Cost Modeling Accuracy (CMA). It also lists NAFCOM a and b values, which one might even derive from a single data-point [26]. The final column shows which of the two sets of coefficients was selected for this particular research.

Costs of the entire theoretical first production unit (T1) of the rocket may be approximated by solving the cost-mass power curve for each subsystem element, with corresponding a and b values from Table 2, and adding these costs into a total costs. Uncertainties explained by the Cost Modeling Accuracy (CMA), which is the amount of

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[1] Learning curve factorized, inflation adjusted and currency converted [1]

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variance explained by the input data, were correlated to obtain a total system cost uncertainty according to best practices stipulated by Covert [27], with a correlation coefficient of $\rho_0 = 0.2$ [12].

Table 2: Subsystem elements' Cost Estimating Relationships

	Regression			**NAFCOM**		
Equipment Element Name	***a* value**	***b* value**	**RSE/CMA**	***a* value**	***b* value**	**Used**
Solid Casing, loaded mass	90.72782	0.44422	12.9%	321.12767	0.30	Regression
Pressurizant Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Fuel Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Oxidizer Tank	19.99465	0.71253	27.6%	22.21748	0.70	Regression
Thrust Cone	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Skirt	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Thermal Control	2.79930	0.91199	12.6%	9.39259	0.70	Regression
Engine(s)	31.48271	0.78811	35.8%	322.07959	0.50	Regression
Thrust Vector Control	33.90978	0.60977	13.7%	35.44885	0.60	Regression
Pressurization System	11.50618	1.06948	49.8%	72.19775	0.60	Regression
Pipes	8.95877	0.68815	34.3%	8.96336	0.70	Regression
Valves	8.95877	0.68815	34.3%	8.96336	0.70	Regression
Stage Harness	27.45211	0.44623	34.9%	14.20721	0.75	Regression
Payload Adapter	124.86209	0.31031	13.0%	26.01794	0.70	Regression
Payload Fairing	4.09558	0.96587	9.2%	23.59239	0.70	Regression
Comms	*One data point only*			51.11253	0.80	NAFCOM
Power	56.13918	0.66916	*Two points*	42.01174	0.80	NAFCOM
Data Handling	141.82428	0.79249	16.3%	141.68203	0.80	Regression
GNC	69.05491	0.82458	23.8%	72.86034	0.80	Regression
Avionics Harness	27.45211	0.44623	34.9%	14.20721	0.75	Regression
Attitude Control Module	44.04074	1.06207	88.6%	257.84198	0.75	Regression
Interstage Structure	6.70369	0.68041	19.3%	6.16655	0.70	Regression

CERs are in the form $C = aM^b$ derived from sample data, accompanied by Cost Modeling Accuracy. Also listed are standard NAFCOM b-values [26] with a-values based on sample data. Dry mass (unless otherwise stated) and cost are in kilogram and k€ respectively

2.3 Development Estimate

Before a launch vehicle can enter production, it must be developed. The effort to perform this development includes activities ranging from design to hardware verification and building test models[2], typically starting at project Phase C up and until the end of Phase D [3, 12, 28].

In later phases (after B1), efforts required to develop a launch vehicle may be estimated from a build-up of individual engineering activities performed by a prime- or subcontractor's team. However, because of insufficient knowledge of system specifics in early project phases, which is a stage of development that most proposed smallsat launchers are currently in, it is required to use a heuristic approach to estimation, using modifiers of analogous systems where historical data exists [29]. In this case, development costs are approximated with equivalents to the Theoretical First Unit costs (T1/FU) per equipment element.

The non-recurring costs have two major contributors [30]:

1. *Design and development* effort that amounts to the engineering work performed, which depends on the technical specifications of the system,
2. Building and testing work performed on system and subsystem models, also called the *model philosophy*.

Both these contributions were modeled with *T1 Equivalents* multipliers, in which prototype articles or design work were represented by an equivalent quantity of flight units [17]. A third contribution, the *Management and Product Assurance* (M/PA) portion, was modeled as an overhead level-of-effort cost [20, 21] to both major elements.

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[2] including one flight model

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Before the equipment element T1 costs were used as a basis for the development estimate, management and product assurance percentage initially as contained in the data-points constituting the CERs had to be excluded, as in Equation 3.

$$FM1 = T1/(1 + M/PA\%) \tag{3}$$

FM1 is an approximation of the manufacturing costs of hardware only, called the *First Flight Model*. The *Management* and *PA* effort, under traditional development and production structures, were estimated at 10% and 5% respectively [12, 21]. Before re-adding them to the estimate however, these were modified to suit commercial development. This concept is explained in Section 2.3.1.

In the development cost build-up, FM1 costs of each equipment element were used to construct the total development cost. FM1 was combined with the factors Design and Development (DD) and System Test Hardware (STH) to obtain the Engineering (ENG) and hardware (MAIT) cost estimates respectively. Both elements had a management (M/PA) overhead contribution facilitating their processes modeled.

That total management (M/PA), coupled with the Engineering (ENG) functions together make up the Project Office (PO), which comprises all desk-focused activities that do not involve manufacturing. Work that does involve manufacturing was approximated with the STH FM1 equivalents factor of 3.1, which describes the work performed on test models such as a Design Model (DM), Engineering Model (EM), Qualification Model (QM) and Flight Model (FM, equal to T1), which together make up the Manufacturing, Assembly, Integration and Test (MAIT) work. A cost-saving protoflight approach was assumed throughout that combines the QM and FM into a Protoflight Model (PFM). All these models' FM1 equivalents and whether these are selected is listed in Table 3 [21].

Table 3: Development cost contribution equivalents to FM1 [21]

	STH = 3.1					**DD=3**
	DM	**EM**	**QM**	**FM**	**PFM**	**DD**
FM1 Factor	0.3	1.3	1.3	1	1.5	3 (+ΔTRL)
Baseline Amount	1	1	0[a]	0[a]	1[a]	1

[a] Protoflight model philosophy assumed

Together, the PO and MAIT support functions costs make up the equipment level development cost. This way of building up the development estimate from the FM1 is shown in Figure 2.

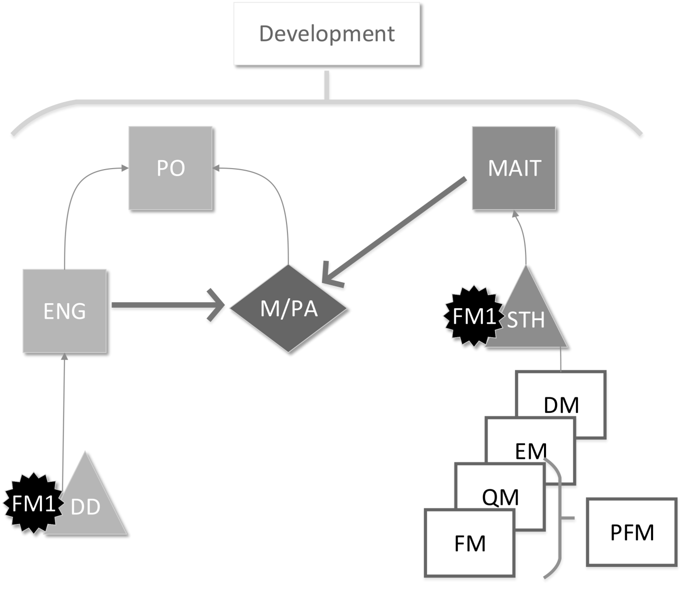

Figure 2: Development cost build-up from a First Flight Model (FM1) basis

Finally, launch vehicle integration was approximated by another prime contractor Management (M/PA_p) and Integration and Test ($I\&T_p$) level-of-effort cost, the latter of which is discussed in Section 2.4.2, and is set at 9% [12, 31, 32, 33]. For all intents and purposes, M/PA_p is the same as M/PA.

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As noted, FM1 STH equivalent factors and amount of test hardware are shown in Table 3, and were accompanied by a DD factor [12, 21]. The DD factor of 3 may be supplemented with the additional Technology Readiness Level (TRL) steps required during development, before the system is fully matured and ready for operations. In this case however, no additional TRL steps were assumed necessary, as the kerosene technology available to most new rocket startups has been pioneered decades ago.

In this way of reasoning, if for example the FM1 cost of a rocket equipment element (say the engine) would be 20 M€, and one DM, one EM, one PFM, and overall engineering work DD was performed during development, the development costs pf this engine excluding M/PA contributions would be $FM1(DM + EM + PFM + DD) = 20(0.3 + 1.3 + 1.5 + 3) = 122$M€.

2.3.1 Subcontractorship

Commercial development of a Launch Vehicle (LV) has an impact on the M/PA support function element in the cost buildup of Figure 2, as Koelle [3] suggests that companies with a lower number of subcontractors to manage and a lower percentage of work contracted out experience reduced management effort, and at typical subcontracting rates for government-centric aerospace companies (60%) and commercial launch service providers (20%), this was found to yield a cost decrease of 13.7% [12] for commercial companies.

In order to approximate this cost saving, a management effort decrease scaling factor of $S_m = 2.85$, applied to the M/PA, M/PA$_p$ and I&T$_p$ support functions, was proposed as a augmented approach. In a similar vein, employing less subcontractors leads to profit retention within the primary company, which on a nominal profit of 8% [34] and typical subcontracting rates of 20% instead of a Business as Usual (BAU) approach of on average 60% subcontracted [3], leads to cost savings of 3% compared to BAU development [12]. This necessitates the introduction of a profit retention factor of $c_p = 0.970$.

2.3.2 Development Learning Cost Improvement

The final found influence on development costs is a cost reduction factor associated with production learning during development L_d. This is a function of the times a specific hardware element is re-used on the launch vehicle, $\#HW$. In the case of 12 elements, L_d is the addition of all twelve T1 equivalent costs at 90% learning, namely $1T1 + 0.9T1 + 0.846T1 + 0.81T1 + \ldots + 0.685T1$, divided by the total number of hardware elements 12, to achieve an average learning factor of 0.78. Multiplied by $\#HW$ this yields total batch costs. This concept of learning is especially relevant to manufacturing, found in Section 2.4.

2.3.3 Development Cost CERs

Incorporating the concepts detailed above into the non-recurring costing framework yields the eventual equipment-level development CER of Equation 4. [3, 25]

$$\begin{aligned} DEV_e &= c_p(PO + MAIT) = \\ &c_p\Big(\big[ENG + (MAIT + ENG) \times (S_m^{-1} M/PA\%)\big] + \big[FM1 \times STH \times L_d \times \#HW\big]\Big) \end{aligned} \tag{4}$$

Applying the scaled prime contractor Management and Integration and Test cost overhead to the sum of all elements' estimates e, yields the overall launch vehicle development cost in Equation 5

$$DEV = \big(1 + S_m^{-1}(M/PA_p\% + I\&T\%_p)\big) \times \sum_{1}^{e} \big(c_p(PO + MAIT)_e\big) \tag{5}$$

2.4 Manufacturing Estimate

Although some manufacturing activity takes place in the development phase in the form of the System Test Hardware (STH), the main manufacturing work is performed when production is ramped up. In this phase, investments are made in dedicated production facilities. This is more the case for launch vehicles than for satellites. This is because LVs are produced in large batches, unlike satellites, with some notable exceptions [3]. In fact the manufacturing costs make up the highest percentage of total Life Cycle Costs (LCC) of LVs in work-years, reaching values up to 75% [35].

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[3] Galileo navigation satellites and Sentinel satellites which are part of the ESA Copernicus program for example

Again the T1 estimate was used in an approximation, this time for the production costs of actual units. Two major contributions to the manufacturing costs are identified [21]:

1. *Manufacturing, Assembly, Integration and Test of hardware* [4] (MAIT), the latter three sometimes referred to as AIV - Assembly, Integration and Verification [36].
2. *Management and Product Assurance* (M/PA), which now makes up the whole Project Office (PO) - all desk-focused activities supporting the manufacturing process. This is contrary to the development phase, where additional Engineering (ENG) was performed under PO as well.

Because of the similarities in approaches between development and manufacturing estimates, the resulting manufacturing CER will look much the same as the one for non-recurring costs.

2.4.1 Learning Cost Improvement

As indicated previously, production cost improvement takes place in the form of learning. To model this cost reduction effect, a Unit Learning Theory or Crawford Learning Curve [24] with a learning factor of 90%[5] was selected aided by research by Fox *et al.*[25]. This implies that each doubling of production sees costs of manufacturing a specific unit decrease with a constant percentage. This means the cost of the n-th unit U_n in Equivalent T1 units is as in Equation 6 [25, 37] . The exponent $b = ln(p)/ln(2)$ is a function of the learning factor $p = 90\%$, the factorial cost decrease associated with doubling production.

$$U_n = T1\, n^b \tag{6}$$

The n-th unit costs normalized with respect to T1 is $\frac{U_n}{T1} = n^b = L_m$, the fraction of T1 that the n-th unit is estimated to cost. The cumulative costs of a batch from unit m to unit n are then represented by Equation 7 [22, 37].

$$L_{c_{m \to n}} = L_{c_n} - L_{c_{m-1}} = \sum_{1}^{n} L_{m_n} - \sum_{1}^{m-1} L_{m_{m-1}} \tag{7}$$

2.4.2 Integration and Test Level-of-effort

After an analysis of historic project performance at NASA [31, 32] and lessons learnt at ESA [21] the level-of-effort cost of overarching prime contractor Integration and Test (I&T$_p$) work was set at 9% of hardware costs. It was also shown that this percentage was not sensitive to variations in magnitude of total hardware costs [12]. This project cost was augmented through the proposed subcontractor management scaling factor to reflect reduced I&T effort for prime contractors involved in manufacturing systems themselves. After scaling, the I&T$_p$ factor is 3.2%. This is an intuitive way of modeling the cost savings that are achieved at lower subcontracting rates, when less transportation from subcontractor's to prime contractor's facilities takes place, and less re-checking and de/re-assembly takes place at company interfaces.

2.5 Manufacturing Cost CERs

Combining the concepts discussed, the total batch manufacturing costs per equipment element will be described by the CER in Equation 8, using again the First Flight Model (FM1) as a basis. Naturally, the more identical elements a launch vehicle has, the lower the learning batch cost improvement factor will be. The resulting costs will therefore also be lower.

$$MAN_{b_e} = c_p\Big(FM1 \times L_{c_{n \to m}} \times (1 + M/PA\%)\Big) = c_p\Big(FM1\Big(\sum_{1}^{n} L_{m_n} - \sum_{1}^{m-1} L_{m_{m-1}}\Big) \times (1 + M/PA\%)\Big) \tag{8}$$

Simplified, the manufacturing of the n-th equipment element unit is shown in Equation 9.

$$MAN_{n_e} = c_p\Big(FM1 \times L_{m_n} \times (1 + M/PA\%) = c_p\Big(FM1 \times n^{ln(p)/ln(2)} \times (1 + M/PA\%)\Big) \tag{9}$$

In an analogous fashion to the development cost estimate, the sum of all equipment level elements batch manufacturing costs are the batch manufacturing cost of a single launch vehicle [12]. Included as well were the scaled prime contractor M/PA$_p$ and I&T$_p$ factors in Equation 10.

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[4] Including software

[5] Based on production quantities of 11-50 units per batch

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$$MAN_b = \left(1 + S_m^{-1}(M/PA_p\% + I\&T\%_p)\right) \times \sum_{1}^{e} MAN_{b_e} \tag{10}$$

In a similar vein, the single n-th launch vehicle manufacturing costs are described with Equation 11.

$$MAN_n = \left(1 + S_m^{-1}(M/PA_p\% + I\&T\%_p)\right) \times \sum_{1}^{e} MAN_{n_e} \tag{11}$$

2.6 Operations Estimate

For determining the second part of the recurring costs, and the last of the three-part cost estimate for commercial vehicles, the most recent TRANSCOST [3] method's capabilities were leveraged. It is the only publicly available model for estimating space transportation operations costs; sources of historical operations and support costs are not readily available because the space industry guards this data closely [38].

The definition of operations throughout the research was restricted to NASA's definition of *Launch Operations*, which does not include management of payload/crew on orbit, which is considered *Mission Operations* [3, 39]. TRANSCOST divides operations costs into two categories:

1. *Direct Operating Costs* (DOC) are costs that are related to the launch itself, and include *Ground Operations*, *Materials & Propellants*, *Flight and Mission Operations*, *Transport and Recovery* and launch-related *Fees and Insurance*. The DOC have as a cost driver the number of launches per year, the vehicle complexity and size, the way transportation to the launch pad is handled, and the way the vehicle is launched. Koelle identifies the launches per annum (LpA) as the most important driver.

2. *Indirect Operating Costs* (IOC) are company costs not directly related to the launch itself. These include staff and administrative personnel costs, marketing activities and technical support such as vehicle procurement from producers [3], all of which are also termed *Commercialization Costs*.

The CERs developed by Koelle or derived from Koelle's work utilized are listed in Table 4 [3, 12], with symbols and units listed in Table 5.

Table 4: CERs from TRANSCOST [3]

Direct Operating Costs (DOC)	**CER**
Ground Operations[a]	$W \cdot 8 \cdot M_0^{-0.9} \cdot N^{0.7} \cdot f_v \cdot f_c \cdot L \cdot f_8 \cdot f_{11}$
Propellant Cost [40]	$\frac{M_p}{r+1} \cdot c_f + (M_p - \frac{M_p}{r+1}) \cdot c_{ox} + M_{pres} \cdot c_{pres}$
Flight and Mission Operations	$W \cdot 20 \cdot Q_N \cdot LpA^{-0.65} \cdot f_v \cdot f_8$
Transportation Costs	$T_s \cdot M_0$
Fees and Insurance Costs	$I/1000 + F + c_{payl} \cdot P$
Indirect Operating Costs (IOC)	$40 \cdot S + 22.5 \cdot LpA^{-0.379} \cdot W$

[a] Learning factor L assumed constant for an average 50 units

Both indirect and direct operating costs in Table 4 are costs-per-flight, and can be summed into a total operations cost per flight, $OPS_n = IOC + DOC$.

2.7 Cost per Flight

To obtain a Cost-per-Flight (CpF) figure, the development costs were amortized [3] over a fixed number of flights (N_a) at the estimator's discretion. For this estimate 50 flights were chosen. The amortization costs were subsequently added to the launch vehicle unit manufacturing costs and operations cost, as in Equation 12.

$$CpF_n = DEV/N_a + MAN_n + OPS_n \tag{12}$$

Because of the learning factor incorporated in the manufacturing estimate MAN$_n$, the cost per flight decreases with increasing number of units produced [3, 41].

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Table 5: TRANSCOST Operating Cost CERs [3]

Parameter	Units	Symbol
Launches per Year		LpA
Assembly and Integration factor	-	f_c
Country productivity factor	-	f_8
Vehicle type factor	-	f_v
Vehicle complexity factor	-	Q_N
Commercial factor	-	f_{11}
Average learning factor operations	-	L_o
Work year costs	k€	W
Number of stages	-	N
Fuel and oxidizer mass	kg	M_p
Gross Lift-off Weight (GLOW)	Mg	M_0
Pressurizant Mass	kg	-
Mixture ratio	-	r
Public damage insurance	M€	I
Payload capacity	kg	P
Payload charge site fee	$€\,kg^{-1}$	c_{payl}
Launch site fees	k€	F
Specific transportation cost to launch site	$€\,kg^{-1}$	T_s
Percent of work subcontracted out	-	S

Various options to determine a Price per Flight (PpF) from the CpF were explored [6], and it is emphasized that any and all of these methods may be a consideration when pricing an actual launch [12]. However, a transparent cost-based PpF was selected to evaluate the developed methodology's results with. In this approach, a profit margin of nominally 8% [34] is added to the cost per flight to trivially obtain a price per flight as in Equation 13.

$$PpF_n = CpF_n + 8\% \tag{13}$$

3. Results

As many smallsat launch vehicles are in early stages of development, and engineering details about these are scarce [7], there is no amount of data available to conclusively state the proposed methods developed hold for small launch vehicles. However, the synthesized estimates for development cost, manufacturing cost and operations costs, as well as the price per flight approximation, were applied to two reference small LV's that have a sufficient amount of equipment-level configuration and mass data available. These were the Falcon 1 launch vehicle, a retired rocket previously manufactured by commercial launch venture SpaceX, and the Pegasus XL rocket, produced by Orbital ATK. To discover the proposed method's validity for larger launch vehicles, where possible it was applied to cost larger vehicles such as SpaceX's Falcon 9 rocket. The operations cost estimate specifically, which relies on previously developed and referenced work by Koelle [3], will be featured indirectly in the Price per Flight results of Section 3.3. For a comprehensive overview of model input parameters assumed, and masses used to obtain these results, please refer to [12].

3.1 Development Cost Estimate Results

Results for the non-recurring costs for all three reference cases, compared to actual development costs of these rockets, are listed in Table 6.

Important to note is the cost year of each of the estimates, as the Pegasus XL was developed more than 20 years before the Falcon launch vehicles.

3.2 Manufacturing Cost Estimate Results

Manufacturing costs for both the Falcon 1 and Pegasus XL vehicle were compared to the ones obtained through the developed methodology, as no actual manufacturing cost data was available for SpaceX's Falcon 9. However, the Maxus 9 sounding rocket proved a useful reference comparison, as the proposal for its manufacture was available

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[6] Such as a Net Present Value (NPV) analysis and Break-even Analysis using beta curve expenditure profiles [20, 42]

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Table 6: Non-recurring cost estimates compared to reported costs [43, 44, 45, 46]

Launch Vehicle	Model NRC Estimate	Reported Development Costs	Difference
Falcon 1	\$96M (2010)	\$90M (2010) [43]	+7%
Falcon 9	\$419M (2010)	\$372M (2010) [43]	+13%
Pegasus	\$56M (1988)	\$50M (1988) [44, 45]	+12%

through ESA. Its closeness in size to smallsat launch vehicles and rocket engine developed for orbital application merits an estimate, even through the actual manufacturing figures are non-publishable. A summary of obtained results is shown in Table 7.

Table 7: Manufacturing cost estimates on three reference cases, compared to actual reported costs [12]

Launch Vehicle	Model Manufacturing Estimate	Reported Manufacturing Costs	Difference
Maxus 9 Top-level	*redacted*	*redacted*	+5.9%
Maxus 9 M/PA and I&T	*redacted*	*redacted*	-2.4%
Maxus 9 Hardware-only	*redacted*	*redacted*	+8.1%
Falcon 1	\$6.1M (2005)	\$5.9M (2005) [12]	+3.4%
Pegasus XL Solid Casing	7,095 k€ (2015)	7,401 k€ (2015) [47]	-4.1%

3.3 Price per Flight Results

Price per Flight estimates obtained through the developed costing method were compared to commercial launch price quotes for the Falcon 1 and Pegasus XL vehicles. The methodology was applied straightforwardly to the Pegasus XL launch vehicle. In fact, due to the ready availability of historic launch rate and launch price data, the methodology's historical performance over time could be judged. Figure 3 shows the yearly cost estimates, based on the achieved launch rates also shown, compared to a linear interpolation of actual historical cost data. 70% of prices were approximated appropriately within the desired 20% of actual costs. Taking into account the Cost Modeling Accuracy, which is the amount of variance explained by the input data and was found to be 8.47%, that figure increased to 83%. The increase in price at a decrease in launch rate is clearly visible.

The development of the Falcon 1 on the other hand was fully covered by United States government funding [9, 46, 48], and therefore development amortization costs were not included in this PpF estimate. Also, the operations costs needed to be adjusted for an unknown amount of public subsidy received while using the government's launch base at Kwajalein. The first few manifested flights also carried uninsured government payloads [49], mitigating insurance costs. The price per flight (PpF) results including these adjustments are listed in Table 8. As the number of launches per year is an important cost driver for the operations costs, the values assumed for this parameter are also listed.

Table 8: Price per Flight estimates on two reference cases, compared to actual reported costs [6, 50, 51, 52]

Launch Vehicle	Model PpF Estimate	Reported Price	Difference
Falcon 1, 10 LpA [50]	\$8.7M (2008) [a]	\$7.9M (2008) [51]	+10%
Pegasus XL 12, LpA	20.0 M€ (2015)	20.3 M€ (2015) [6, 52]	+1.5%
Pegasus XL ($0 < LpA < 5\frac{1}{3}$)	70%	-	within 20% target range
Pegasus XL ($0 < LpA < 5\frac{1}{3}$)	83%	-	within 28% CMA range

[a] Adjusted for government subsidies [12, 49]

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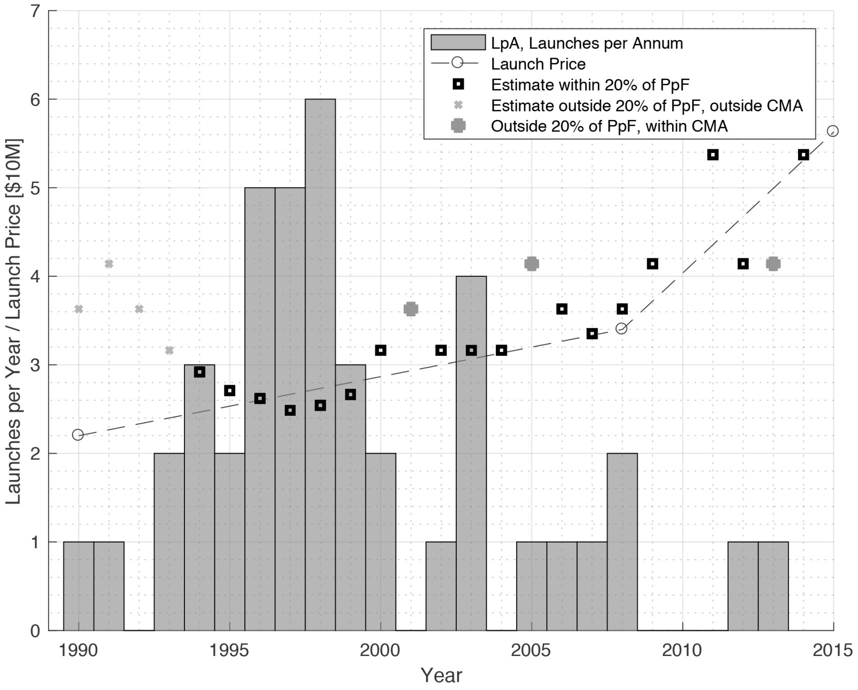

Figure 3: Pegasus XL launch rate, launch price and price estimates from 1990 until 2015

4. Discussion

Even through scarcity of reference data, it has proven feasible to approximate within 20% the costs of small commercial launch vehicles. This was demonstrated by the interim results per phase estimated in this new proposed approach. It was also shown that this is possible for the overall launch price; the Price per Flight estimates in Section 3.3 were able to represent actual price quotes to the desired 20% accuracy. However, care should be taken by an estimator to not only take the CERs developed in this research at face value and apply these blindly. This can lead to mitigating factors being overlooked, such as demonstrated by the need to modify the Falcon 1 PpF estimate to suit actually incurred costs. Any application of a cost model will therefore necessarily always require additional judgment on the part of the estimator on a case-by-case basis [10, 12].

The year-by-year results from the Pegasus XL PpF estimate in Figure 3 fall favorably within target range considering the variance expected in the model input data. The only unsatisfactory results were witnessed in the first four years of operations. It is thought that these larger deviations stem from the fact that pricing early on is based on an optimistic target maximum achievable launch rate of 12 LpA, and that the initial ramp-up of the program is a phase where the number of vehicles produced does not yet match the quantity required for a lower price point.

For a detailed discussion on the sensitivities of the model on important cost driving input parameters, please refer to [12].

It is inherent to an early-phase parametric estimate that the uncertainties will initially be high [10]. Especially the development cost estimate features input parameters which provide rough factorization of often large one-off project costs, and actual incurred costs will deviate from the first approximation. However, cost estimates should be treated as a living variable, to be continuously updated throughout the design and manufacturing process [10]. When more system details become available as a project passes through its development stages, the assumptions made can be critiqued and adjusted where necessary. The same analogously holds for the scarcity of data available for reference. As new smallsat LVs are developed and built, a better case can be made for a certain approach to estimating as a whole. There will always remain a need for continued evaluation of the tool when more data becomes available in the future.

4.1 Other Important Findings

As far as individual estimates go, the manufacturing costs are sensitive to selection of a cost improvement learning factor. Fox *et al.* [25] have shown that selecting typical learning factors between 82% and 96% may lead to overestimating or underestimating manufacturing costs by as much as +39% or -54% respectively. Therefore it is advised an

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estimator take particular care when selecting such a factor for costing.

Operations costs on the other hand are subject to increases at lower launch rates. This presents a particular risk for small launch vehicle operators. Indirect Operating Costs, which include for example launch pad costs, are not a function of vehicle Gross Lift Off Weight, and are not reduced by launching a smaller rocket. At lower launch rates, it was found that Indirect Operating Costs make up an increasingly large percentage of small rocket launch costs: cost increases of up to a factor of 2 could be witnessed at lower LpA figures, to the point where small rockets might become economically unfeasible to operate. Operations costs will be within a typical range of $\leq$ 35% of recurring costs at 4 launches per year or more [12]. To partially offset this risk, it is recommended that smallsat launch service providers lease their required launch facilities.

5. Conclusions

Prices per flight of small commercial launch vehicles were approximated by combining a parametric cost estimating methodology used frequently in the context of space agencies such as ESA and NASA, called the *T1 Equivalents* method, with another parametric three-part estimate developed by Koelle [3] for development, manufacture and operations phase costs. The first two phases were estimated through the T1 method, while the operations costs were modeled with TRANSCOST.

Two important cost saving strategies employed by commercial launch companies were identified:

1. Reduced subcontractor management effort with lower costs for the prime contractor, by employing a lower subcontracting rate and producing more in-house.
2. Profit retention, achieved through contracting a lower percentage of work out.

New additions to the T1 equivalents method that suit these cost reductions were developed, and proposed in the form of level-of-effort scaling factors.

First, the factors corresponding to reduced subcontractor management effort were identified in the T1 equivalents method. These were the business-as-usual Management and Product Assurance (M/PA) and Integration and Test (I&T) level-of-effort overhead costs. In order to model commercial cost improvements, these two factors were scaled by almost a factor 3 to account for potential commercial cost reductions of up to 14%. Integration and Test was also considered for this scaling because some of the I&T work by subcontractors is redone by the prime contractor; this repetition does not occur when less work is subcontracted out commercially.

Increased profit retention for the prime company at lower subcontracting rates was also modeled, by introducing a cost reduction factor representing up to 3% savings compared to BAU costs.

The model developed was able to approximate costs of development, manufacture and price per flight of three commercial rockets to within 20% of actual reported costs or prices. However, it is recommended the model is refined as more reference cost data, especially on a subsystem level, as well as pricing for these smaller rockets becomes available in the coming years.

With these new additions, a first step has been made towards quantifying costs for small commercial launch vehicles, to be expanded and refined upon in the years to come. By utilizing the developed model as a way to make important early design decisions, the aerospace industry will be aided in successfully making a business case for smallsat launch vehicles, providing the much needed dedicated access to space for a new generation of small satellites.

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