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Small Orbital Launch Systems, a Tentative Initial Cost Estimate

Nigel T. Drenthe



Technische Universiteit Delft

TU Delft

esa

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Small Orbital Launch Systems, a Tentative Initial Cost Estimate

by

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Abstract

Small rockets have the potential to play an important role in the changes that are now occurring in the space-flight domain. Currently, satellite miniaturization is opening up new possibilities to form constellations capable of full-time global coverage for internet service, real-time earth observation applications, and disaster monitoring. Such programs involving small satellites require low-cost and frequent access to orbit.

A new class of launch vehicles is uniquely positioned to offer these small satellites dedicated access to space, with no restrictions on target orbit height or inclination traditionally associated with current ride-share arrangements. A number of new launch service providers has stepped up to this challenge, developing systems with decreased size and payload capability in a commercial way. Their offerings are priced lower than costs traditionally associated with a rocket launch. However, most of these firms do not have hardware in production yet, so the question arises whether or not these early price quotes are realistic with respect to the actual costs incurred.

This research has made a first step towards answering this question, by developing a way to estimate costs for such systems in partnership with the European Space Agency's Cost Engineering Section. All aspects of the estimating process were addressed, from gathering and selecting data, to building Cost Estimating Relationships, detailing cost-risks, and employing existing - and developing new - parametric relationships, whilst exploring their applicability to systems that have a lower payload capacity and gross lift-off weight than traditionally larger rockets.

An early phase parametric cost estimate was synthesized with which it is now possible to approximate for commercial liquid and solid propellant rockets in the 100-700 kg payload range the development, production and operating costs, and their cost-based price per flight to within 20% of reported costs. By doing so at an equipment-level depth, novel contributions to theory could be made by adapting the Theoretical First Unit T1 method of estimating, mirroring the reductions in cost achieved by commercial launch operators through profit retention and reduced subcontractor management effort. Whilst exploring these new launch vehicles' costs, it was also discovered that small rockets in particular require a launch rate of over 4 per year to keep program commercialization expenses from causing up to a threefold increase in launch prices.

An ESA liquid methane vehicle concept was central to the estimate; it was however concluded that this rocket ineffectively addresses the LEO market at a price point that is too high to gain market share. Nonetheless, other future proposals for small launch systems can now be evaluated for their cost feasibility, either by potential investors or agencies seeking shared technology development with commercial partners.

Preface

I would like to take this opportunity to thank some people important to me, and use this page as an excuse to borrow a few quotes, which are sometimes old, but definitely silly.

Direct acknowledgment for their contributions to this work in particular go to Barry Zandbergen, whose sharp eye for detail and nuance has never failed to surprise, and Ricky Curran, for steering this work towards academic contribution to theory. Barry suggested looking into launch vehicle costing back in 2015, but both of us would not have guessed that I would eventually graduate the TU Delft specializing in cost estimating.

"If you think in terms of a year, plant a seed; if in terms of ten years, plant trees; if in terms of 100 years, teach the people"

- Confucius

A special thank you is reserved for Michel van Pelt, who granted me the opportunity to join the *Cost Engineering* family while writing my thesis. Michel re-introduced me to the joy and wonder of spaceflight at a time where the academics of the whole endeavor seemed daunting. In addition to giving me solid advice on cost estimating, Michel has unfalteringly managed to review every small bit of documentation sent his way. This generous support for the past year is something I will never forget.

"Never was so much owed by so many to so few"

- Winston Churchill

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"Standing on the shoulders of giants"

- Bernard of Chartres

Not least I would also like to thank all others in the *Cost Engineering* section who have made my time at ESA unforgettable: Elisabetta Lamboglia, Giorgo Cifani, Grace Smith, Hervé Joumier, Mara Rosado, Paolo Martino, and of course Massimo Magazzu.

"Det er vanskeligt at spaa, især naar det gælder Fremtiden"
"It is difficult to predict, especially the future"

- Niels Bohr

Culminating 23 years of education in a master's degree, I would finally like to extend my sincerest gratitude towards those that have selflessly stood by me throughout some, if not all these years. In the first place to the two people that have been cheering me on since my own launch at $t = 0$, Sylvana de Vos and Jack Drenthe. To my brother Kevin for being the bestest of best friends always. To Else for her loving support and welcome distractions from work. And finally, to all those family and friends who I will have to convince that their support is worth more to me than a few words printed on page v can ever say. You know who you are.

"Deeds will not be less valiant because they are unpraised"

- J.R.R. Tolkien

As for myself, whatever new adventures the future may hold:

"What's behind you doesn't matter"

- Enzo Ferrari

Nigel T. Drenthe
Delft, November 2016

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List of Acronyms

AC	Attitude Control
ACM	Attitude Control Module
ADS	Airbus Defence and Space
BAU	Business As Usual
BLUE	Best Linear Unbiased Estimator
BOE	Basis of Estimate
BY	Base Year
CAD	Computer-aided Design software
CBS	Cost Breakdown Structure
CDF	Concurrent Design Facility
CEH	Cost Estimating Handbook
CEM	Cost Estimating Method
CER	Cost Estimating Relationship
CES	Cost Estimating Structure
CMA	Cost Modeling Accuracy
CNES	Centre National d'Études Spatiales
CONAE	Comisión Nacional de Actividades Espaciales
COTS	Commercial Orbital Transportation Services
COTS	Commercial Off The Shelf
CpF	Cost Per Flight
CRS	ISS Cargo Resupply Service
CSRUH	Joint Agency Cost Schedule Risk and Uncertainty Handbook
CY	Current Year
DD	Design and Development T1 Equivalent
DDT&E	Design, Development, Test and Evaluation
DEV	Development Cost
DM	Development Model T1 Equivalent
DMM	Design Maturity Margin
DOC	Direct Operating Costs
DoD	Department of Defense
EADS	European Aeronautic Defence and Space Company
EC	Economic Conditions
ECOS	ESA Costing Software
EJ	Expert Judgment
ELV	Expendable Launch Vehicle
EM	Engineering Model T1 Equivalent
ENG	Engineering Support Function
EPE	External Project Events
ESA	European Space Agency
EU	European Union
FFP	Firm Fixed Price
FM	Number of Flight Models
FM1	First Flight Model
FMR	Recurring Flight Models

FU	Flight Unit/First Unit
GRA	Ground Rules and Assumptions
HTPB	Hydroxyl terminated polybutadiene
HW	Hardware
I&T	Integration and Test
ICE	Independent Cost Estimate
IMU	Inertial Measurement Unit
IOC	Indirect Operating Cost
ISS	International Space Station
ITAR	International Traffic in Arms Regulations
LCC	Life-Cycle Costs
LEAP	Launcher Exploitation Accompaniment Program
LEO	Low Earth Orbit
LOX	Liquid Oxygen
LpA	Launches per Annum
LV	Launch Vehicle
M/PA	Management & Product Assurance
MAIT	Manufacture, Assembly, Integration and Test
MAN	Manufacturing Cost
NAFCOM	NASA Air Force Cost Model
NASA	National Aeronautics and Space Administration
NPV	Net Present Value
OECD	Organisation for Economic Co-operation and Development
OLS	Ordinary Least Squares
OPS	Operating Costs
OSC	Orbital Sciences Corporation
PA	Product Assurance
PAA	Payload, Avionics and Attitude Control Module
PBS	Product Breakdown Structure
DPU	Power Distribution Unit
PFM	Protoflight Model T1 Equivalent
PLC	Product Life Cycle
POE	Project Owned Events
PS	Pressurization System
QM	Qualification Model T1 Equivalent
RDP	Research, Development and Production
ROI	Return on Investment
ROM	Rough Order of Magnitude
RSC	Refurbishment and Spares Cost
RSE	Relative Standard Error
RMSE	Root Mean Squared Error
S&M	Support and Maintenance
S3	Swiss Space Systems
SD	Standard Deviation
SE	Standard Error
SLS	Space Launch System
SpaceX	Space Exploration Technologies
SRB	Solid Rocket Booster
SSCAG	Space Systems Cost Analysis Group
SSO	Sun Synchronous Orbit
SSTL	Surrey Satellite Technologies Ltd.
STH	System Test Hardware T1 Equivalent
SW	Software
T1	Theoretical First Unit
TEC-SYC	ESA Cost Engineering Section
TRL	Technology Readiness Level
US	United States
USCM	Unmanned Space vehicle Cost Model
VLM	Veículo Lançador de Microssatélites
WACC	Weighted Average Cost of Capital
Wyr	Work Year

List of Symbols

Roman Symbols

$\#HW$	number of hardware elements (-)
a	a-value mass cost power curve (-)
A	development amortization charge (k€)
a_{log}	a-value power curve, logarithmic
a^*	a-value power curve in dollars, pounds
b	b-value mass cost power curve (-)
b_{log}	b-value power curve, logarithmic, equal to b
C	cost (k€)
$C_\$$	cost in dollars (k$
C_{low}	lower 1 σ standard error (k€)
c_{payl}	payload charge site fee (€kg^{-1})
C_{upp}	upper 1 σ standard error (k€)
c_i	subcontractor cost increase factor (-)
c_p	profit retention factor (-)
c_s	subcontractor management reduction factor (-)
$CAC(Q)$	cumulative average batch cost (k$)
CpF_a	average cost per flight (k€)
DD'	TRL adjusted design & development factor (-)
dof	degrees of freedom (-)
$E[X]$	mean cost, arithmetic (k€)
E	launch market price elasticity (-)
F	launch site fee (k€)
f_{11}	commercial cost reduction factor operations (-)
f_8	country productivity factor (-)
f_c	assembly and integration factor (-)
f_v	vehicle type factor (-)
I	public damage insurance (M€)
k	discount rate (-)
L_a	average batch learning factor
L_c	cumulative learning factor (-)
L_d	development cost improvement/learning factor (-)
L_m	manufacturing cost reduction/learning factor (-)
L_o	average operating cost improvement/learning factor (-)
LpA	launches per year (-)
M	mass (kg)
m	number of coefficients in regression (-)
M_{lbs}	mass (lbs)
M_0	gross lift-off weight (kg)
M_p	propellant (fuel & oxidizer) mass (kg)
MAN_a	average manufacturing costs (k€)
n	unit number or sample data points (-)
N	number of stages (-)
N_a	number of amortization flights (-)
p	learning factor (-)

P	payload capacity (kg)
$PpF^{\%}$	cost-based price per flight (k€)
PpF^{NPV}	net present value price per flight (-)
PpF^{Y}	Y-year break even price per flight (k€)
q	market demand or nominal profit percentage (-)
Q	number of units in batch (-)
Q_N	vehicle complexity factor (-)
r_e	exchange rate (€\$$^{-1}$)
$RMSE$	root mean squared error
$RMSE$	mixture ratio (-)
S	percent of work subcontracted out (-)
S_{BAU}	business as usual subcontractor percentage (-)
S_{COM}	commercial subcontractor percentage (-)
S_m	management scaling factor (-)
$SD[X]$	arithmetic cost standard deviation (k€)
T	student's t-distribution random variable (-)
T	thrust (kN)
t	discount period (-)
t_{crit}	critical value on t-distribution (-)
t_{obs}	observed value on t-distribution (-)
t_c	burn time (s)
T_s	specific transportation cost (€kg^{-1})
TI	total impulse (klbss)
U_n	n-th unit cost (k€)
ν_1	F-statistic coefficient 1 (-)
ν_2	F-statistic coefficient 2 (-)
W	work-year costs (k€)

Greek Symbols

α	beta distribution coefficient (-)
β	beta distribution coefficient (-)
$\Gamma(t)$	gamma function (-)
ΔTRL	TRL steps required during development (-)
μ	point estimate (mean), logarithmic (ln(k€))
ρ	correlation matrix (-)
ρ_0	standard correlation coefficient (-)
σ	logarithmic standard error (ln(k€))

1 Introduction

The spaceflight environment is changing rapidly, with new commercial companies establishing themselves in all segments of the industry [13]. 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 particularly interesting. 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 [7]. Space Exploration Technologies' (SpaceX) founder Elon Musk has, in an address to Congress, even expressed his belief that a launch price of 1,100 € per kilogram to orbit could become reality in the near future [86]. SpaceX is able to offer a Falcon 9 rocket launch at a price of $62M, while launches with similar payload capacity are offered exclusively at costs of more than $150M [90].

NASA initiated the creation of that private-sector space launch market by establishing the Commercial Orbital Transportation Services (COTS) and ISS Cargo Resupply Service (CRS) programs in 2006 [53]. By initially offering up the government launch market and providing a small amount of public seed money, a valid purpose for commercial firms to engage in launch activities was established. Once the commercial market matured launches could be procured at lower cost, and other commercial space markets could develop as well. [64]

Commercial companies have changed their way of doing business compared to traditional aerospace hardware manufacturers. For example, even though storable propellants such as a combination of Kerosene/ LOX may not yield a specific impulse as high as cryogenic liquid hydrogen, these are nevertheless used by commercial companies in their rockets [13]. Because their handling is less complex, using such propellants reduces the manpower requirements when fueling the rocket on its launch pad. It also mitigates the risk that when a launch is scrapped, the entire vehicle needs to be disassembled in order to replace single-use cryogenic valves [83]. Costs are also lowered by restricting the amount of work contracted out and producing most if not all vehicle parts in-house [45]. In this way profit is retained, and subcontractor management effort is reduced [13]. The latter factors were identified to have an important impact on cost in preparatory work performed for this research, and will be discussed in detail throughout this report.

1.1. Small Launch Vehicles

Miniaturization of technologies has led to the development and rise in popularity of small satellites [6] and the emergence of small satellite manufacturers starting in the 80's [80]. The market for small satellites is expected to exhibit an increase in demand [61], which in Europe is now mainly institutional [80]. Performance increases will enable more applications in civil and earth observation fields with these satellites, mainly for land monitoring and energy resource discovery [80]. A requirement for a viable program involving small satellites is low-cost and frequent access to space [6]. 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 [74]. There is an identified need for a dedicated launch system to loft 100-700 kg satellites into orbit [13], which will be the payload range of rockets considered throughout this text. 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 [20].

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 [74]. The launch vehicles in the payload range considered are listed in Table 1.1.

Table 1.1: Companies competing for the 100-700 kg small satellite launch market. Highlighted are government-developed systems in grey, semi-government-developed systems in light-grey, and commercial systems are unhighlighted [10, 61, 62, 74]

System Name	Company	Payload LEO(SSO) [kg]	Launch Cost [$M]
Electron	Rocket Lab	(100)	4.9
Prometheus-1	SpaceLS	100	-
Arion-2	PLD Space	150	1.5 [66]
VLM-1	Brazilian Space Agency	100-200[37]	-
Demi-Sprite	Scorpius Space Launch	160	3.6
Tronador II	CONAE	200	6
SOAR	Swiss Space Systems “S3"	250	<10
Super Strypi/SPARK	ISLP	(250)	15 [104]
Kuaizhou	CASIC	300	-
Shavit	Israel Aerospace Industries	350	-
VLS-1	Brazilian Space Agency	350	-
Firefly α	Firefly Space Systems	400 (200)	9
LauncherOne	Virgin Galactic	400 (200)	<10
Shtil	Makeyev	430	0.47 [24]
Haas 2C	ARCA Space Corp	400	-
M-OV	MISHAAL Aerospace	454	-
Pegasus XL	Orbital ATK	468	11,30 [86], 56.3
Falcon 1 cancelled	SpaceX	570	7
Minotaur I	Orbital ATK	584	20 [10]
Start 1	MITT	632	9
Long March 11	CAST	700 (350)	-
Athena Ic	Lockheed Martin	700 (470)	20[10]

These companies quote prices-per-kilogram to orbit that are often significantly lower than current launch options[1]. Most of the companies listed are new entrants that have no demonstrated flight hardware. The question then arises: are these prices realistic considering their new development? With no purpose-built tool yet available to estimate costs for small rockets, there is no way to find out. This research is aimed at filing this gap, and a way to estimate small rocket's costs and cost-based price at the TU Delft or at the European Space Agency (ESA) will be its result.

1.1.1. Research Question

The difficulty with constructing a cost model to characterize these small launch vehicle (LV) costs rests in two issues.

The first is that spaceflight cost engineering, the discipline in which engineers assess a space system's cost based on its technical characteristics, is centered around methods and tools that, up and until now, were specialized in predicting costs incurred for systems developed for and by an agency. These tools do not take into account costs savings brought about by commercial companies' changed way of doing business. A typical example for this were the conclusions NASA drew after seeking to estimate development costs for the new Falcon 9 rockets, manufactured by SpaceX, with its ubiquitous NASA Air Force Cost Model (NAFCOM). Estimates, which first assumed Business As Usual (BAU) working conditions, needed to be revised down significantly when SpaceX's commercial cost saving strategies became apparent [72]. This means BAU models, if used to cost commercial small rocket systems, will need to be adapted or at least checked for their ability to cost commercial systems. This will be especially important if these models developed by ESA are used in this research.

[1] Table 6.8 shows these values for prospective entrants in the 100-700 kg payload class

Another issue is one of scale. Up until now, satellites developed and launched were not small enough to warrant their own dedicated small launch system. This means such small rockets are a relatively new phenomenon, which explains the wave of new entrants in this field [10, 74]. As of today, dedicated launch vehicle cost models have scarcely adapted to this new reality, and have not yet proven to reliably estimate the costs of such small rockets. For example the publicly available TRANSCOST model by D.E. Koelle [45] has proven to overestimate costs for small systems significantly in a previous TU Delft study by Van Kesteren [97]. In order for such models to be used in researching small rockets' costs, they need to be checked for applicability, and possibly be adapted to suit a system that is smaller than they were originally intended to estimate costs for.

Because it is assumed that in principle the costs for the hardware itself, which includes tooling and raw materials, should be equal between BAU and commercial development all else equal, a choice was made to build up a cost estimate from individual construction parts, called *equipment elements*. Combining these costs should lead to a clear picture of what a specific systems' costs are.

A *Cost per Flight* (CpF) can be established if all program costs are allocated to individual rocket units. Based on this CpF, it is possible to determine a *Price per Flight* (PpF) [45], which is the final figure charged by a launch service provider, and can be compared to public launch price quotes as those in Table 1.1. This will be the eventual goal of the research, to find out if the price of small commercial rockets can be estimated with available and if necessary adapted models that account for smaller - as well as commercial - systems. The research question is formulated as to include the suggestion of building up the estimate from individual elements:

Is it possible to estimate price per flight of a 100-700 kg payload capacity commercial launch vehicle within 20% of actual prices, through costing of individual rocket design elements?

The novelty in answering the question lies in application to commercial systems and smaller-class rockets, as well as in contribution to theory by testing and adapting existing costing methods and tools to commercially oriented small rockets.

A point estimate within 20% of actual costs was chosen because this is a typical accuracy of a cost estimate featuring development of a system [83]. Why a *point estimate* specifically was chosen and not for example a comparison of prices based on the model standard errors is discussed in Section 1.2.5 and Appendix A.

1.1.2. Partnership with the European Space Agency

A partnership was established between the TU Delft and the European Space Agency's Cost Engineering Section *TEC-SYC*, with the aim of developing a model capable of estimating small rocket's costs in an early phase. An opportunity at the European Space Research and Technology Center (ESTEC) arose to determine costs for a concept small launch vehicle that could theoretically be produced commercially by European industry. This was considered an ideal case to base such a novel model around. In doing so, the customer for the estimate would be ESA in general, and not a specific section per-se. Below, the already established liquid-methane propelled rocket concept will be described in more detail.

If such a new tool were available to the TU Delft, it could be incorporated into optimization algorithms such as those developed by Miranda [65] that currently only optimize a rocket design for lowest mass. When incorporated, cost can be treated as a variable with which the design can be optimized.

With such a tool available to the European Space Agency, accurate assessments can be made of for example future shared technology development initiatives with small rocket manufacturers, or made by them for agency funding. This assessment will primarily be based on costs and price targets set out by these firms. In providing this capability, this research might aid in establishing new entrepreneurial ESA-industry relationships in the launch sector.

To potential investors, such a cost engineering tool could also be valuable to determine which potentially profitable launch businesses to fund, and which venture might be overly ambitious in their target pricing.



Figure 1.1: Vega E launch vehicle, whose upper stage liquid methane engine is similar to the one in the concept to be costed [19]

Liquid Methane Rocket Concept

The concept around which the cost estimate will be built up is detailed in this section. In addition to costing this theoretical vehicle configuration, reference cases will be used to insure the validity of the model developed at the end of each stage of the estimate.

The concept that will take center stage in the estimate is a two-stage-to-orbit rocket that is propelled by a fuel/oxidizer combination of Liquefied Methane (CH_4) and Liquid Oxygen (LOX). The rocket has a payload to LEO (SSO) capacity of 300kg, and therefore falls within the payload range considered of interest to this study. It is a purely conceptual example of how a low-cost launch vehicle, inheriting much of the necessary hardware from the European space sector, could be constructed. Liquid methane was the propellant of choice for this vehicle as it is only lightly cryogenic, and is not subject to the handling constraints that liquid hydrogen systems have [45, 83]. This is one of the traits that commercial vehicles have been found to exhibit in preparatory work [13]. The engine design could be re-used potentially from a different program. This saves effort developing a new propulsion system, which is the most resource intensive part of a rocket [45]. The vehicle also features contemporary electric thrust vector control powered by batteries.

As no liquid methane engine was developed and produced in series, there is an uncertainty as to whether costs will more resemble lower kerosene engine production costs, or the higher hydrogen engine costs [50]. A choice was made to construct a Cost Estimating Relationship (CER) for the engine that featured both types of engines' costs as input data, and while the uncertainties from such a hybrid CER would be larger, at least the median costs would become clear without the risk of making an error in judgment between the two choices. The overall development cost risk would then be reflected in the engine Cost Modeling Accuracy (CMA), which is a function of the data spread.

The entire mass breakdown and details of this vehicle are shown in Appendix B, Table B.1 and B.2. Each subsystem's mass is listed alongside the number of times it is used. In these tables, each subsystem's mass is allocated to an equipment-level breakdown element that exhibits similar complexities as the subsystem, the results of which is shown in Chapter 2 through Tables 2.7 and 2.8 for the first and second stages respectively. This mass allocation will be used to drive the Flight Unit estimate, the first step of the cost estimate and a concept explained further in Section 1.2.5.

1.1.3. Aim

A typical accuracy found for a development phase cost estimate is ±20%, which improves to ±10% for the manufacturing phase estimate [83]. The model will be considered to have a satisfactory degree of accuracy if the price of the methane launch vehicle can be estimated to within ±20% of actual costs, because the price consists of both development and manufacturing estimates. This will be tested with a number of reference cases in Chapter 6.

The next section will describe standard practices in cost engineering and estimating, the importance of early phase estimates such as these, and the modeling choices made in order to make the rocket estimable within a reasonable time frame and the desired accuracy.

1.2. Cost Estimating

This section will discuss the way cost estimates are regarded in the space industry, and also explore the consequences that the estimate to be developed might have for the launcher program. Shortly thereafter, previous work on launch vehicle cost estimating will be highlighted, before making the modeling choices and setting up the cost estimate's Ground Rules and Assumptions (GRA's).

1.2.1. Defining an Estimate

Cost estimating is defined as the process of approximating the costs of a certain output, which results in an estimate. In spaceflight, it entails predicting the costs of a technical system and its related program expenses. This estimate should be a living variable, continually updated to reflect the system's current technical characteristics or changes in program schedule and management, as opposed to just a static or deterministic value. [94]

There are many uses for a cost estimate, which range from Project Office formulation and implementation assistance, what-if exercises, affordability studies, and economic analyses to support a multitude of decisions related to space projects. These decisions can for example be the approval to proceed to a next phase of development. [69]

Cost estimates themselves are part of a larger multi-faceted science called *cost engineering*, which addresses estimation and control of project schedules, business planning and profitability analysis [94]. These aspects will certainly be discussed later on in the research, after the initial estimate is completed.

1.2.2. Importance of Cost Estimates

Establishing accurate cost estimates for space missions is extremely important, and has recently become more important still. This has a number of reasons:

- Traditionally, space agencies strove to design their systems to optimize performance. When recently the COTS and CRS programs were introduced by NASA [53], 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 [45, 94] in order to maximize competitiveness and profitability. This way, cost estimates have become an important design tool for space systems under recent changes in the space industry structure. [13]
- 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 for 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 contact. Underestimation risks the project making a loss. Inaccurate estimates are therefore a risk. [30, 94]
- In an agency environment, this previously named selection pressure could results in projects' costs being underestimated deliberately in order to increase chances of selection. This influences the project manager's decision-making process significantly. [13, 30, 94]

The estimated costs for the liquid methane launch vehicle program will have a direct influence on the decision-making process around it. Estimating in the most accurate and transparent manner possible will aid making choices for developing such a concept further. However, a significantly over- or underestimation of costs could have undesired consequences on this decision. It is therefore crucial to validate the methods and tools used, and provide clear reasoning behind the rationales involved in the estimate.

1.2.3. Previous Work on Launch Vehicle Cost Estimating

The perceived high cost of space transportation is viewed as one of the biggest obstacles to space commercialization and exploration [24]. Unsurprisingly then, there have been countless studies into ways to characterize and subsequently reduce these costs. The problem was addressed by both academics such as Koelle [42–45] and space agencies such as NASA and ESA alike.

Also, 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 [45], 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 [13] of these tools is their availability to be used, as some are restricted to government use and/or paid-for commercial tools. The only publicly available tool is the dedicated rocket costing tool TRANSCOST. [13, 94]

1.2.4. Modeling Choices

There are three main classic cost estimating methodologies (CEMs) that are prevalent throughout the aerospace industry [11].

The *engineering build-up* method is also referred to as "grassroots" or "bottom-up estimating", as is performed at the lowest level of detail [13, 94], namely the "work package" level. Costs for each work package in a Work Breakdown Structure (WBS) are then summed to arrive at a total cost estimate [69]. There is too little detail known about this launch vehicle program, and published publicly on other small rocket programs, to build up such an estimate. For example, the size of the ground infrastructure and team during mission operations can not be guessed without more information from the program side, which typically becomes known in later phases.

An *analogy cost estimate* is an estimate which is made by comparing the system to be developed with an already existing system, and taking into account differences and similarities by adjusting the estimate accord-

ingly [69, 94]. As there are few analogous systems in the way of small launch vehicles that are in production and are available to compare the liquid methane concept with, this option is limited.

Finally, the *parametric cost estimating* method, as the name implies, is based on varying parameters to suit mission specific details that need to be reflected in the final cost estimate. These parameters can be based on the system's technical characteristics. Parametric cost estimating is best done in early project phases, when details about a project are not yet clear and requirements still have to take shape [94]. At best, only a rough system configuration of the is available for some small rockets. It is therefore that the parametric approach is the ideal choice to model their costs with.

It was also concluded that advanced estimating methodologies such as those featured in Curran [11] have not matured enough to perform this estimate with, especially since estimates on novel small rocket systems in a new commercial context have not been demonstrated at all yet [13].

Figure 1.2 [94] shows which CEMs are common throughout the various project phases. The more a project matures, the more detailed bottom-up methods are employed. From Figure 1.2 it is clear that indeed the parametric approach is dominant in the early phases, and this confirms the method of choice to develop this estimate with. Certainly, the available TRANSCOST tool features parametric Cost Estimating Relationships (CERs) that are linked to launch system costs. This tool is therefore suitable for such an early phase estimate.

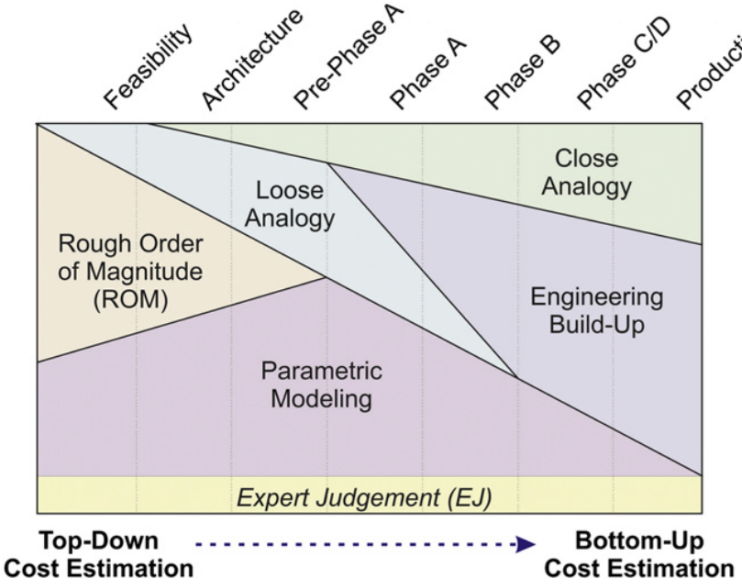


Figure 1.2: Cost Estimating Methods applied per project phase. Parametric estimates feature prominently in early estimates, and form the basis of the research estimate to be developed [94]

Throughout all program phases, traditional CEMs are often complemented by Expert Judgement (EJ) opinions [108] that critically nuance a model's assumptions, inputs and outcomes. Also in this case, the expert opinions of *TEC-SYC*'s Georg Reinbold, Michel van Pelt, and Hervé Joumier were generously available for consultation during the development of this early phase parametric cost model.

Mass as a Parameter

Many different parameters are used in parametric cost modeling, and can range from performance and physical parameters such as power requirements and volume, to programmatic parameters that address issues related to the way programs are operated [11]. Ideally, an independent variable or "cost driver" should be selected as a parameter, because there is a strong relationship between these parameters and cost [69]. Mass is a very logical choice for a free variable cost driver, because it is a parameter that is available and worked with throughout the entire design process [38]. This is why mass is featured centrally in all estimating tools, and will also be central to the parametric estimate developed here.

1.2.5. Tools and Methodology

As highlighted previously, Koelle's TRANSCOST is the only publicly available tool to perform a cost estimate with [13]. It is however not preferred to rely on that tool for an estimate, because it was proven to overestimate costs for small launch vehicles [97]. Therefore this reliance is kept to a bare minimum. Wherever it is inevitable to use this tool, it should be checked for its applicability to small launchers. TRANSCOST separates recurring costs from non-recurring costs in a useful way however. *Development* costs are non-recurring, and *manufacturing*/*operations* costs are recurring costs per launch vehicle [45]. The way these three elements are combined into a cost and price per flight is a useful approach taken in TRANSCOST that will be employed here.

Flight Unit Methodology

In order to keep reliance on the TRANSCOST model to a minimum, another way of transparently approximating the methane vehicle's costs was identified: the development and manufacturing costs can be estimated by employing a parametric costing method based on the concept of a *Flight Unit* (FU, NASA), also termed the *Theoretical First Unit* (T1, ESA/NASA).

This approach is one of two methods proposed by Mandell [34] to estimate costs in early phases[2]. It is also common practice to use a subsystem or system T1 as a basis within tools such as NAFCOM [71] and *TruePlanning*, and it is also a way of estimating applied extensively at the European Space Agency and NASA [69]. 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 [58, 82].

The approach first involves establishing the cost of a first theoretical production unit, the T1/FU costs, which is derived by costing individual hardware elements with data-driven CERs, and combining these for the entire rocket. This step in the methane concept's estimate will in fact be done in Chapter 2. Then, the non-recurring costs of developing the rocket are approximated using the FU/T1. To achieve this, typical expenditures on System Test Hardware (STH) and Design and Development (DD) engineering work in the development phase are described as a function of the T1. These *T1 Equivalents* and the assumptions they rely on feature in Chapter 3. It is 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. This process is highlighted in Chapter 4.

Finally, it is not possible to define a T1 equivalent for the launch and operations phase of a rocket, so Chapter 5 uses TRANSCOST to estimate these costs. Naturally, it may only be applied if it is not prone to the earlier discussed overestimation for small rockets in found in [97], so this method is also tested accordingly before assumed as valid.

Once the development, manufacturing and operations cost estimates are completed, a Cost per Flight (CpF) and cost-based Price per Flight (PpF) can be established, with which the vehicle's cost and pricing can be compared to its closest competitors and typical values found in literature. This is the subject of Chapter 6, and will be the final step towards answering the research question and achieving the research goal. The entire proposed estimating process is shown graphically in Figure 1.3.

As there is no information on the data spread of the TRANSCOST CER's, the PpF will not feature an uncertainty range in this research. This is why also the research question accuracy is based on a *point estimate*. Of course ideally a method should be used that does provide these operating cost uncertainties, which is left as a recommendation for future work. In that case, also the CMA at 1σ can be evaluated against reference case PpF figures. For now however, in lieu of developing the necessary cost estimating framework for assessing new systems' costs, the Flight Unit uncertainties will be assigned to the final PpF directly. More information on this procedure can be found in Appendix A.

[2] The other method suggests attempts to normalize the state of development and also the development culture [34] within a firm into an estimate. This approach was not chosen, as an approximation for the development culture of a commercially operating company would be difficult to synthesize within the European Space Agency framework of this thesis

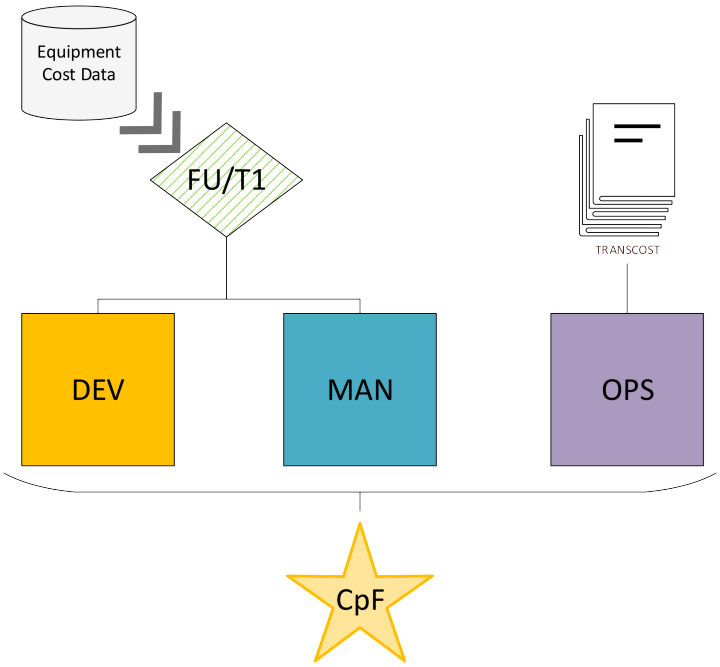


Figure 1.3: Cost per Flight (CpF) estimating process proposed for this research, which uses data-driven CERs converted into T1 Equivalents [34, 71, 82] to approximate development (DEV) and manufacturing (MAN) costs, and TRANSCOST [45] to establish a baseline operations (OPS) effort

Method Adaptations

Equipment-level T1 Equivalents and the TRANSCOST method will be combined in a single estimate for the very first time in this research. It will also be the first time these are applied to small, commercially produced vehicles.

Even though TRANSCOST includes suggestions to take commerciality into account, this research will have to prove that the operations CERs developed by Koelle still hold for small vehicles. It will also have to adapt the T1 Equivalents process of costing, which was developed within agency frameworks, to the new paradigm of commercial rocketry outside of the agency scope. If successful, these adaptations will prove a significant contribution to cost estimating theory that will allow the costs of a new class of systems to be evaluated in the future.

The entire model developed within this research will be referred to as SOLSTICE; Small Orbital Launch Systems, a Tentative Initial Cost Estimate.

Ground Rules and Assumptions Every estimate should be accompanied with a list of Ground Rules and Assumptions (GRA's) under which the approximation holds [69]. Instead of including these in the introduction as customary, these will for the sake of brevity be included in Appendix A.

Study Limitations

This study will be subject to limitations that hold for all cost estimates. Especially early phase estimates have a higher degree of uncertainty compared to later phase ones [94]. This is because an approximation of the total program's cost must be made based on development and manufacturing assumptions, such as the amount of system test hardware, that actually differ significantly from launcher program to program. The most an estimator can do in this case is to approach the problem in a transparent fashion, and that is why many of these assumptions remain fixed and constant throughout the research text. In this way, an emphasis can be put on further developing and adjusting the parametric early phase costing methods to suit these particular launch vehicles.

2

Flight Unit Cost Estimate

Following the methodology outlined in Section 1.2, first the Theoretical First Unit (T1, ESA) or Flight Unit (FU, NASA [70]) costs will be determined on an equipment level.

First, this chapter will break down a launch vehicle into equipment level elements in Section 2.1. For each of these elements, a point estimate with corresponding uncertainties is made, which is constructed based on historic cost estimating relationships which link mass to cost. This point estimate with uncertainties is determined in Section 2.2 The total cost is built up by summing all point estimates. Also, a final uncertainty value on the total FU costs is determined statistically. The total Flight Unit cost estimate is shown in Section 2.3. Flight Unit costs in this chapter will be augmented with modifiers that approximate commercial development in Chapters 3 and 4.

By fitting standardized NAFCOM cost/mass coefficients to the aforementioned historical data, an alternative cost estimate is derived that can serve both as a sanity check on the produced equipment regression curves, and a replacement to curves who lack sufficient data to pass significance tests that will be detailed here too. The point estimates made are outlined in Tables 2.7 and 2.8, and corresponding standard errors (1σ) are listed under Appendix I in Tables I.2 and I.1, both based on regression curves and on NAFCOM values, referenced in Appendix H. [88]

2.1. Launch Vehicle Equipment Breakdown

In this section, typical launch vehicle equipment level parts are identified. These are summarized in Table K.1 in case the launch vehicle is liquid propelled, and shown in Table K.2 when the launch vehicle has solid propellant. By distinguishing between solids and liquids on a "stage" level only, a FU cost estimate of a multi-staged liquid-solid rocket can also be achieved in a straightforward fashion by adding the differing stages' cost together. The main difference between both stage estimates is that the liquid propelled rocket is broken down into more detail than the solid. This is because cost data is also available for solid stages as a whole.

Each *part* is provided with a unique ID, which depends on the *unit* and *equipment* it belongs to. For example the stage "Thermal Control" part *S-SS-THM* is a subordinate to the "Stage Structure" equipment *S-SS*, which is itself integrated into the "Stage" unit *S*. A description of what is included and what isn't included is shown in Table E.3.

For each of the equipment elements a parametric cost estimating relationship (CER) is set up which links mass to equipment cost.These will be used to construct a single point cost estimate for the entire launcher system. The way a single equipment level CER is derived is shown in the next section, with the solid rocket stage casing *S-SC-* as an example.

2.2. Equipment Level Estimates

This section will show how data points are used to construct a CER for an equipment element of the rocket, and how alternatively a NAFCOM CER can be used in the absence of enough data [88]. The method is illustrated by setting the Solid Casing *S-SC-* as an example, and deriving its CER. A similar procedure is followed for all breakdown elements, all of which have their regression curve CERs listed in Appendix E. It is assumed the range that CERs derived are applicable is between the lowest and highest mass components used as input data points. These data points are shown in Appendix L, and the CERs' applicable ranges are outlined in Table

Table 2.1: Solid Launch Vehicle Breakdown

Unit	Equipment	Part	Part ID
Stage	Solid Casing (incl. nozzle)		S-SC-
	Thrust Vector Control		S-TV-
	Stage Harness		S-SH-
Interstage	Interstage Structure		I-IS-
Payload	Payload Adapter		P-PA-
	Payload Fairing		P-PF-
Avionics	Avionics	Comms	A-AV-COM
		Power	A-AV-PWR
		Data Handling	A-AV-DHL
		GNC	A-AV-GNC
		Avionics Harness	A-AV-HNS
Attitude Control	Attitude Control Module		C-AC-

Table 2.2: Liquid Launch Vehicle Breakdown

Unit	Equipment	Part	Part ID
Stage	Pressurizant Tank		S-PT-
	Fuel Tank		S-FT-
	Oxidizer Tank		S-OT-
	Stage Structure	Thrust Cone	S-SS-TRC
		Skirt	S-SS-SKI
		Thermal Control	S-SS-THM
	Engine(s)		S-EN-
	Thrust Vector Control		S-TV-
	Propellant	Fuel	S-PR-FUE
		Oxidizer	S-PR-OXI
		Pressurizant	S-PR-PRE
	Pressurization System		S-PS-
	Pipes & Valves	Pipes	S-PV-PIP
		Valves	S-PV-VAL
	Stage Harness		S-SH-
Interstage	Interstage Structure		I-IS-
Payload	Payload Adapter		P-PA-
	Payload Fairing		P-PF-
Avionics	Avionics	Comms	A-AV-COM
		Power	A-AV-PWR
		Data Handling	A-AV-DHL
		GNC	A-AV-GNC
		Avionics Harness	A-AV-HNS
Attitude Control	Attitude Control Module		C-AC-

E.2. Later on in this text the Falcon 9 vehicle's costs are estimated as an example of application outside of the scope of the CERs derived. Necessarily also the liquid rocket engine CER will need to be applied outside its underlying data range for the liquid methane concept, because of a lack of cost data on rocket engines of that size smaller than the SpaceX's Merlin engine. However, costs for such a size engine were verified internally at ESA to keep the estimate consistent.

2.2.1. Equipment Level Point Estimates

Achieving a cost estimate for commercial launch vehicles requires the set up, through regression, of individual CERs based on historic data for each equipment system. As mentioned in Appendix A on assumptions, all cost estimating relationships are assumed to follow a power curve without constant coefficient which is widely used as a way of representing costs versus system mass [45, 82], in the form of:

$$C = a \cdot M^b \tag{2.1}$$

This might not necessarily be the best regression fit for historical mass and cost data points of different equipment on the launch vehicle, but it does allow the resulting power curve to be compared to standard NAFCOM curves qualitatively in Appendix L.2.

It is recognized that mass is not the only variable of influence. Also parameters such as volume and power requirements have an impact on cost. Ignoring these parameters and only varying mass, will mean that errors encountered during the regression analysis will include some influences between these independent variables through covariation. For this first estimate these effects are ignored, but performing a multiple regression analysis and checking for multicollinearity is recommended for future work. Ignoring these effects implies the regression errors are uncorrelated and random [1], the last of which means that the individual CERs are homoscedastic, and that an Ordinary Least Squares estimator is a Best Linear Unbiased Estimator through the Gauss-Markov theorem that applies. In turn, the Root Mean Squared Error of the data spread is equal to the square root of the standard deviation: $RMSE^2 = \sigma$.

These equipment level masses will be assumed constant and without uncertainties stemming from technical risk. Errors will therefore not be modeled from a technical risk standpoint. This means uncertainties in cost stemming from uncertainties in final subsystem masses will not be incorporated into each CER. [70, 93]

Also, the regression curve uncertainties which make up the CMA are not (yet) propagated into the three cost estimate phases of development, manufacturing and operations. To arrive at an expected variance in the Cost and Price per Flight results at the end of this research, it is assumed that the CMA found for the Flight Unit is equal to that of the CpF and PpF. For the development and manufacturing phases this makes perfect sense: the T1 Equivalents method assumes a purely linear relationship between the costs of these phases and the FU costs, described only by multiplicative factors and overhead percentages. This means the relative error for these phases is the same as the FU CMA derived analytically. It was also shown in Chapter 5 that operations costs are often assumed as a constant percentage of total recurring costs [45, 73]. So if this direct translation from FU accuracy holds for the manufacturing phase, it will also hold for the second part of the recurring costs: the operations phase. Of course eventually, it is desirable to involve the data spread directly into the program phase estimates, so truly this research will remain a first step of a work in constant progress.

Before these historical data-points can be used, they must be normalized.

Data Normalization

Given cost and mass data on a production unit number (n-th unit), in a specific cost financial year (FY), and with a certain currency (EUR or USD), three normalization steps are performed.

1. Learning factorization involves converting a known n-th unit cost to first unit or FU cost
2. Costs are adjusted for inflation to 2015 Constant Year (CY) costs
3. Dollar quotes are transformed into Euro (EUR)

Learning Factorization to First Unit (FU) cost Given the cost of unit number n, this n-th unit cost is transformed to the FU cost by multiplying by the cost reduction factor L_m outlined in Section 4.1.1 [44, 45], namely $L_m = n^{\frac{\ln p}{\ln 2}}$. p is the learning factor, which dictates how quickly costs are reduced as a function of the number of units produced. For this analysis, the learning factor is frozen to 0.9, or 90% based on research by Fox [22] and considerations further outlined in Chapter 4. It means that with each doubling of the production, unit cost will decrease by ten percent. With the first unit cost of 1, unit two will cost 0.9, unit four will cost 0.81 etc... For a detailed overview of the curve used, refer to Appendix F.

Inflation to Constant Year (CY) cost Unit costs in a specific year were adjusted with inflation factors to reflect CY costs in 2015. NASA figures by Hunt [35] are used if the system price was expressed in US dollars and manufactured in the United States, and OECD data on European Union inflation was used to adjust figures for European manufacturing conditions [76]. European inflation data is not available for years before 1997, so average inflation across the European Union (28 countries) was calculated from individual countries' data where available. Both tables are available in Appendix C.

[1] I.e. uniform, this is checked for in individual CERs

Dollar-Euro Currency Adjustment Finally, dollars are converted to Euros according to 2015 exchange rates (as it is already adjusted for inflation). The exchange rates for other years are taken as averages per year if necessary. These exchange rates are shown in Appendix D [75].

Regression on Data Points

As discussed, regression takes place on all historical data points using the "least squares" method, assuming the data are normally distributed in log-space about the observed mean value for the point estimate. The regression is performed in log-space with Excel's built in LINEST function, where Equation (2.1) is transformed into:

$$\ln C = \ln a + b \cdot \ln M \tag{2.2}$$

This is of the form $y = a_{log} + b_{log} \cdot x$. The coefficients a and b in the power curve are determined from these linear regression coefficients obtained in log-space. More precisely, the output constant a_{log} of the LINEST function is $\ln a$ and the output slope is b. This means that only the a_{log} coefficient needs to be transformed through an exponential operation: $a_{log} = \ln a \rightarrow a = e^{a_{log}}$. The b coefficient is equal to that in log-space.

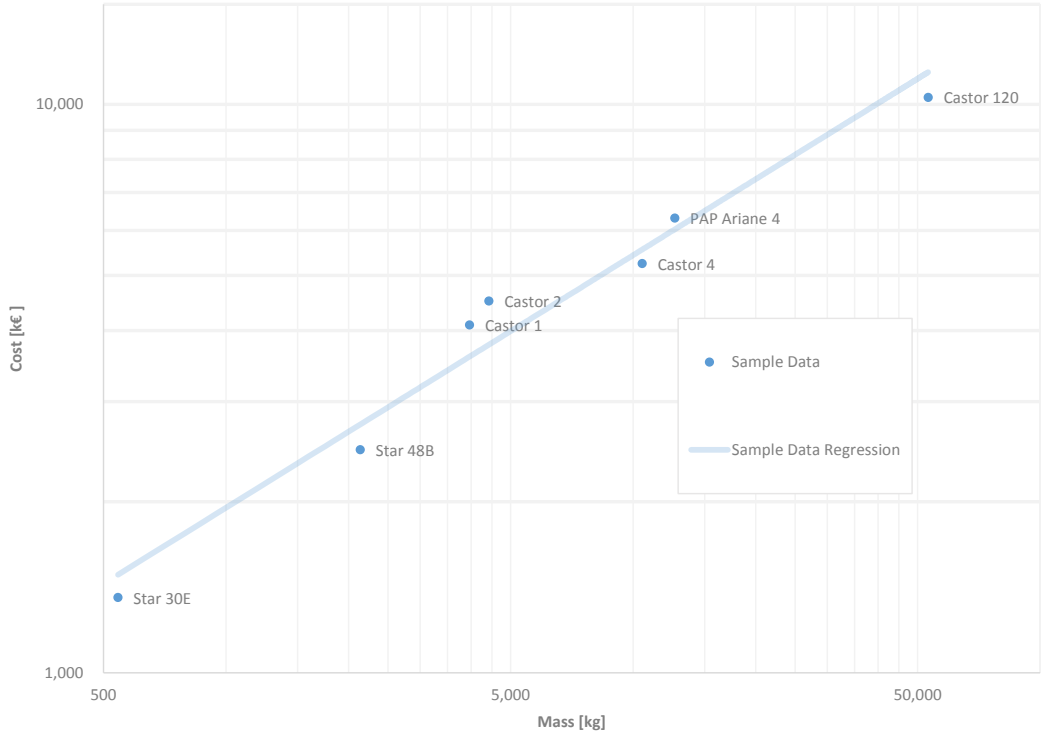


Figure 2.1: Linear regression in log-space for solid rocket stages including propellant, *S-SC-*

The resulting regression, which is exemplified for solid stages in Figure 2.1, is also performed for all *equipment* elements in Table K.2 and Table K.1. The statistics for the solid casing example *S-SC-* regression are listed in Table 2.3 in k€. For all equipment elements that make up the FU cost, the regression curves are shown in Appendix L.2. The a and b values of the regression curves derived for all subsystem elements feature in an overview in Appendix E.

There are two coefficients to determine, and 7 data points, which leads to 5 degrees of freedom. The F statistic is used to indicate whether the relationship between mass and cost occurs by chance, as explained below. Standard errors of the regression coefficients a and b are also given Table 2.3. The R^2 value indicates how close the data fits the regression line, with values closer to one better.

Most statistics are listed in log-space, because the assumption that the costs are normally distributed in log-space requires the equipment cost standard errors to be joined together into a total system cost estimate in log-space as well.

Table 2.3: Solid rocket stage (S-SC-) regression statistics (Figure 2.1)

Statistic [kg k€]	**Value *(log)***	**Value**
a-value (aM^b)	4.51	90.73
b-value (aM^b)	0.444	0.444
Standard Error a-value	0.314	-
Standard Error b-value	0.036	-
Standard Error	0.128	-
F Statistic	151.99	-
Degrees of Freedom	5	-
R-squared	0.9682	-

With the a and b values for the regression determined, it is trivial to obtain a point cost estimate for the subsystem. In the example of the solid rocket stage with coefficients listed in Table 2.3, the costs for a 25,000 kg stage are 8.2 M€, shown in Equation (2.3). These point estimates for the first stage of the liquid methane concept, and the regression curves on which they lie, are featured in Appendix L.2.

$$C_{S-SC-} = a \cdot M^b = 90.73 \cdot 25,000^{0.444} = 8,155\text{k€}(500 - 50,000kg) \tag{2.3}$$

Significance Tests The regression described previously will make a point estimate for any subsystem possible, as long as sufficient data-points exist to build a CER with. Whether or not these are sufficient is determined by performing the two significance tests here. But is it possible to say whether the relationship between the points plotted in Figure 2.1 is significant? What if only two data-points are known? Is it safe to perform a point estimate on the line drawn between these points and say that cost estimate is representative of a whole class of subsystems? To answer these questions a test of the observed t-values, and the second of the F statistic is performed.

The first test determines whether or not the coefficients of the regression curve are adequate to estimate costs for the subsystem. Because the estimates are samples, and the underlying distributions are assumed to be normal with unknown mean and standard deviation, the samples will follow a student's t-distribution [28]. The tests involve evaluating the observed t-values of the regression, and accepting the a and b coefficients when their t-values are higher than the critical t-value on the student's t-distribution [107]. The observed value of the t-statistic for both coefficients is simply their values divided by their standard errors in Table 2.3. For this research it is deemed acceptable if there is a 5% chance of incorrectly accepting the coefficients a and b. Although this value was chosen because of its common usage, care is taken not to use this as a distorting license to implied truth [99]. It is in this case only a user-defined way of demarcating a choice for another method. The 5% means that the critical t-value is obtained from a two-tailed inverse student's distribution for the regression's degrees of freedom at that percentage. The example solid rocket stage subsystem has 7 data-points, and 5 degrees of freedom, so the critical t-value in a two-tailed student's t distribution is $T(5) = 2.57$ from standard t distribution tables. Table 2.4 gives an overview of the observed and critical t-values, where it is clear that both a and b coefficients pass the test because their t-values are higher than the critical one.

Table 2.4: Solid Rocket Stage t-value significance test

Coefficient	**Value**
t_{obs}(a)	14.36
t_{obs}(b)	11.67
t_{crit}	2.57

The second test of the F statistic will inform whether the relationship between mass and cost occurs by chance. Of course if it did, then the resulting CER would not yield a relationship worth using. In the F distribution, the probability of a higher F value (stronger relationship) is determined with $\nu_1 = n - dof - 1$, and $\nu_2 = dof$, where n is the number of samples or data-points, and dof the degrees of freedom. Again, this research requires a definition of a threshold at which this chance is no longer negligible. For simplicity that threshold will again be held at 5%. In the solid stage example $\nu_1 = 1$, $\nu_2 = 5$, and the chance of a higher F-value occurring (i.e. a better fit) than 151.99 is $1.217 \cdot 10^{-5}$, which is significantly less than 5%.

Trough both tests, the a and b regression coefficients have been tested for significance, and the relationship between mass and cost established to be non-coincidental. These test are performed on all subsystem CERs that were derived. If however a certain dataset does not pass these significance tests, for example due to the fact that not enough publicly available data-points to construct the CER are available in the first place, there is an alternative method to construct a CER. This is done by using NAFCOM b values, through which a relationship can be derived even with only one data-point [88].

Data-driven CERs and their regression curves are listen in Appendix L.2; each curve also shows whether or not both significance tests outlined above were passed. If these are, then the data-regression curve is used. If the tests are not passed, the NAFCOM CERs are used as the gathered data is not coherent enough. This is also shown in Appendix E, where the a and b values of the regression and NAFCOM curves are listed.

Alternative NAFCOM CERs

The NASA Air Force Cost Model Database provides b values featuring in Equation (2.1), that are based on extensive underlying historical cost databases. These values are listed in Appendix H. With the cost and mass of a single subsystem known, an a value for that subsystem can be derived, with which a cost curve can be constructed [88]. If multiple points are known, an average a value is computed with which a curve is made. This methodology is employed if subsystem estimates do not meet 5% significance criteria of t- and F-tests.

However, all coefficients in Table H.1 are in lbs and dollars. Using the cost power equation $C_{\$} = a^* \cdot M_{lbs}^b$, and taking the exchange rate from Euro to USD to be r_e, a*-value coefficients may be adjusted a values in Euros and kilograms through Equation (2.4). That being said, b values stay identical to those in NAFCOM.

$$C_{EUR,kg} = \frac{a^*}{r_e} \cdot 2.20462^b \cdot M_{kg}^b \rightarrow a = \frac{a^*}{r_e} \cdot 2.20462^b \tag{2.4}$$

The power regression curve belonging to the NAFCOM b values is plotted in Figure 2.2 alongside the regression curve for the *S-SC-* solid stage equipment.

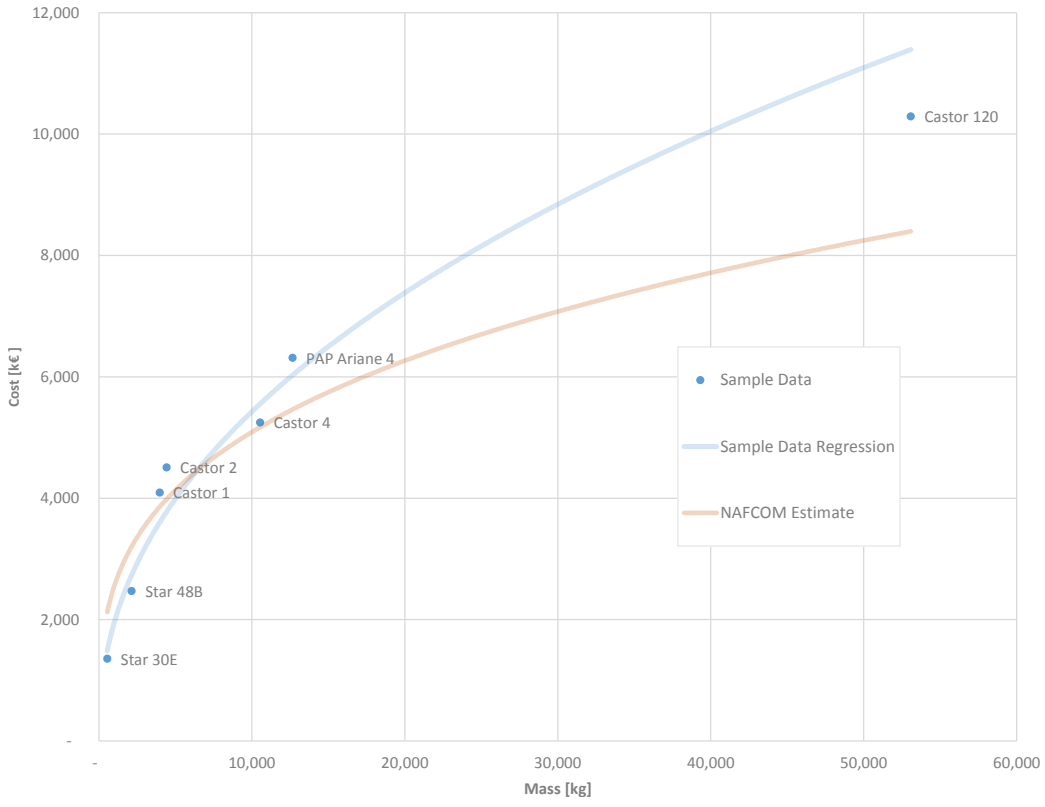


Figure 2.2: Power regression and NAFCOM alternative curve for solid rocket stages

The coefficients of this example NAFCOM mass-cost curve are $a = 321.13$ and $b = 0.3$ consistent with Table H.1. The point estimate for a 25,000 kilogram solid rocket stage are shown in Equation (2.5). This quite different from the estimate using regression data, but falls near the standard error bounds that result from the regression spread in Table 2.5. The uncertainties from the NAFCOM curve in Table 2.6 also almost include the point estimate of the regression.

$$C = a \cdot M^b = 321.13 \cdot 25,000^{0.3} = 6.7\text{M€} \tag{2.5}$$

NAFCOM curves for all different equipment elements are also shown in Appendix L.2. NAFCOM a and b values are also featured in Appendix E.

2.2.2. Equipment Level Uncertainty Estimates

With the point estimate for all subsystems found, the uncertainties of this estimate due to the dispersion of the gathered data-points on the regression needs to be determined. Also, the uncertainties in the NAFCOM Alternative CERs are modelled from the variances in exponent b values pre-provided in Table H.1.

Regression Uncertainties

Under the assumptions listed in Appendix A, the errors are both normally distributed in log-space and homoscedastic, which means the errors in the developed CERs are not correlated and are random (i.e. uniform). This means Ordinary Least Squares (OLS) regression is the best linear unbiased estimator (BLUE) under the Gauss-Markov theorem [112]. Also, because this analysis applies to sampling, the standard deviation (SD) of the population around the regression curve derived from the sample is termed the standard error (SE), however the terms SE and SD are used interchangeably here.

The SE of the regression is constant in log-space, but becomes an asymmetrical percentage in normal space. To illustrate this point, consider the log-space standard error σ, and its addition and subtraction on the natural logarithm of the point cost estimate C. Equation (2.6) and Equation (2.7) transform the definitions of upper and lower cost bounds C_{upp} and C_{low} into fractions, then into percentages.

$$\ln C_{upp} = \ln C + \sigma \rightarrow C_{upp} = C \cdot e^{\sigma} \rightarrow \left(\frac{C_{upp}}{C} - 1\right) \cdot 100\% = \left(e^{\sigma} - 1\right) \cdot 100\% \tag{2.6}$$

$$\ln C_{low} = \ln C - \sigma \rightarrow C_{low} = \frac{C}{e^{\sigma}} \rightarrow \left(\frac{C_{low}}{C} - 1\right) \cdot 100\% = \left(\frac{1}{e^{\sigma}} - 1\right) \cdot 100\% \tag{2.7}$$

This means that there is a constant standard deviation σ in log-space, which results in a percentage change on the regular scale. For the upper bound the percentage change is $e^{\sigma} - 1$ and for the lower bound it is $\frac{1}{e^{\sigma}} - 1$. This way, the upper and lower bounds of the costs are determined from the SE. Table 2.5 shows the values for upper and lower values of the standard error cost estimate for the solid rocket stage example *S-SC-*. The logarithmic standard errors per subsystem element are listed in E.

Table 2.5: Upper and lower Standard Error bounds for the *S-SC-* regression equipment estimate

Cost Parameter	**Value** [k€]	**Percentage change**
C_{upp}	9,271	13.7%
C	8,155	
C_{low}	7,173	-12.0%

NAFCOM Uncertainties

If not enough data points are available for the regression to pass significance tests, NAFCOM point estimates are used. The corresponding uncertainties can be modelled with NAFCOM tables which also provide the variance of b values associated with the power curve exponents in the database (Table H.1 [88]). These b values are varied over their standard deviation range for each data-point, and afterwards an average a value for upper and lower σ cases is obtained. This average a allows for the redrawing of the corresponding NAFCOM curves. The range of b values' standard deviations are shown in Figure 2.3 for the solid stage *S-SC-* example.

A 25,000kg solid stage case point estimates with uncertainties at one standard deviation according to NAFCOM, are listed in Table 2.6.

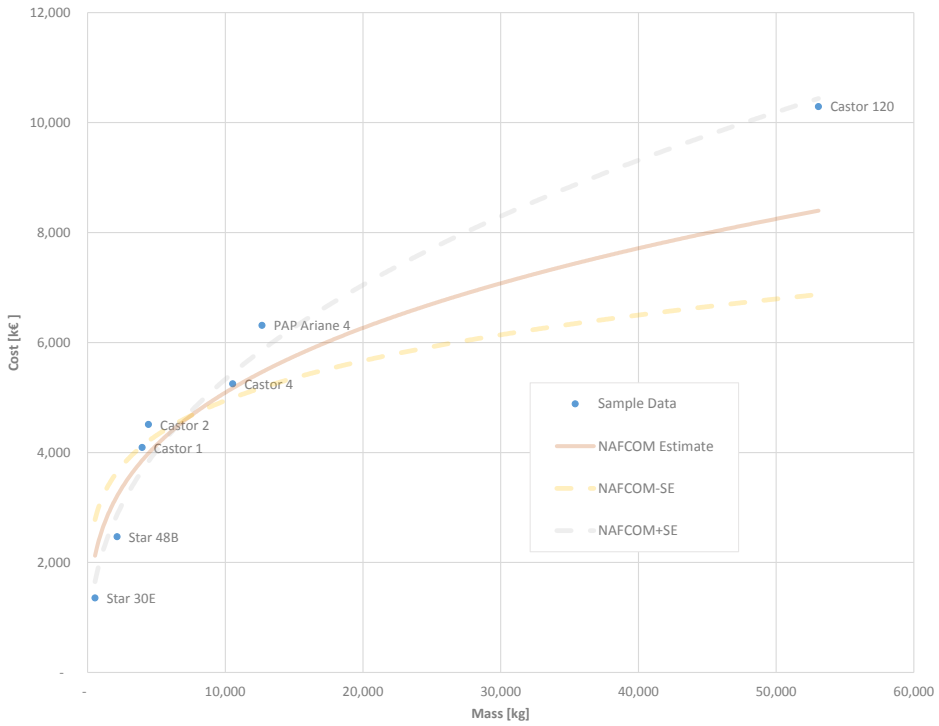


Figure 2.3: Standard Error of NAFCOM alternative CER. The variance in b-values given by NAFCOM causes the uncertainty standard error lines to cross

Table 2.6: Upper and lower Standard Error bounds for the *S-SC-* NAFCOM equipment estimate

Cost Parameter	**Value** [k€]	**Percentage change**
C_{upp}	7,709	15.1%
C	6,700	
C_{low}	5,923	-11.6%

The RSE upper and lower bounds for the regression in Table 2.5 are comparable to those found for NAFCOM in Table 2.6. For the regression curves and where necessary the NAFCOM curves, the point estimates are included in Tables 2.7 and 2.8, and the uncertainties are shown in Tables I.2 and I.1 for each equipment breakdown element in Table K.1 and Table K.2.

2.3. Flight Unit Cost Estimate

This section will illustrate the way FU point estimate is obtained from the individual subsystems' point estimates. It will also show how a total modeling uncertainty is derived from the individual subsystems' uncertainties.

2.3.1. Flight Unit Cost Point Estimate

The total FU point estimate, which will serve as a basis for the development and manufacturing phase cost estimates, is simply the sum of all individual cost contributions in the point estimates from each subsystem. This estimate naturally takes into account the number of times each element is used in the launch vehicle. At this point it is worthwhile to investigate the way the cost of the conceptual liquid methane rocket concept, introduced in Section 1.1.2, is built up. This build-up is shown in Table 2.7 for Stage 1 and the Payload, Avionics and Attitude Control Module (PAA).

The second stage costs are accumulated in a similar fashion to stage one in Table 2.8. Additionally, the choice for the Integration & Test overhead percentage is highlighted in Section 4.1.2 within the manufacturing phase cost specification of Chapter 4. The upper stage avionics that remain with the rocket throughout its

Table 2.7: Liquid Methane Concept Flight Unit Cost for Stage 1. The I&T percentages are derived in Chapter 4

Unit	Equipment	Part	Part ID	Mass [kg]	Number	FU [k€]
Stage 1		*Liquid Stage*		**5,778**		**36,867**
	Solid Casing		S-SC-	-	-	-
	Press. Tank		S-PT-	103	1	543
	Fuel Tank		S-FT-	727	1	2,187
	Oxidizer Tank		S-OT-	873	1	2,492
	Stage Structure					
		Thrust Cone	S-SS-TRC	180	1	319
		Skirt	S-SS-SKI	656	1	1,038
		Thermal Control	S-SS-THM	24	1	51
	Engine(s)		S-EN-	250	12	29,315
	TVC		S-TV-	113	1	606
	Press. Syst.		S-PS-	-	-	-
	Pipes & Valves					
		Pipes	S-PV-PIP	65	1	158
		Valves	S-PV-VAL	30	1	93
	Stage Harness		S-SH-	7	1	65
Payload				**250**		**1,365**
	Payload Adapter		P-PA-	50	1	402
	Payload Fairing		P-PF-	200	1	963
Avionics				**67**		**2,412**
	Avionics					
		Comms	A-AV-COM	26	1	696
		Power	A-AV-PWR	28	1	599
		Data Handling	A-AV-DHL	13	1	1,116
		GNC	A-AV-GNC	-	-	-
		Avionics Harness	A-AV-HNS	-	-	-
Attitude Control				**51**		**4,921**
	ACM		C-AC-	51	1	4,921
I&T				**3.2%**		**1,440**
	Stage I&T		I&T		1	1,165
	PAA I&T		I&T-P-		1	275

flight are included within Stage 1 of the estimate because the vehicle will have at least one stage, and will always require this avionics package. It is something born of convenience to be able to disable the second stage without the need to re-include this avionics package in the first stage estimate.

2.3.2. Flight Unit Cost Modeling Accuracy

A proper estimate will always feature a description of the degree to which the estimate is valid, in the form of uncertainty statistics. It is termed the Cost Modeling Accuracy (CMA), and will be determined here in the 1 σ range. It is not to be confused with the desired accuracy defined in the research question, which is the degree a point estimate approximates a reference case's actual costs. CMA uncertainty is based on each individual subsystem element's standard error of regression (or NAFCOM standard error when selected) which are listed in Table I.2 for the first stage, and Table I.1 for the second stage of the vehicle in Appendix I. To simply sum these errors into a total stage uncertainty would be incorrect, because when errors propagate they include a covariance term, which depends on the amount of correlation between the elements.

Take the function $f = A\bar{x} + B\bar{y}$, where A and B are constants, and $\bar{x}$ and $\bar{y}$ each have standard deviations $\sigma_{\bar{x}}$ and $\sigma_{\bar{y}}$ respectively. The total standard deviation of f is shown in Equation (2.8).

$$\sigma_f = \sqrt{A^2\sigma_{\bar{x}}^2 + B^2\sigma_{\bar{y}}^2 + 2AB\sigma_{\bar{x}\bar{y}}} \tag{2.8}$$

$\sigma_{\bar{x}\bar{y}}$ is the covariance between x y. The covariance can be further decomposed as in Equation (2.9).

$$\sigma_{\bar{x}\bar{y}} = \rho_{xy}\sigma_x\sigma_y, \tag{2.9}$$

$\rho_{xy}$is the correlation between x and y, and has a value between $[-1;1]$ [47]. Negative correlation implies an inverse relationship while a positive one indicates variability in the same direction.

What does this mean in practice? It means that each individual element's cost $(\bar{x},\bar{y}...)$ must be multiplied by the number of times this element is reused in the rocket $(A,B...)$ and multiplied by the matrix correlating the element costs together, leading to the variance. The square root of this variance is the standard error. Most of the terms are already known, save for the so-called correlation matrix containing inter-element ρ's.

Table 2.8: Liquid Methane Concept Flight Unit Cost for Stage 2. The I&T percentages are derived in Chapter 4

Unit	Equipment	Part	Part ID	Mass [kg]	Number	FU [k€]
Stage 2	*Liquid Stage*			**1,740**		**6,955**
	Solid Casing		S-SC-	-	-	-
	Pressurizant Tank		S-PT-	45	1	300
	Fuel Tank		S-FT-	611	1	1,932
	Oxidizer Tank		S-OT-	168	1	770
	Stage Structure					
		Thrust Cone	S-SS-TRC	50	1	100
		Skirt	S-SS-SKI	516	1	834
		Thermal Control	S-SS-THM	8	1	19
	Engine(s)		S-EN-	250	1	2443
	Thrust Vector Control		S-TV-	49	1	365
	Pressurization System		S-PS-	-	-	-
	Pipes & Valves					
		Pipes	S-PV-PIP	20	1	70
		Valves	S-PV-VAL	15	1	58
	Stage Harness		S-SH-	7	1	64
Interstage				**25**		**60**
	Interstage Structure		I-IS-	25	1	60
Stage I&T				**3.2%**		**222**
	Stage Integration & Test		I&T		1	222

Intuitively this reasoning also makes sense because the size of some elements will invariably be dependent on the size of others. For example a larger stage mass will require a larger engine to propel it forward. More on this reasoning below.

Correlation

Correlating the logarithmic standard errors in Tables I.2 and I.1 in their current form is not possible. Summing an error term in log-space will lead to an unrealistically high cost modeling accuracy.

Lognormal Transformation The standard errors are transformed arithmetically, with the arithmetic [93] mean being $E[X]$ in Equation (2.10).

$$E[X] = e^{\mu+\frac{1}{2}\sigma^2} \tag{2.10}$$

Where the logarithmic mean μ is the elements' point estimate in log-space, and σ their logarithmic standard error. From this mean, the arithmetic standard deviation [93] follows in Equation (2.11).

$$SD[X] = E[X]\sqrt{e^{\sigma^2}-1} \tag{2.11}$$

For example the arithmetic mean cost for the pressurizant tank is 564k€, slightly higher than the mean of 543k€. Intuitively, this makes sense because the lognormal cost distribution is skewed upwards, so the arithmetic mean was expected to be higher than the mean, which is converted directly from the normal distribution in log-space. The standard error (or alternatively the standard deviation of the lognormal cost distribution) of the pressurizant tank is 156k€.

The transformed standard errors according to Table 2.5 are graphically illustrated in Figure 2.4 along with the data regression for the example *S-SC-* case. If another confidence interval percentage is desired, the model has also been adapted to determine the upper and lower bounds for this interval. For example, an 80% confidence interval will have an upper bound of 9.6M€, and a lower bound of 6.9M€.

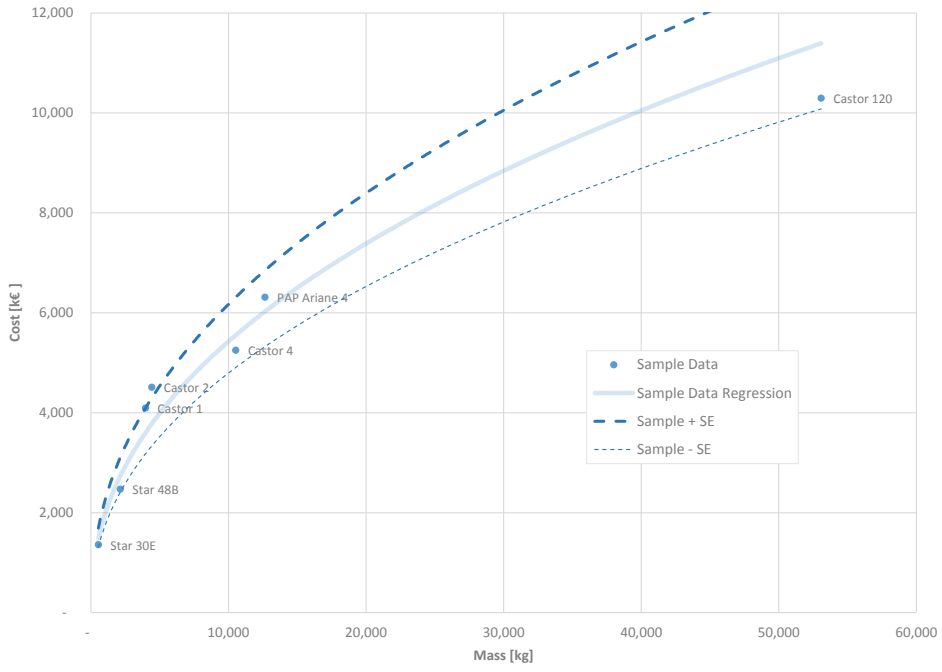


Figure 2.4: Standard Error of regression for the solid stage example

Determining the relative error arithmetically, is similar to determining the Relative Standard Error (RSE) of the data spread, with the addition of accounting for a skewed lognormal distribution corresponding with a 1σ uncertainty. For example for the *S-SC-* equipment, if the data were normally distributed, the RSE is

determined with Equation (2.12), where n is the number of data points (7), m the number of coefficients in the regression (2) and $\frac{y_i}{f(x_i)}$ the ratio of observed versus modeled costs for each data point.

$$RSE_{S-SC-} = \sqrt{\frac{1}{n-m}\sum\left(\frac{y_i}{f(x_i)}-1\right)^2} = 13.2\% \tag{2.12}$$

The RSE tells us that there is a 1σ chance that the actual values lie within the predicted range of ±13.2%. However, the distribution is skewed upwards lognormally, so the symmetric uncertainty range is distorted into the true unsymmetrical range from Table 2.5. In fact, the Relative Standard Error in arithmetic terms, referring to Equation (2.11) and using the lognormal standard error σ from Table 2.3, is:

$$\frac{SD[X]}{E[X]} = \sqrt{e^{\sigma^2}-1} = \sqrt{e^{0.128^2}-1} = 12.9\% \tag{2.13}$$

It is the RSE that will be referred to when discussing the so-called Cost Modeling Accuracy (CMA), a concept explored further on in the chapter.

Correlation Coefficients With no functional relationships between the element masses defined, there is no direct way to obtain the inter-element correlation coefficients through calculation. However, when it is suspected that the cost estimates' independent variables are correlated, a constant inter-element correlation may be selected to reflect it. This principle, introduced by Steve Book, is informally termed the *knee-in-the-curve* method. It involves selecting a fixed value for the correlation ρ between all elements of a system. Most commonly used when lack of time or information precludes deriving the correlations between program WBS element costs [26], this rule-of-thumb is reflected in the plot of total theoretical percentage underestimation of total cost standard deviation if correlation is assumed to be zero instead of its true value ρ [9] in Figure 2.5.

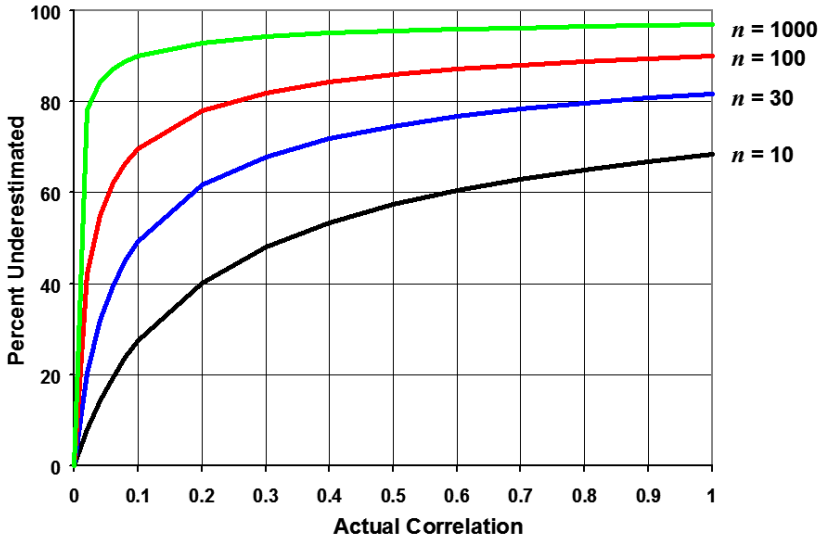


Figure 2.5: Theoretical maximum underestimation of percent total cost standard deviation by assuming zero correlation, all variances σ^2 equal for the number of elements correlated n [9]

If all elements of the two-stage liquid methane concept were correlated with each other, with 21 elements on the first stage and 14 on the second making a total of 35 elements. From Figure 2.5 would lead to a 65% underestimation of the actual standard deviation if the actual degree of correlation was 0.2. After about roughly 0.2-0.3, the least change in underestimation of the total standard deviation occurs. Therefore, if it known a priori that a certain amount of correlation exists, it is always better to select a value after the *"knee"* of the curve than it is to completely ignore this correlation and risk severe underestimation of the total standard deviation. Doing so will capture a substantial amount of cost variance over doing nothing [9]. While Covert [8, 9] advises filling an inter-element correlation matrix with a fixed value of 0.2, the Cost Schedule Risk and Uncertainty Handbook (CSRUH) [93] recommends 0.3. However the ESA Cost Engineering - Cost Risk Procedure [16] recommends filling the correlation matrix with a value of $\rho_0 = 0.2$, which will be used in this research. The effect on the final FU uncertainty of selecting $\rho_0 = 0.3$ instead of 0.2 in the specific case of the launch

vehicle is 1.5% more uncertainty (higher standard error) due to more correlation between subsystems. This difference is less than the maximum error in Figure 2.5 between 0.2 and 0.3 at $n = 30$ approximately, as not each subsystem variance is equal, and also because some elements are not assumed to correlate with each other, see Table I.3.

Correlation Methodology Cost estimate uncertainties are correlated per subsystem element group. After that the total CMA is approximated by the way these groups relate to each other. On the one hand this makes assigning the correlation coefficient between elements easier, avoiding the need to assess the correlation between seemingly unrelated system elements from different element groups. The way these groups correlate can be approximated in a straightforward fashion as will be seen later. However, as a constant correlation coefficient is chosen according to the *knee-in-the-curve* rule of thumb, this advantage is of minor importance. Of more importance on the other hand is that using this approach, one obtains a useful cost risk breakdown on a subsystem group level. High risks on such levels can indicate an area where the risk assessment is to be improved.

As an example, the correlation matrix for the stage 1 *Tanks* element group, which consists of the pressurizant tank, fuel tank and oxidizer tank, is shown in Table 2.9, with ρ_0 equal to 0.2. Of course the correlation of an element with itself on the diagonal is 1.

Table 2.9: Correlation matrix of pressurizant, fuel and oxidizer tanks

	S-PT-	S-FT-	S-OT-
S-PT-	1	0.2	0.2
S-FT-	0.2	1	0.2
S-OT-	0.2	0.2	1

An example of how this correlation matrix is used to determine the *Tanks* group standard error for the first stage is shown in Equation 2.14, with the individual element standard errors being $SD_e = \begin{bmatrix} SD_{S-PT-} \\ SD_{S-FT-} \\ SD_{S-OT-} \end{bmatrix}$

$$SD^2_{tanks} = SD_e^T \cdot \rho_{tanks} \cdot SD_e = \begin{bmatrix} 156 & 627 & 714 \end{bmatrix} \cdot \begin{bmatrix} 1 & 0.2 & 0.2 \\ 0.2 & 1 & 0.2 \\ 0.2 & 0.2 & 1 \end{bmatrix} \cdot \begin{bmatrix} 156 \\ 627 \\ 714 \end{bmatrix} \rightarrow SD_{tanks} = 1,090\text{k€} \quad (2.14)$$

Flight Unit Point Estimate and Uncertainty

Table 2.10 includes element correlation groups and their lognormal standard errors $SD[X]$, along with their arithmetic equivalent of the mean point estimate $E[X]$, together with the percentage error.

This arithmetic percentage error is roughly equivalent to the average of lower and upper standard error bounds as shown in Table 2.5, while the lognormal point estimate is only slightly above the true point estimate. It will not be elaborated on further here, but it is right to keep this in mind. To this aim, a tornado [93] chart Figure 2.6 of the relative standard error percentage in the true point estimate provides a good overview of the cost risk in certain areas. It is skewed because of the lognormal cost distribution. As can be seen a high cost uncertainty exists for the attitude control subsystems group.

However the absolute deviation of the subsystems groups' estimates lends a more nuanced interpretation to this error, as seen in Figure 2.7.

All group error estimates are combined into a total stage error estimate through an inter-group correlation matrix featured in Appendix I, Table I.3. The total procedure to obtain an FU cost estimate for each stage is identical to that of the element groups. Point estimates and their uncertainties are featured Table 2.11.

Finally, the stages are assumed to vary in size with each other, and are correlated together for a whole launch vehicle flight unit CMA estimate. Again the standard correlation coefficient is taken to be $\rho_0 = 0.2$. This is listed in the summary Section 2.5, Table 2.12.

It should be noted that the uncertainty determined for the cost estimate is only the Cost Modeling Accuracy (CMA), which is itself part of a wider range of project cost risk contributors whose contributing factors are listed in Appendix I, in Figure I.1.

Table 2.10: Lognormal flight unit point estimate and standard error per subsystem group

Element	Element Group	SD[X] [k€]		E[X] [k€]		Percentage [-]	
		Stage 1	Stage 2	Stage 1	Stage 2	Stage 1	Stage 2
S-SC-	**Solid Stage**	-	-	-	-	-	-
S-PT- S-FT- S-OT-	**Tanks**	1,090	662	5,417	3,115	20.1%	21.2%
S-SS-TRC S-SS-SKI S-SS-THM	**Structures**	147	110	1,418	961	10.3%	11.4%
S-EN- S-TV-	**Engine and TVC**	11,151	939	31,745	2,963	35.1%	31.7%
S-PS-	**Pressurization System**	-	-	-	-	-	-
S-PV-PIP S-PV-VAL	**Pipes & Valves**	72	36	266	135	27.1%	26.6%
S-SH-	**Stage Harness**	24	24	69	67	34.9%	34.9%
P-PA- P-PF-	**Payload Structure**	112	-	1,372	-	8.1%	0.0%
A-AV-COM A-AV-PWR A-AV-DHL A-AV-GNC A-AV-HNS	**Avionics**	205	-	2,429	-	8.5%	0.0%
C-AC-	**Attitude Control**	5,826	-	6,575	-	88.6%	0.0%
S-IS-	**Interstage**	-	12	-	61	0.0%	19.3%

Table 2.11: Flight unit stage cost and CMA estimate

	Arithmetic mean and RSE [k€]		**Cost Estimate** [k€]	
	Stage 1	**Stage 2**	**Stage 1**	**Stage 2**
Point Estimate	49,292	7,302	47,005	7,237
Standard Error	13,965	1,302	0.2799	0.1769
Relative Error	28.3%	17.8%	32.0% -24.3%	19.3% -16.2%

2.4. Validation

Although it is of course nonsensical and above all impractical to validate a Theoretical First Unit (T1) cost estimate, mainly because launchers are produced in batches and average production prices are figures which have an actual meaning, there is however a worthwhile case with which to assess the methodology with which the T1 cost is built up. This case is a cost estimate made by NASA of the Falcon 9 rocket [72].

Although not particularly classified as a small launch vehicle by any standards (compared to the payload mass of 300 kg to LEO for the liquid methane concept this LV has a payload capacity of 11,000+ kg), a cost estimate may be made on this vehicle to check whether the method proposed approximates this cost listed in the NASA Associate Deputy Administrator estimate.

First off, the NASA estimate shows development costs including two Falcon 9 flight units. Under a Firm Fixed Price Acquisition, these 2 units are estimated at $M143.6 (2010), or 71 M€ per unit (2015) [72]. Compare

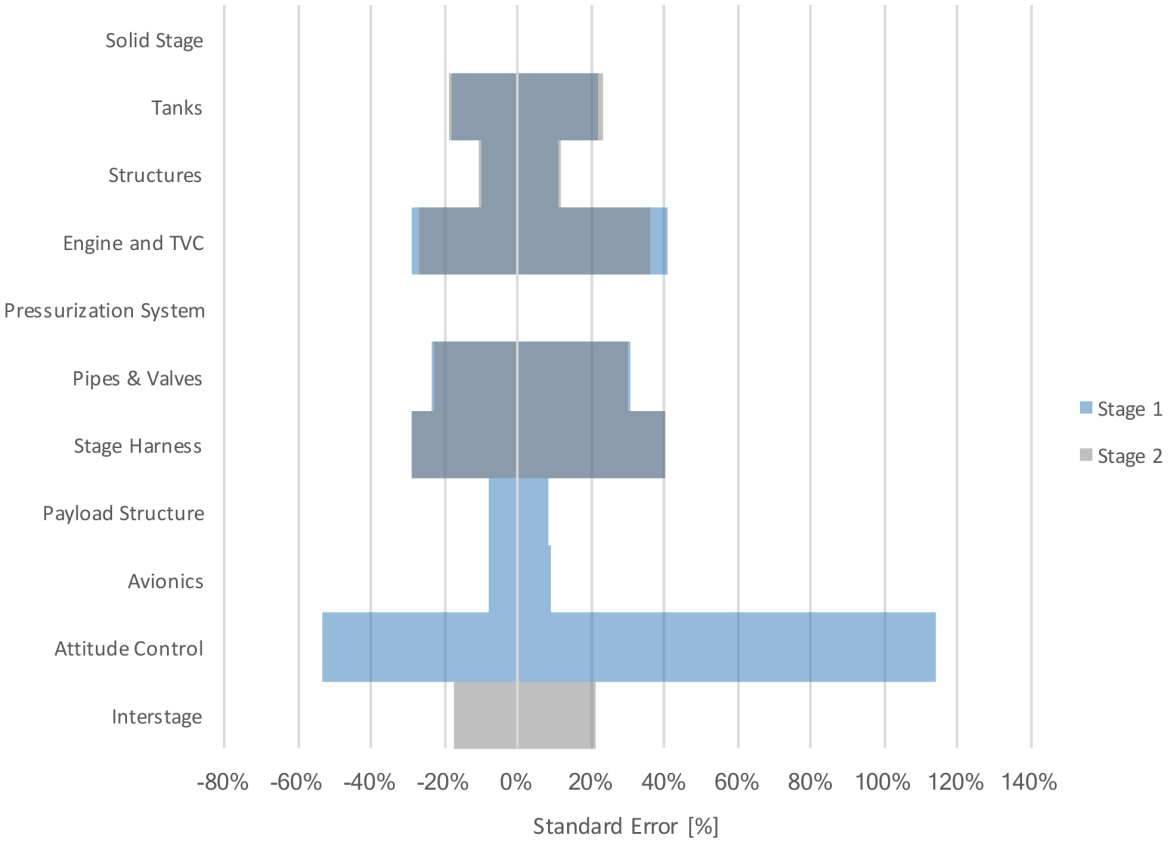


Figure 2.6: Tornado chart of Flight Unit subsystem groups' cost estimate percentage standard error

this with the FU cost estimate developed for Falcon 9 with SOLSTICE in Table 3.9 totalling 87 M€ and it can be concluded that the Flight Unit estimate is 23% higher than actual commercial FU costs of SpaceX. This lies within the CMA described for the FU. However, as the flight unit serves only as a basis of two of the three identified life cycle stages, namely development and manufacturing, and can not be viewed as a metric on itself, little can be inferred from this difference. For the FU to actually reflect production costs and those which are quoted by NASA, learning on the production of the Falcon's 9 engines should be taken into account in the FU, which it is currently not. Moreover, the augmentations to the methodology to reflect commercial development, as described in more detail in Sections 3.4.4 and 3.3.2 have not yet been applied to the FU. Both of these facts make that actual production costs will be lower.

A rough calculation will follow for the true costs of these units as manufactured, based on adjustments explained in detail in the next chapters, so it would be of the interest to the reader to return to these paragraphs after the rest of the research has been explored.

The changes proposed take into account commercial cost reduction measures that were defined in the literature research [13]. The adjustment, taking into account commercial cost reduction measures, recognizes that costs are reduced further due to the low amount of work contracted out by commercial companies, in this case SpaceX. On the one hand, extra profits are retained with less work contracted out (reduction factor c_p detailed in Section 3.4.4). On the other, less management effort goes into steering contracting companies (reduction factor c_s with which reduced management effort is simulated by scaling the FU costs, explained in Section 3.3.2). Incorporating these factors in the commercial flight unit FU_c costs determined through this method used to determine traditional FU_t costs, as explained above yields Equation 2.16. It should be noted that the corrections to I&T efforts through scaling with c_s were already included in the FU.

$$FU_t \cdot c_p \cdot c_s = FU_c \tag{2.15}$$

$$FU_c = 87 \cdot 0.970 \cdot 0.863 = 73\text{M€} \tag{2.16}$$

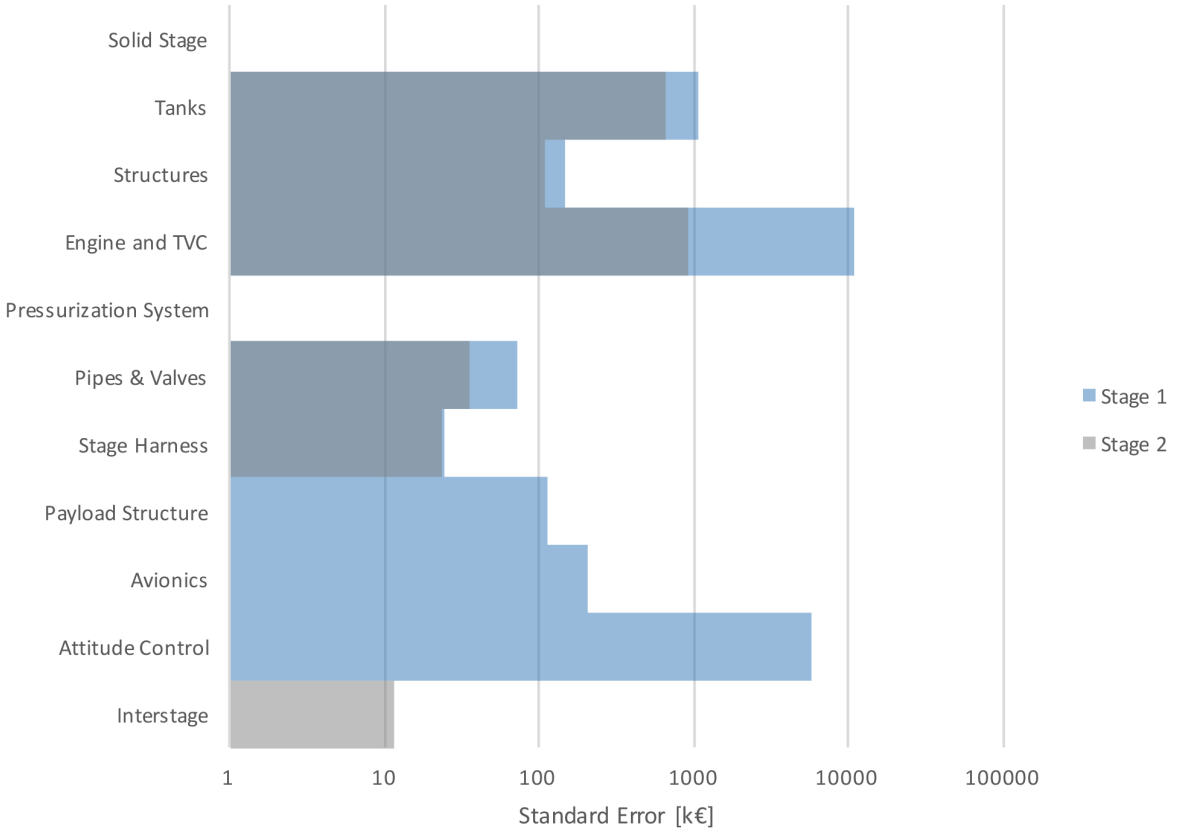


Figure 2.7: Absolute standard errors of the Flight Unit subsystem groups' cost estimate

This augmented FU_c cost of 73 M€ (2015) is significantly closer to the actual FU cost of 71 M€ (2015) reported by NASA [72].

2.5. Flight Unit Cost Estimate Summary

In this chapter, the flight unit cost estimate, which will serve as a basis for estimating development and manufacturing costs, was developed. The estimate was built up by first selecting an appropriate way to break down the launch vehicle into system elements. For all of these elements CERs were constructed from data-points which are relevant for commercial launch vehicles. This way inherently the estimate will take into account commercial launch vehicle development. It was also made sure the CERs cover the spectrum of smaller parts needed in a smaller launch vehicle. Once the CERs yield an estimate for the element costs, the element costs were summed in Section 2.3. Finally, the uncertainty and more specifically the cost modeling accuracy (CMA) on the point estimate developed was estimated from the individual subsystems CER uncertainties. The uncertainties were correlated together using the *"knee in the curve"* method proposed by Stephen Book, with a constant correlation coefficient or $\rho_0 = 0.2$. CMA figures were obtained on a subsystem group level and on a stage level, facilitating the identification of high cost-risk contributors. Assuming the 3% I&T cost contribution (explained in Chapter 4), the final flight unit cost estimate along with its uncertainty based on 1 σ is featured in Table 2.12.

2.6. Method Critique

A way to develop mass and cost data into CERs was developed above. The CERs provided point estimates at a certain subsystem mass, which could be combined into a total Flight Unit cost. The method employed here to estimate uncertainties is standard industry practice and widely applied in many commercially available cost engineering tools [94]. However the scarcity of public data with which to construct the model that was the aim of this research means that some uncertainties in the cost estimates are high. This is especially evident

Table 2.12: Flight Unit total cost and uncertainty

		Cost [k€]	**Upper**	**Lower**
Flight Unit Cost		**54,242**	**28.2%**	**-22.0%**
Stage 1	**Total**	47,005	32.0%	-24.3%
	Stage	36,867		
3.2%	**Stage I&T**	1,165		
	Payload Module	1,365		
	Avionics	2,412		
	Attitude Control	4,921		
3.2%	**PAA I&T**	275		
Stage 2	**Total**	7,237	19.3%	-16.2%
	Stage	6,955		
	Interstage	60		
3.2%	**Stage I&T**	222		

from Figure 2.7, where the cost risk of the Engine *S-EN-* is a large contributor to the CMA portion of the cost risk. Although the CER employed to determine the first unit cost is based on a Falcon 1 T1 cost of 2,800 k€ (FY2010) at a mass of 520 kilograms from a reputable source at ESA, making the point estimate for the liquid methane concept intuitively reliable, the remaining datapoints for low-cost engines still show a high spread. On the total launch vehicle, the engine costs are definitely a driver of total cost, as can be seen clearly from the mean cost $E[X]$ in Table 2.10. Therefore in refining the estimate in the future, special care needs to be taken with the data used with which the CER is constructed. In any case, in an environment where confidentiality of data is not an issue, the model was developed to be as accurate as the data input by the user.

An interesting discussion may be had about the scope of the CMA. As Koelle states in TRANSCOST [45], because actual cost data is used, the inaccuracies can be seen as including the part of the spread associated with development risk, so-called Project Owned Events (POE). Also (and to a lesser extent because of their infrequent nature) External Project Events (EPE), such as politics, could be said to be included in the spread of data for the flight unit cost estimate. This means that the cost risks illustrated here could be regarded as being representative of the full risk spectrum. This study will go so far as to define this uncertainty at least as the CMA, with potentially more cost risk contributors included that are mentioned in Appendix I.

With the Flight Unit cost estimate now rounded up, it is time to use this as a basis for estimating development and manufacturing costs.

3

Development Cost Estimate

Before a launch vehicle can enter production, development of the vehicle must take place. The effort to perform this development includes activities from design to hardware verification and the test models built[1], typically starting at project Phase C up and until the end of Phase D[17, 45].

Once the project is in a later phase (after B1), efforts required to develop an LV may be estimated from a build-up of individual engineering activities performed by a prime- or subcontractor's team. However early phase cost estimates are hampered by insufficient knowledge of mission parameters, as well as configuration and environmental parameters. Therefore it is required to use a heuristic approach to estimation, using modifiers of analogous systems where historical data exists [59].

These modifiers will be applied to the methodology outlined in Section 1.2.5, in order to synthesize an estimate for the non-recurring costs of the liquid methane LV that is the centerpoint of this study. The *flight unit* or *theoretical first unit* costs T1, treated in Chapter 2, are used as a basis for the development effort estimate. Below is explained first how the equivalent T1 modifiers are derived according to the assumed *model philosophy*, and how they constitute the basic build-up of the development costs. After that, the detailed development cost build-up method is presented, with which both the Project Office (PO) costs are estimated along with the Manufacture, Assembly, Integration and Test efforts (MAIT) that are associated with the hardware test regime choices during the development phase.

Commercial development decreases non-recurring costs mainly through reduced efforts spent on Management and Product Assurance overhead factors, as well as reduced Integration and Test efforts. An adaptation for these overhead factors will be proposed in this chapter. In principle, the estimate is developed with a firm-fixed price contract in mind without program support or contingencies, as this results in reduced costs [72].

3.1. Development Cost Considerations

In this section the methodology is outlined with which costs are estimated for the development phase, and the T1 equivalent unit choices are explained. With this T1 equivalent units method, T1 costs are combined with modifiers belonging to test hardware & engineering to approximate their development costs. In early project phase estimates, this type of parametric approach is commonly used to estimate costs. In fact, complemented with expert judgement knowledge and experience, these parametric approaches can already be quite accurate. However, the same type of accuracy as in later phase estimates when requirements have crystallised is not to be expected. [94]

Assigning costs to equivalents of the first unit is one of the two methods proposed by Mandell [34] to estimate costs in early phases, when prevented from constructing a detailed cost build-up characteristic of later project phases [94]. The other method suggested attempts to normalize the state of development and also the development culture [34] into an estimate. This approach was not chosen, as an approximation for the development culture of a commercially operating company would be hard to synthesize within the European Space Agency framework of this thesis.

Continuing with the T1 equivalent method, two major contributions to non-recurring costs are identified [87]:

[1] including one flight model

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

Both these contributions are modeled with *T1 Equivalents*. In this method, a prototype article is represented by an equivalent quantity of flight units [34]. A third contribution, the *management and product assurance* portion, is a function of the *model philosophy* [69] and *design and development*, and is modeled as an overhead to both major elements.

3.2. T1 Equivalents Definition

The T1 Equivalents approach involves the major parts of the development cost being modeled as multiples of the flight unit costs. In the case of the liquid methane LV, the inputs to the development cost model are listed in Tables 2.7 and 2.8. These T1 costs are augmented with modifiers that depend on both amount of hardware tested and the engineering effort needed to develop that specific subsystem element. In accordance with ESA standards [16], the modifiers are defined in the framework of ESA Costing Software (ECOS) support functions, listed in Table 3.1

Table 3.1: ECOS Elements or “Support Functions" [82]

Cost Element	Subelement	Meaning
PO		Project Office
	MGMT	Management
	PA	Product Assurance
	ENG	Engineering
MAIT		Manufacturing, Assembly, Integration, Test
	DM	Development Model
	EM	Engineering Model
	QM	Qualification Model
	FM1	First Flight Model
	FMR	Recurring Flight Models

Management and Product Assurance are modeled as level-of-effort [82] costs, which means they depend on the amount of work done throughout MAIT and ENG. Tooling and Software are incorporated in the System Test Hardware (STH) costs for development, consisting of a Development Model (DM), Engineering Model (EM), Qualification Model (QM) and First Flight Model (FM1). This STH is the translation of the chosen *model philosophy* into costs. Recurring Flight Models (FMR) are part of the production run, of which the cost estimate is outlined in Chapter 4. Finally, the Operations and Logistics (O&L) support function costs are treated in Chapter 5 on operations.

With the range of modifiers now defined, each of them are assigned a value with respect to the Theoretical First Unit T1, based on the work needed on both the test procedures of an STH element and the development engineering work [38]. These values are based on previous historical project performance and estimator experience. Together with an overhead Management & Product Assurance (M/PA) contribution, these equivalent T1 costs represent the total development cost of the vehicle. A benefit of such an approach is that the costs are built up in a transparent way, and are easily interpretable by an observer unacquainted with costing principles. [82]

For this purpose, equivalents are adopted from conferences or proceedings of the Space Systems Cost Analysis Group (SSCAG), an international working group comprised of member organisations developing estimating products for the space industry [91]. The choice of modifiers equivalent to T1 assumed for this research is shown in Figure 3.1, where the Design and Development (DD) T1 equivalent corresponds to the Engineering (ENG) support function.

3.2.1. Design and Development T1 Equivalent

The engineering development costs are approximated by a Design and Development (DD) T1 equivalent of 3.0, which is based on the scope of design effort needed - determined by one of two launch vehicle manufac-

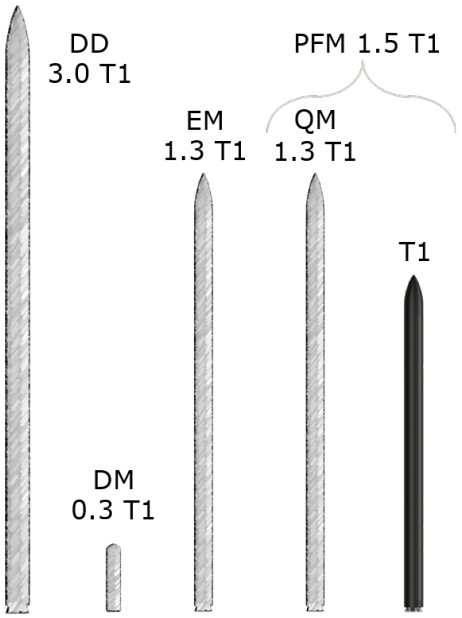


Figure 3.1: *T1 Equivalents* - System Test Hardware models and Design and Development defined as an equivalent to the Theoretical First Unit [71]

turers in Europe, Airbus Defence and Space (ADS) formerly EADS Astrium, see Appendix L. It is estimated to be between "Extensive Modification" and "Re-Design" in Figure L.2. Typically in this scope of effort, if a system requires a change in the Technology Readiness Level (TRL factor, see Figure L.1) of 1 level upwards, the DD factor also increases by 1 [82]. If the TRL of the methane launch vehicle would need to be increased from for example 6 to 9, the DD factor would be $DD' = DD + \Delta TRL = 3 + 3 = 6$. For low-cost launch vehicles the assumption is that matured technology such as storable propellants is used so no additional TRL steps need to be made. This way the DD factor is kept at 3. However, should these assumptions change the developed model was adapted with the flexibility to incorporate these changes.

3.2.2. System Test Hardware T1 Equivalents

The methodology outlined in Section 1.2.5 also allocates a specific amount of work that is proportional to the Theoretical First Unit to each STH element. Jaeger [38] proposes a different T1 equivalent effort for structural Development Models (0.1) and thermal models (0.2), but for the initial cost estimate this factor will be fixed to 30% of the T1 cost based on internal discussions [2]. The Engineering Model manufacturing requires the same amount of manpower and resources devoted to the T1, but also test facilities and testing personnel that take up approximately an additional 30% of resources equivalent to T1 [71]. The Qualification Model has identical hardware to the First Flight Model. It has similar costs to the Flight Model as well, but the testing campaign is also resource intensive. It is therefore that the QM is also more costly than the T1 [3]. Finally, the first unit to be produced is of course equivalent to T1. [71]

3.2.3. Protoflight Model Approach and T1 Equivalent

In an alternative model philosophy, a developing company or agency may opt for a *protoflight* approach. To reduce costs, the Qualification Model, which contains flight-ready elements, can be re-used as a Flight Model. This model is then termed the Protoflight Model (PFM). Goddard pioneered the concept in the mid 1960s, after it was found that Qualification Models did not sustain major damage that precluded them from being reused as flight models [103]. Refurbishment necessary after this testing campaign [22] means that the PFM is marginally more expensive than the Qualification Model itself. Jaeger proposes the refurbishment constitutes one fifth of the T1 costs in addition to the QM costs, making the overall PFM 50% more resource

[2] EJ opinion subject to sensitivity analysis
[3] EJ opinion with NAFCOM96 origin

intensive than the T1 [38]. This is also suggested in the documentation of the NAFCOM96 model, which is part of the NAFCOM NASA Air Force Cost Model series, a key cost model [94] used in the US Aerospace Industry. As the focus of this research is on lower-cost launch vehicles, the protoflight approach will be assumed for estimating costs of the liquid methane launch vehicle concept as well.

Although there is a lack of alternatives to compare these proposed PFM, QM and EM factors to, the fact that their origin lies in NAFCOM [69, 71] (which is itself rooted in a comprehensive historical database [94]) lends them credibility as a base to construct a development effort model on. The impact on final cost of the DM variation between 0.1 and 0.3 however needs to be examined in a sensitivity analysis.

This way of scaling T1 costs is analogous to adding design complexities to each specific CER mass-cost relationship, and a link between the two approaches has been identified before [87]. However, by using the T1 as a single point of reference the need to scale CERs individually and subjectively is avoided. Actually, a slightly modified version of T1 is used as a reference point, which we will see in the next section.

3.3. Detailed Development Cost Breakdown

Before the T1 costs can be used as a basis for the cost estimate, these need to be augmented by excluding program management overhead

3.3.1. First Flight Model Buildup

Data used to construct the CERs developed in Chapter 2 include the cost of program management overhead. To be able to specify and model management and product assurance separately from hardware cost, the T1 costs excluding this support function cost contribution must be established. To this end the M/PA costs are broken away from the T1 to form the First Flight Model (FM1) costs, which comprises only hardware. It is derived by subtracting the M/PA contribution as a percentage of the theoretical first unit (level-of-effort based), as in Equation (3.1). Intuitively, a more complex and expensive system requires a larger effort to manage, so even though this is a rough approximation a change in overall cost will result in a proportional delta in M/PA costs. It implies there is a "standing army" of personnel following the project throughout the life cycle [69].

$$FM1 = T1 - M/PA\% \tag{3.1}$$

The Management and PA effort have been determined, under traditional development and production structures, to be set at 10% and 5% of T1 costs respectively. This is based on historical project performance at a space systems manufacturing company, see Appendix L, Table L.4. A look at the space shuttle management portion confirms these assumptions, at least for a government case [102]. However this is an appropriate time to reflect on whether or not these assumed fractions hold for commercial launch vehicle producers as well. This will be discussed in more detail in Section 3.3.2, and the percentage shown in Equation (3.1) will be augmented for commercial development in Table 3.2.

In the total detailed development cost build-up, FM1 costs are used as a basis for the Design and Development and System Test Hardware (STH) equivalents as engineering and hardware estimates respectively. Both elements then have a management contribution facilitating the processes. The total management (M/PA) and Engineering (ENG) functions together make up the Project Office (PO), which is all desk-focused activities that do not involve manufacturing. On the other hand, the STH FM1 equivalents together make up the Manufacturing, Assembly, Integration and Test (MAIT) work. Together, the PO and MAIT support functions cost make up the total Development Cost. This way of building up the development estimate from the FM1 is shown in Figure 3.2.

3.3.2. Subcontractorship

In this subsection a sidestep will be made to discuss the implications of commercial LV development on the M/PA support function element in the build-up discussed shown in Figure 3.2. It has been suggested by Koelle [45] that companies with a lower number of subcontractors to manage, as well as a lower share of the total work contracted out, experience reduced management effort. This stems from the fact that these companies spend less resources managing and redoing work their contractors performed [13]. For example SpaceX has around 20% of production contracted out [12], while for traditional launch vehicle development in an agency context this amounts to 100%, or roughly 60% at prime contractor level [83]. This type of cost reduction is not taken into account by the 15% management/PA allotment, and that is why this research proposes to scale this contribution such that the effects are in line with those described in Koelle [44, 45]. In fact the same

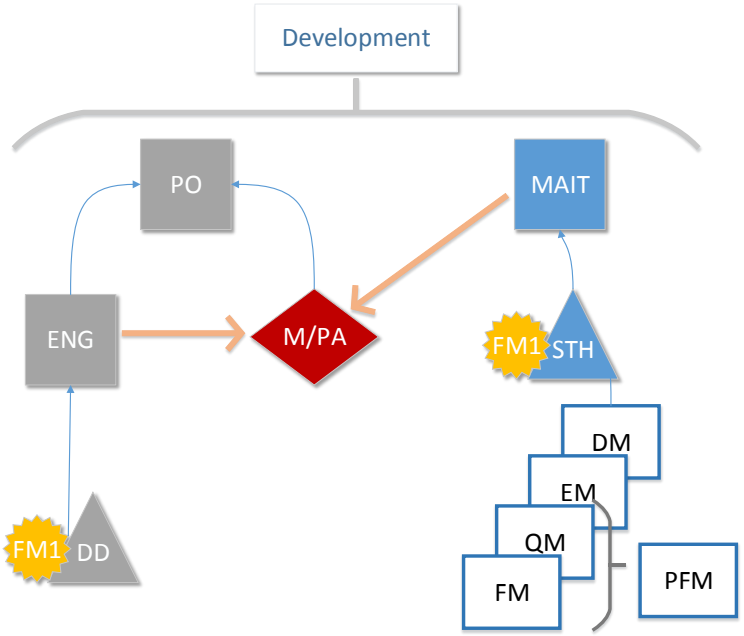


Figure 3.2: Development Cost Build-up from a First Flight Model (FM1) basis

procedure is also applied to the individual stage integration and test (I&T) efforts by subcontractors as shown in Chapter 2 (9%), because these are partly redone in overlap by prime contractors. This will not be necessary at a lower subcontractor share. Table 3.2 shows the way this scaling is applied to M/PA and I&T.

The target scaling to be achieved is determined via Figure 3.3, which shows increased cost with a higher percentage of work contracted out. The assumption is made of 5 major (hardware) subcontractors that need to be managed, as SpaceX has [60] [4].

The cost decrease realized by commercial development is determined through Equation (3.3), where c_i is the cost increase at a specific percentage of work subcontracted in Figure 3.3, and c_s is the overall cost scaling factor associated with a reduced management effort.

$$\frac{c_{i_{60\%}}}{c_{i_{20\%}}} = \frac{1.24}{1.07} = +15.9\% \tag{3.2}$$

$$c_s = \frac{1}{1.159} = 0.863 \tag{3.3}$$

A 14% cost decrease is to be expected from the lower subcontracting rates at commercial companies. Now according to Table 3.2, the required Management, Product Assurance and Integration and Test scaling to reflect similar cost reduction of 14% for commercial launch vehicle operators is with a Management Scaling Factor of $S_m = 2.85$, derived in Table 3.2.

These scaled percentages will be used to estimate costs for the liquid methane and LOX propelled LV under study, using the method to build up the development cost illustrated in Figure 3.2.

All inputs to the development model are summarized in Table 3.3.

3.4. Conceptual Launch Vehicle Development Cost Estimate

This section will explore what the points made previously in this chapter mean for the cost estimate made of the conceptual liquid methane launch vehicle. First, the project office (PO) costs, consisting of M/PA and ENG support functions will be investigated (left side of Figure 3.2). After that the MAIT support function is detailed, which depends on the amount of system test hardware (STH) chosen to develop the rocket with. Throughout the manufacturing performed in the development phase, the learning curve effect is also present, which is

[4] 9 subcontractors, 5 hardware subcontractors

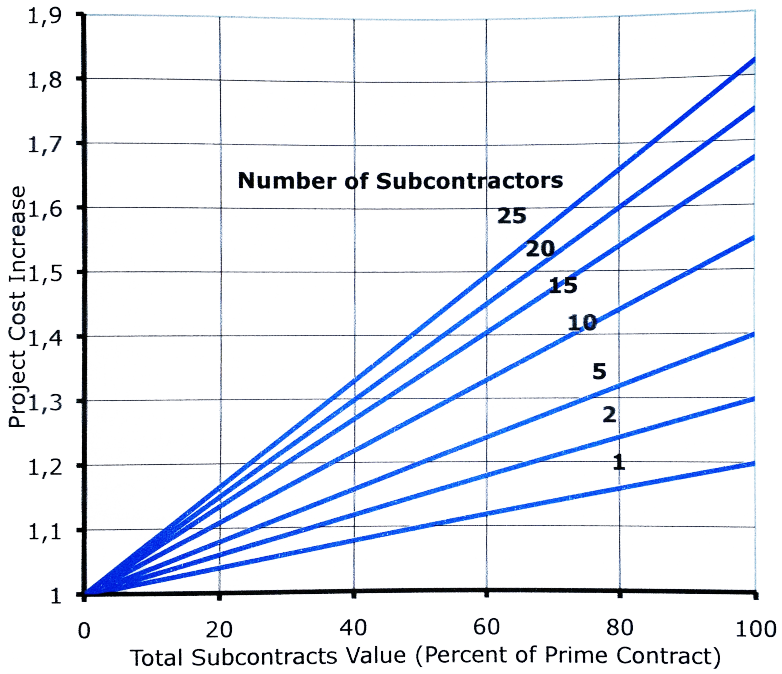


Figure 3.3: Cost increase due to number of subcontractors, versus percent of work subcontracted [45]

Table 3.2: Proposed scaling of Management, Product Assurance and I&T [45]

	Scale Factor S_m	2.85
	Original Cost Contributions	**Scaled Commercial Cost Contributions**
Management (M)	10%	3.5%
Product Assurance (PA)	5%	1.8%
Integration & Test (I&T)	9%	3.2%
Total Development Cost Contribution	26%	8.6%
Cost Reduction		**-13.7%**

something that will be highlighted as well. For an in depth discussion on the learning curve, please consult Chapter 4.

The level this estimating methodology will be applied to is at equipment element level defined with the hardware breakdown in Chapter 2.

3.4.1. Project Office Cost Estimate

The PO estimate is, as described earlier, composed of the desk-focussed activities of the support functions ENG and M/PA. First the First Flight Model (FM1) costs are determined by extracting the M/PA portion from the FU cost, according to Equation (3.1). Next, the total ENG support function costs is the FM1 combined with the DD T1 Equivalent from Section 3.2, such as in Equation (3.4). Of course the development effort needs only to be performed once, and is therefore independent from the number of hardware elements present on the system.

$$ENG = DD \cdot FM1 \tag{3.4}$$

The total project office cost includes administrative Management and Product Assurance (M/PA, which is shown in Section 3.4.3), in conjunction with the Engineering work. This combination is shown in Equation (3.5).

Table 3.3: Overview of development phase model input parameters

Input Paramters		**Value**
Number of STH	DM (0.3)	1
	EM (1.3)	1
	QM (1.3)	0
	PFM (1.5)	1
	T1 (1)	0
Desing and Development	DD (Scope of Effort+ΔTRL)	1
TRL Change Required	ΔTRL	0
Percent Subcontracted Commercially		20%
Assumed BAU Sucontracted Percentage		60%
Nominal Profit	q	8%
Development Learning Factor	L_d	90%

$$PO = ENG + M/PA \tag{3.5}$$

3.4.2. Manufacturing, Assembly, Integration and Test Cost Estimate

The MAIT support function costs are determined again from the FM1 and combining this with the STH T1 Equivalents. In the development phase however some learning and process efficiency improvements are implemented. This is mainly a function of the times a specific hardware element is re-used on the launch vehicle, and is especially relevant considering the 12 engines on the liquid methane launch vehicle under study. It is therefore that a development learning factor L_d is applied to the MAIT cost estimate as well.

For the engines for example, L_d is the addition of all twelve T1 equivalent costs at 90% learning, namely $1 \cdot T1 + 0.9 \cdot T1 + 0.846 \cdot T1 + 0.81 \cdot T1 + \ldots + 0.685 \cdot T1$, divided by the total number of hardware elements 12, to achieve an average learning factor of 0.78. The learning curve and this cumulative procedure are explored in depth in Section 4.1.1.

The total MAIT costs determined up until this point is still for one subsystem, and therefore the number of times this subsystem is re-used on the launch vehicle needs to be accounted for as well in $\#HW$. This total MAIT effort for all equipment hardware elements is outlined in Equation (3.6).

$$MAIT = FM1 \cdot STH \cdot L_d \cdot \#HW \tag{3.6}$$

The total system test hardware STH in Equation (3.7) is the addition of the T1 equivalents in Figure 3.1, assuming a protoflight approach.

$$STH = DM + EM + PFM = 3.1 \tag{3.7}$$

3.4.3. Management and Product Assurance Cost Estimate

The M/PA cost estimate is the sum of Management (Mgmt) and Product Assurance (PA) costs, which are level-of-effort costs on top of the MAIT and ENG support functions, as in Equation (3.8).

$$M/PA = (MAIT + ENG) \cdot M/PA\% \tag{3.8}$$

The M/PA is accounted for under the Project Office cost estimate in Section 3.4.1.

3.4.4. Development Phase Cost Estimate Results

Together, the Project Office and Manufacturing, Assembly, Integration and Test costs make up the total development phase costs DEV, through simple addition as in Equation (3.9).

$$DEV = PO + MAIT = \left[ENG + (MAIT + ENG) \cdot M/PA\%\right] + \left[FM1 \cdot STH \cdot L_d \cdot \#HW\right] \tag{3.9}$$

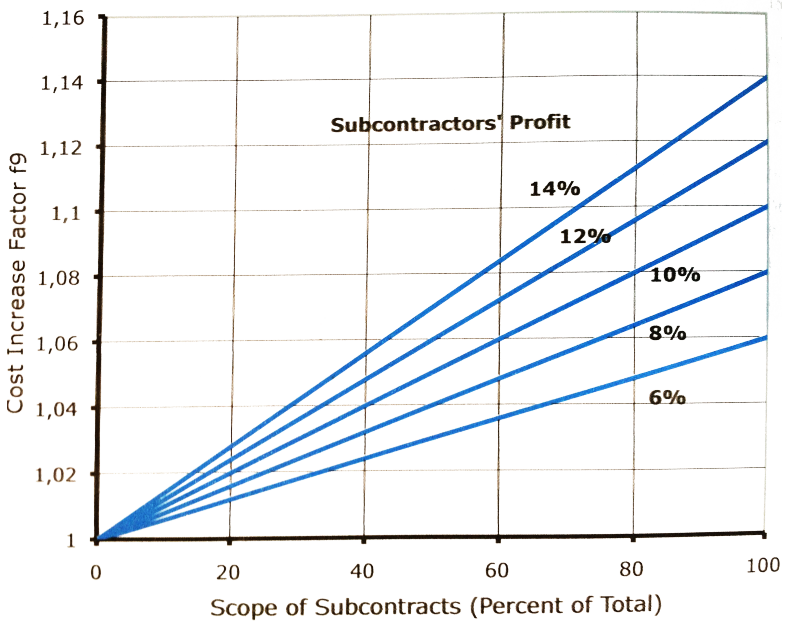


Figure 3.4: Cost increase by scope of subcontracts and profit loss [45]

The results of the development cost estimate applied to the liquid methane launch vehicle are shown in Table 3.4 for the first stage, and Table 3.5 for the second stage. The attentive reader will have noticed that the sum of PO and MAIT support functions is slightly more than the total development cost in both these tables. This is because, after scaling subcontractor management costs in Section 3.3.2, another cost reduction factor is incorporated. It is the profits a contracting company retains (does not lose) out to subcontractors it would have had with a higher percentage of work contracted out [45]. So expanding Equation 3.9 to incorporate this profit retention cost reduction factor c_p, would yield Equation 3.10.

$$DEV = c_p \cdot (PO + MAIT) \tag{3.10}$$

From TRANSCOST then, the value of c_p can be inferred from Figure 3.4 [45].

Scope of subcontracts in Figure 3.4 for traditional development will be around 60%, and for a commercial party such as SpaceX this value is more likely to be at 20% [12]. A measure of additional costs under Business As Usual (BAU) (or commercial cost reduction) are then found by examining the percentage increase of costs due to subcontractor profits according to the relationship in Equation 3.11, which was derived from Figure 3.4. It takes into account the amount of profit a subcontractor is making q, as well as the scope of subcontracted work under BAU and commercial development, s_{BAU} and s_{COM} respectively.

$$c_p = \frac{s_{COM} \cdot q + 1}{s_{BAU} \cdot q + 1} \tag{3.11}$$

The model constructed has been adapted to flexibly take into account the amount of subcontractor profits assumed, and the choice has in this case fallen on 8%, as this is a value typical for ESA, and part of its framework tender system *"emits"* [14] [5].

With this input, Equation 3.11 combined with Figure 3.4 result in a c_p value of 0.970. This makes for a rough 3% decrease in costs compared to BAU development.

[5] In fact variable and based on type of cost. *Profit 1*, 8% is applied on "Base Rate", while *Profit 2*, 4% is applied on "Labor Industrial Overheads and Facilities" [14]. As a simplification, and because most costs belong to the first category, *Profit 2* is lumped as 8% as well, and is therefore subject to a sensitivity analysis

Table 3.4: Development cost estimate of the first stage of the liquid methane rocket concept, using T1 equivalent units [34, 45, 82]. I&T costs are a percentage of the sum of all FM1 costs or FU costs. Payload, Avionics and Attitude Control (PAA) I&T included separately

						T1 Equivalents		**Project Office Contributions**		**Development Cost Contributions**		**Learning**	**Development Phase Cost [k€]**
Unit	**Equipment**	**Part**	**Part ID**	**Total FU [k€]**	**FM1**	**DD**	**STH**	**ENG**	**M/PA**	**PO Total**	**MAIT**	L_d	**DEV**
Stage 1		*Liquid Stage*		**36,867**									**88,631**
	Solid Casing		S-SC-	-	-	3.0	3.1	-	-	-	-	1.0	-
	Pressurizant Tank		S-PT-	543	515	3.0	3.1	1,545	203	1,747	2,111	1.0	3,740
	Fuel Tank		S-FT-	2,187	2,072	3.0	3.1	6,217	815	7,032	8,496	1.0	15,053
	Oxidizer Tank		S-OT-	2,492	2,361	3.0	3.1	7,082	929	8,011	9,679	1.0	17,150
	Stage Structure												
		Thrust Cone	S-SS-TRC	319	302	3.0	3.1	907	119	1,026	1,239	1.0	2,196
		Skirt	S-SS-SKI	1,038	983	3.0	3.1	2,949	387	3,336	4,031	1.0	7,142
		Thermal Control	S-SS-THM	51	48	3.0	3.1	144	19	163	197	1.0	350
	Engine(s)		S-EN-	29,315	2,315	3.0	3.1	6,944	1,985	8,929	28,875	0.78120	36,649
	TVC		S-TV-	606	574	3.0	3.1	1,722	226	1,947	2,353	1.0	4,169
	Pressurization System		S-PS-	-	-	3.0	3.1	-	-	-	-	1.0	-
	Pipes & Valves												
		Pipes	S-PV-PIP	158	150	3.0	3.1	450	59	509	615	1.0	1,090
		Valves	S-PV-VAL	93	88	3.0	3.1	265	35	299	361	1.0	641
	Stage Harness		S-SH-	65	62	3.0	3.1	186	24	210	254	1.0	450
Payload				**1,365**									**9,396**
	Payload Adapter		P-PA-	402	381	3.0	3.1	1,144	150	1,294	1,563	1.0	2,769
	Payload Fairing		P-PF-	963	912	3.0	3.1	2,736	359	3,095	3,740	1.0	6,626
Avionics				**2,412**									**16,602**
	Avionics												
		Comms	A-AV-COM	696	660	3.0	3.1	1,980	260	2,239	2,706	1.0	4,794
		Power	A-AV-PWR	599	568	3.0	3.1	1,703	223	1,927	2,328	1.0	4,125
		Data Handling	A-AV-DHL	1,116	1,058	3.0	3.1	3,173	416	3,589	4,336	1.0	7,684
		GNC	A-AV-GNC	-	-	3.0	3.1	-	-	-	-	1.0	-
		Avionics Harness	A-AV-HNS	-	-	3.0	3.1	-	-	-	-	1.0	-
Attitude Control				**4,921**									**33,871**
	ACM		C-AC-	4,921	4,662	3.0	3.1	13,987	1,834	15,821	19,116	1.0	33,871
I&T				**1,440**									**9,911**
	Stage I&T		I&T	1,165	1,104	3.0	3.1	3,312	434	3,746	4,526	1.0	8,019
	PAA I&T		I&T-P-	275	260	3.0	3.1	781	102	884	1,068	1.0	1,892

Table 3.5: Development cost estimate of the second stage of the liquid methane rocket concept, using T1 equivalent units [34, 45, 82]. I&T costs are a percentage of the sum of all FM1 costs or FU costs. Payload, Avionics and Attitude Control (PAA) I&T included separately

						T1 Equivalents		**Project Office Contributions**		**Development Cost Contributions**		**Learning**	**Development Phase Cost [k€]**
Unit	**Equipment**	**Part**	**Part ID**	**Total FU [k€]**	**FM1**	**DD**	**STH**	**ENG**	**M/PA**	**PO Total**	**MAIT**	L_d	**DEV**
Stage 2		*Liquid Stage*		**6,955**									**47,876**
	Solid Casing		S-SC-	-	-	3.0	3.1	-	-	-	-	1.0	-
	Pressurizant Tank		S-PT-	300	284	3.0	3.1	853	112	965	1,166	1.0	2,067
	Fuel Tank		S-FT-	1,932	1,831	3.0	3.1	5,492	720	6,212	7,506	1.0	13,299
	Oxidizer Tank		S-OT-	770	730	3.0	3.1	2,189	287	2,476	2,991	1.0	5,300
	Stage Structure												
		Thrust Cone	S-SS-TRC	100	95	3.0	3.1	284	37	321	388	1.0	688
		Skirt	S-SS-SKI	834	790	3.0	3.1	2,371	311	2,682	3,240	1.0	5,741
		Thermal Control	S-SS-THM	19	18	3.0	3.1	55	7	63	76	1.0	134
	Engine(s)		S-EN-	2,443	2,315	3.0	3.1	6,944	911	7,855	9,490	1.0	16,815
	TVC		S-TV-	365	346	3.0	3.1	1,037	136	1,173	1,417	1.0	2,511
	Pressurization System		S-PS-	-	-	3.0	3.1	-	-	-	-	1.0	-
	Pipes & Valves												
		Pipes	S-PV-PIP	70	67	3.0	3.1	200	26	226	273	1.0	485
		Valves	S-PV-VAL	58	55	3.0	3.1	164	22	186	224	1.0	398
	Stage Harness		S-SH-	64	60	3.0	3.1	181	24	205	248	1.0	439
Interstage				**60**									**412**
	Interstage Structure		I-IS-	60	57	3.0	3.1	170	22	193	233	1.0	412
I&T				**222**	**-**								**1,526**
	Stage I&T		I&T	222	210	3.0	3.1	630	83	713	861	1.0	1,526

The total development cost for the two stage liquid methane concept, including an additional management overhead which is the prime contractor's share, is shown in Table 3.6. The overall development cost is around the 220 M€ mark.

Table 3.6: Development Cost Build-up summary for the liquid methane launch vehicle concept, using SOLSTICE. I&T costs are taken as a percentage of hardware costs, and M/PA costs are modeled as an overhead percentage on all other costs

		Flight Unit Cost [k€]	**Development Cost** [k€]
		54,242	**218,555**
M&PA			**10,331**
5.3%	**M/PA**		10,331
Stage 1	**Total**	**47,005**	**158,410**
	Stage	36,867	88,631
3.2%	**Stage I&T**	1,165	8,019
	Payload Module	1,365	9,396
	Avionics	2,412	16,602
	Attitude Control	4,921	33,871
3.2%	**PAA I&T**	275	1,892
Stage 2	**Total**	**7,237**	**49,814**
	Stage	6,955	47,876
	Interstage	60	412
3.2%	**Stage I&T**	222	1,526

3.4.5. Alternative Development Effort Estimate & Verification

There is an alternative method for estimating development cost which may be used to verify the order of magnitude of the estimate. It is based again on using the First Flight Model FM1 estimate derived from the Flight Unit (FU).

In this chapter, the project office contributions per subsystem consisted of subcontractor ENG and M/PA support functions, and later an addition of a prime contractor M/PA contribution. Instead, in the new approach each equipment element of the launch vehicle has it's own I&T contribution (9%, scaled by S_m to 3.2%). There is also one PO multiplier which accounts for the entire management and engineering effort of a project without making a prime/subcon distinction (30%, scaled by S_m to 17.5%) and a synthesizing *Systems Engineering* factor (7%, scaled by S_m to 2.5%).

At around 226,000 [k€] compared with the original 218,555 [k€] estimate, the new method is near 3% of the one originally proposed. Interestingly, comparing both methods, the systems engineering factor in this new method accounts for the lack of multiplication of both the subcontractor and prime contractor M/PA contributions in the original research method proposed.

3.4.6. Sensitivity of the Development Cost

There are a number of parameters with uncertain values listed in this chapter, which form the basis of the development cost estimate. This subsection will in short show what a change in these parameters means for the end results of this estimate. The first parameter in question is the Development Model (DM) T1 Equivalent of 0.3 (mentioned in Section 3.2), which could be reduced according to Jaeger [38] to 0.1. The second is the amount of subcontractor profit assumed for calibrating the cost estimate for commercial purposes, discussed in Section 3.4.4, which was variable between 8% and 4% for ESA. However, Koelle [45] identifies profits as high as 14%, so the sensitivity analysis will extend to this range as well. Finally, the percentage subcontracted out is included as this is an important parameter that defines commercial development. While SpaceX contracts roughly 20% out, a change to a hypothetical 10% would not be unthinkable. With 60% subcontracted out traditionally, a midway point of 40% between commercial and traditional would also be interesting to evaluate.

Table 3.7 shows the effects of varying these parameters one by one, resulting in a cost increase or decrease.

Higher assumed subcontractor profits under BAU development correspond to lower costs in the commercial case. Based on the results, it can be seen that these assumptions have a maximum effect of -2.5% and +1.6% on the total development costs.

Table 3.7: Development cost sensitivity to changes in DM T1 equivalent, assumed subcontractor profit, and the percentage of work subcontracted out. Parameters are varied one by one

Parameter	**Cost Decreasing** [k€]	**Nominal** [k€]	**Cost Increasing** [k€]
Development Model T1 Equivalent	0.1	**0.3**	-
Development Cost Sensitivity	212,987	**218,555**	-
Percentage Change	-2.5%	-	-
Subcontractor Profit	14%	**8%**	4%
Development Cost Sensitivity	213,793	**218,555**	221,916
Percentage Change	-2.2%	-	1.5%
Percentage Subcontracted	10%	**20%**	40%
Development Cost Sensitivity	216,834	**218,555**	221,977
Percentage Change	-0.8%	-	1.6%

3.5. Validation

The validation of the development cost model approach will be done first by comparing the estimate with an already established and employed rule-of-thumb for approximating non-recurring costs. After that, the methodology will be applied to three reference launch vehicles, namely the liquid rocket Falcon 1 by SpaceX, the Pegasus XL launch vehicle by Orbital Sciences Corporation, and the not-so-small Falcon 9, in order to test whether the model holds validity on large vehicles that are outside the scope of this research aimed at small LVs. The estimated costs will then be compared to those officially reported.

3.5.1. Rule-of-Thumb Check

Meisl from Rocketdyne published within the SSCAG that development costs for spacecraft are between 1.5 and 7.0 times unit cost depending on the amount of design and new technology used [58]. The range of proposed values are featured in Figure L.3 of Appendix L. A deliberate choice was made for a 50% new design solution for the liquid methane rocket concept, as well as for other launch vehicles to be costed, so the total development costs should lie between 3 and 4 times the T1 cost [58, 82] [6], which is the case for this estimate as well.

$$\frac{DEV}{FU} = \frac{219\text{M€}}{54\text{M€}} = 4 \tag{3.12}$$

The reason why the development costs could be in the higher end of the rule-of-thumb spectrum is because the development also includes engine development. These generally have a higher development effort than generic spacecraft, which pushes the estimate upwards [58].

3.5.2. Reference Cases

In this subsection the validity of the model is tested with two launch vehicles with different types of propellant. The Kerosene/LOX propelled Falcon 1 Launch Vehicle and the Pegasus XL vehicle, using solid hydroxyl terminated polybutadiene (HTPB) as a propellant.

Falcon 1 & Falcon 9 Development Costs

The Falcon 1 rocket was developed by SpaceX, and flown from 2006-2009 [86]. It is one of the only liquid rockets in the 100-700 payload class range for which actual hardware was produced [13]. Investigations by NASA on the low-cost nature of SpaceX development and operations concluded that the development costs for the Falcon 1 LV were around $90M, and those for the Falcon 9 were $300M [2, 72], all in 2010 dollars. This

[6] For spacecraft in general

can be corroborated by the fact that, in August of 2006, SpaceX received under the Commercial Orbital Transportation Services (COTS) agreement, a first funding of $278M and in FY2011 received an additional $118M, totalling $396M [53], or in fact $372M (2010) adjusting both figures for inflation. This is an important fact that should be taken into account when considering cost/price per flight in Chapter 6, as the development costs are already paid for. These reimbursed development costs will therefore not be visible in the price per flight.

The precise mass breakdown of the Falcon 1 vehicle is of course ITAR proprietary information, which means that it is therefore not available for this research. However, due to the similarities with the Ariane 4 (AR4) launch vehicle 2nd stage (liquid, one engine...), an approximation of the mass breakdown is made based on those available AR4 mass fractions, as well on other public data on Falcon 1.

Because the engine equipment element is a major cost driver, the engines masses were entered first based on publicly available data. The mass of a Merlin engine at the time was 630 kg (now it is reduced with enhanced manufacturing to a little over 500 kg). The rest of the dry mass was broken down according to Ariane 4 mass fractions (see Appendix L, Table L.1), with some lumping done under common CER's. For instance the fuel and oxidizer tanks have the same CER, and therefore for simplicity the mass of the dual chambered tank of the Falcon 1 is lumped under *S-FT-*. An analogous approach is taken with the second stage including Kestrel engine. The total Falcon 1 mass and cost estimate may be consulted in Appendix J, Table J.1 and Table J.2. Furthermore it is assumed that the model philosophy is 1 of each model in Figure 3.1 per subsystem, based on a PFM approach.

The Falcon 1 flight unit and development costs are shown in Table 3.8.

Table 3.8: SOLSTICE calculated Falcon 1 Flight Unit and development cost

		Flight Unit Costs [k€]	**Development Cost** [k€]
Vehicle Cost		**13,159**	**95,201**
M&PA		**-**	**4,621**
5.3%	**M/PA**	-	4,621
Stage 1	**Total**	**10,001**	**68,840**
	Stage	8,729	60,085
3.2%	**Stage I&T**	276	1,897
	Payload Module	755	5,197
	Avionics	211	1,451
	Attitude Control	-	-
3.2%	**PAA I&T**	30	210
Stage 2	**Total**	**3,158**	**21,739**
	Stage	2,994	20,607
	Interstage	68	467
3.2%	**Stage I&T**	97	665

As is apparent the development costs estimated by the model SOLSTICE is 95 M€ ($96M, 2010), versus a reported development budget of $90M (2010) [54]. The estimate of the Falcon 1 development costs are within 7% from the non-recurring cost reported by NASA. This is well within the goal of ±20% set out at the start of the research, see Appendix K.

Even the Falcon 9 vehicle costs may be estimated using such an approximated mass breakdown, even though the launch vehicle can not be considered as "small", as the payload capacity is around 11 tonnes [92]. Again, the exact engine mass is critical for the model, as the engines are a large share of total cost contribution. Table J.3 and J.4 in the Appendix show the estimated mass breakdown, which was achieved in a similar fashion as that of the Falcon 1 above.

The Falcon 9 development costs estimated using the SOLSTICE model amount to 407 M€ (2015) from Table 3.9. Adjusted to inflation and in dollars for comparison this totals $419M (2010). Now, compared to the reported development cost of $372M determined above [54], it can be concluded that the estimate is

Table 3.9: SOLSTICE calculated Falcon 9 Flight Unit and development cost

		Flight Unit Costs [k€]	Development Cost [k€]
Vehicle Cost		**87,373**	**407,140**
M&PA		**-**	**19,437**
5.3%	**M/PA**	-	19,437
Stage 1	**Total**	**77,462**	**319,486**
	Stage	55,501	168,323
3.2%	**Stage I&T**	1,753	12,064
	Payload Module	5,237	36,050
	Avionics	8,274	56,949
	Attitude Control	6,079	41,841
3.2%	**PAA I&T**	619	4,258
Stage 2	**Total**	**9,911**	**68,218**
	Stage	8,967	61,720
	Interstage	641	4,410
3.2%	**Stage I&T**	303	2,088

within 13% of actual development cost [7]. In fact NASA determined development cost of the Falcon 9 under a Firm Fixed Price (FFP) acquisition scheme to be roughly $440M (2010) [72]. The lower costs estimated in this research could possibly stem from the redesigns and thrust upgrades that were done on the Merlin engine in the transition period between the Falcon 1 and Falcon 9, which are development costs not accounted for or incorporated in the assumptions here.

Pegasus XL Development Costs

As a commercially operated solid rocket propelled launch vehicle [74] which has been in operation for more than a quarter century, the Pegasus XL [8] launch vehicle, produced by Orbital ATK, is an interesting case to make a cost estimate on. This is because the launch prices should have stabilized over this period, where the learning effect discussed in more detail in Chapter 4 has resulted in a maximum manufacturing cost decrease. For now however, this section will only examine the development cost of this LV and compare it to the reported development cost. As development was ongoing around 1988 [51], there are scarce resources available to get a precise figure for these costs as the development took place some time ago. However, Launius [51] suggests that the development costs is "over $50 million", raising the assumption that it is then between $50M and $60M and closer to the former. A 1990 Fortune article seems to corroborate the $50M development cost [79], as does Hammond [31] in an AIAA education series publication.

As with the SpaceX launch vehicles, the mass breakdown for the Orbital Sciences Pegasus XL is listed under Appendix J, in Table J.5, Table J.6 and Table J.7. It is assumed that because of common elements the Pegasus and Pegasus XL development costs are shared, as is the case of the Falcon 1 and Falcon 9 launch vehicles by SpaceX. A summary of the estimate made for this phase on the Pegasus vehicle is shown in Table 3.10.

The development costs of the Pegasus launch vehicle were estimated using SOLSTICE at 114 M€ in 2015. Adjusted for inflation and currency exchange this totals $56M (1988), which is indeed within the ±20% accuracy expected for the development phase estimate, detailed in the research proposal in Appendix K.

3.5.3. Validation Summary

The magnitude of the development costs were first checked with a rule of thumb proposed by SSCAG [58]. It should lie between 3 and 4 times the flight unit costs; it was determined the estimate on the liquid methane

[7] Hardware developed for Falcon 1 was also used in Falcon 9 with common elements such as the Merlin engine [86]. Therefore it is assumed that the Falcon 9 development costs share in those of the Falcon 1

[8] An enlarged version with commonality to the Orbital ATK Pegasus

Table 3.10: SOLSTICE calculated Pegasus XL Flight Unit and development cost

		Flight Unit Costs [k€]	**Development Cost** [k€]
Vehicle Cost		**15,784**	**114,187**
M&PA			**5,543**
5.3%	**M/PA**	-	5,543
Stage 1	**Total**	**9,803**	**67,478**
	Stage	7,095	48,838
3.2%	**Stage I&T**	224	1,542
	Payload Module	593	4,079
	Avionics	1,815	12,496
	Attitude Control	0	0
3.2%	**PAA I&T**	76	523
Stage 2	**Total**	**3,919**	**26,976**
	Stage	3,799	26,150
	Interstage	0	0
3.2%	**Stage I&T**	120	826
Stage 3	**Total**	**2,062**	**14,190**
	Stage	1,998	13,756
	Interstage	0	0
3.2%	**Stage I&T**	63	434

concept was within this range at 4 FU. For the limited amount of data available on commercial launch vehicle prices with actual hardware flown, the method of estimating development costs based on T1 equivalents gives results that lie within 10% of actual development costs. A summary of the development cost validation is shown in Table 3.11.

Table 3.11: Non-recurring cost estimates by the SOLSTICE model on three reference cases, compared to actual reported costs [31, 54, 72, 79]

Launch Vehicle	**SOLSTICE ESA NRC Estimate**	**Reported Development Costs**	**Accuracy**
Falcon 1	$96M (2010)	$90M (2010) [54]	+7%
Falcon 9	$419M (2010)	$372M (2010) [54]	+13%
Pegasus	$56M (1988)	$50M (1988) [31, 79]	+12%

3.6. Method Critique

There are a generous amount of assumptions made throughout this chapter. Some of these were made within genuine limitations and lack of project data often encountered during early phase first estimates [22, 94]. Others were made that sought to harmonize a plethora of extremely different subsystems with varying degrees of complexity into a simple-to-understand first estimate. This section will briefly explore and recognize the perceived limitations of such a way of estimating.

3.6.1. System Test Hardware Approximations

In the method proposed for this research the number of system test hardware elements of the model philosophy is multiplied with an approximate first unit cost for each specific element. A shortcoming of this approach is that the number of test hardware elements for each subsystem equipment are assumed to be

constant, namely one DM, one EM and one PFM. In reality, if some subsystem hardware element is already developed and space qualified, and can be bought off the shelf, this type of model philosophy is not valid and the number of test hardware elements for that subsystem can be set to zero. This will eventually be an option for the proposed launch vehicle engine, which may be borrowed from other relevant programs.

On the other hand if predevelopment is required on another subsystem due to the TRL being too low, these additional costs will also be part of a design- or engineering model's cost, which results in more units of these T1 equivalents. For example the approach could consist of 2 equivalent DM's, 2 equivalent EM's and one PFM.

In addition to assuming a certain amount of test elements, the equivalent T1 costs for an element are all rounded factors, such as 1.5 for the PFM. Of course the costs of such test hardware will never *exactly* be a round T1 factor. However, such basic and rounded-off factors are included to make the estimate transparent for external observers, and clarifyable towards and understandable for any project team members wishing to know the basis of an early-phase estimate.

The method proposed here attempts to seek a balance between the differences described here for a first estimate, and assumes a certain amount of testing, which is generalized for all subsystems. However, as requirements crystallize [94] the model can be tuned for varying amounts of test elements, and differing T1 equivalent factors based on complexities (for instance engine T1 equivalent factors will be generally higher [82]). Specific T1 equivalents can therefore be developed for each item in the rocket based on previous experience developing that system. In essence the method and estimate proposed here will be a living document which is continuously updated to reflect current requirements and design decisions, just as cost estimate should be [17, 94].

3.6.2. Level-of-effort Assumptions

Management and Product Assurance, as well as Integration and Test are all assumed to be level-of-effort costs [39], which means these depend on the core engineering and manufacturing activities proportionally. In reality, experience varies from team to team [59, 69] and activities are done more efficiently with higher levels of experience, or slower at lower levels of experience. A team may also be over- or understaffed, which also affects time to completion. Moreover, over time management effort may decrease because processes are standardized or automated.

The main point here is that the level-of-effort costs are never always just that, and will include an extremely wide variety of factors that can never be guessed without in-depth interviews and team assessments, which are infeasible at an early project stage [59, 94]. As with the system test hardware elements in Section 3.6.1, as a project progresses, more of these blanks can be filled in to refine the estimate.

An illustration of the degree of variation in this level of effort is given for Management and Product Assurance in Figure L.4, for different types of subsystems over multiple observations. The M/PA level-of-effort may vary between 11% and 22% or hardware costs.

3.6.3. Source of Data

This problem pertains to cost engineering in general. A cost engineer within an agency is often asked for an unbiased assessment of industry prices, the norm for which is derived with industry prices themselves. This could lead to a gradual inflation in the estimate, which is in fact not a reflection of the actual cost or perceived value of a technology itself, but more a result of industry pricing strategy or inclusion of significant outlier data-points in the cost database. Therefore the database from which the estimate stems must be assembled with a critical eye on whether the included prices are normal, and the system to be costed should be evaluated for this normality as well. Higher than usual system costs do not mean a badly designed or developed system per se, but the differences between actual costs and those predicted need to be justified and accounted for [9].

3.6.4. Non-recurring Costs

The boundaries between development and manufacturing, or more precisely non-recurring and recurring costs, could be less clear than defined in this research. There may for instance be additional development or non-recurring costs incurred during manufacturing and operations due to adjustments that need to be made to the design or qualification status of the system, such as the LEAP Launcher Exploitation Accompaniment Program undertaken by ESA on the Vega and Ariane 5 LVs in 2014. This additional development cost stems

[9] Part of accountability procedures at ESA TEC-SYC

from the limits of making an approximation for often one-off space projects, and the uncertainty associated with their development, the so-called Project Owned Events (POE) that are part of development risk [10].

3.6.5. Input parameter uncertainty

Although the model was tested on Falcon and Pegasus reference launch vehicles, there is an uncertainty to the precise input mass fractions because this data is restricted. However, an estimate of these masses was made to the best extent possible based on a known LV configuration, the Ariane 4. Nonetheless, this research has shown that if care is taken in assigning masses to certain cost-driving subsystem elements, and basing other masses on a rough estimate, an acceptable [11] level of accuracy may be achieved on the development cost estimate. Notwithstanding, it is desirable to test the model's acceptability in predicting development costs over a wide range of vehicles. When mass breakdown data on newer launch vehicles becomes available in the level of detail of this approach, this acceptability can be evaluated further.

[10] See also Appendix I, Figure I.1

[11] Within ±20% of reported costs, the research goal set out in Appendix K

4

Manufacturing Cost 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 [1]. After production, a rocket is launched, where operations work becomes a cost factor.

On a program basis, the development costs are so-called *non-recurring costs*, while manufacturing and operation occur again and again per launch vehicle and are called *recurring costs*. The recurring costs are expenses incurred per launch, and will be added up as such, while the previously determined non-recurring development costs are meant to be earned back while selling the launches in the recurring cost phase.

For now this chapter will delve deeper into the first part of the recurring costs, the manufacturing costs. In fact the manufacturing costs make up the highest percentage of total Life Cycle Costs (LCC) in work-years, reaching values up to 75% [50]. Of course this depends strongly on the number of launch vehicles produced in the entire program. At least this figure indicates the importance of estimating the manufacturing costs as best as possible in order to reduce overall program cost risk.

The following chapter will build on the work performed in Chapter 2, where a Flight Unit (FU) or T1 cost estimate was developed. This FU cost is in itself not fully representative of manufacturing costs, as for example learning due to series production has not been applied to it. Nonetheless an attempt to sketch manufacturing costs including learning was made in Section 2.4.

This chapter will do this in a more rigorous fashion. The estimate previously served only as an indication of the right order of magnitude of the Flight Unit estimate, and did not include a Management and Product assurance overhead factor for example, which will be included here. Also, the required learning and I&T factors in the manufacturing cost estimate will be substantiated in this chapter, and applied more in-depth here. For example, the learning curve factor will be applied to all equipment-level elements depending on the number of times these elements are repeated in the launch vehicle. This was not the case in the simple approximation in Section 2.4, where no learning curve was assumed. Therefore, that particular estimate does not reflect the cost improvement experienced, and needs to be substantially expanded on in this chapter to reflect true costs.

illustrating first the support functions that together amount to the total manufacturing costs through the T1 estimate developed previously. After that, the learning curve will be discussed in Section 4.1.1 through an examination of its theoretical basis, the various forms in which it is applied, and the assumptions that form the basis of the approximation. Then in Section 4.1.2, attention will be paid to integration and test efforts that are especially important in the manufacturing of space systems, and which are to a lesser extent also part of the costs of manufacturing the STH employed for development[2]. Finally the Manufacturing costs will be determined for a batch of 50 units of the conceptual liquid methane launch vehicle at the heart of this study. This will be done in Section 4.2, and for three levels of the Maxus 9 validation case in Section 4.3 and Appendix L.

[1] Galileo navigation satellites and Sentinel satellites which are part of the ESA Copernicus program for example
[2] which was outlined in Chapter 3, Section 3.2

4.1. Manufacturing Cost Build-up

This section will explain how, from the T1 estimate made in Chapter 2, the manufacturing costs are estimated.

Previously, the costs of a *theoretical first unit* T1 were used to estimate development costs. In production however a cost engineer is required to develop an estimate for a batch of actual units. Two major contributions to the manufacturing costs are identified [82]

1. *Manufacturing, Assembly, Integration and Test of hardware* [3] (MAIT), the latter three sometimes referred to as AIV - Assembly, Integration and Verification [18]

2. *Management and Product Assurance* (M/PA), which now makes up the whole Project Office (PO) - all desk-focussed activities supporting the manufacturing process. This is contrary to the development phase, where additional Engineering (ENG) was performed under PO as well.

As was the case with the M/PA support functions in Chapter 3, the associated costs are modeled as level-of-effort costs [39], which means they depend on the activities which the work supports. In this case the M/PA support function depends on MAIT activities.

The manufacturing phase is dominated by learning, in which cost improvement is realized over subsequently produced units. Their costs are approximated by a fraction of the first unit cost. This first unit cost is available in the form of a T1. This fits the model philosophy plan from Chapter 3, which is augmented to also include the manufacturing phase in Figure 4.1.

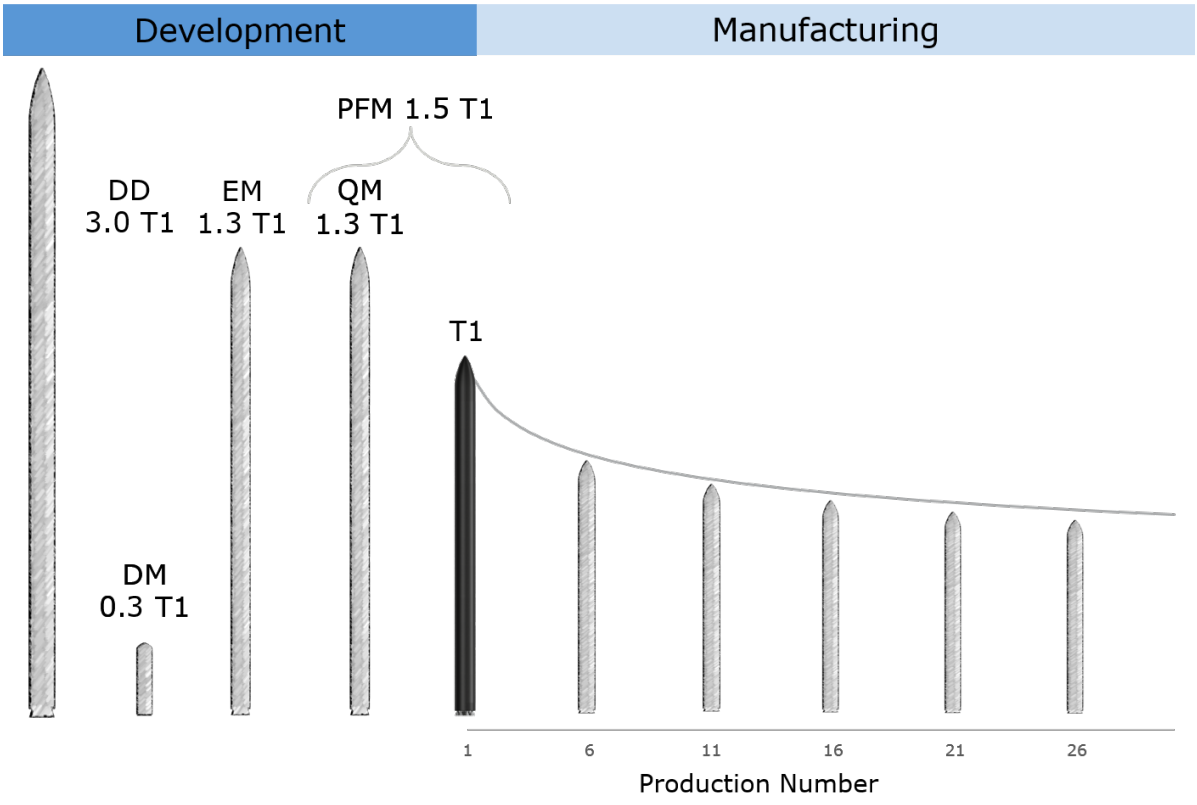


Figure 4.1: Model philosophy including cost improvement during the manufacturing of a launch vehicle, split per phase [82]

A piecewise cost estimate for each subsequently less expensive launch vehicle that is produced would hold little meaning for some companies. This is because production of a launch vehicle like the Ariane is often ordered in batches or so called "lots" [32]. What is more, costs are also often reported in lots [4]. Therefore, a total batch cost is a useful figure to also include in the research.

Once batch costs are known, M/PA costs per subsystem element are added on proportionally. Finally, the prime contractor also adds an additional layer of management overhead to the total costs, and this is

[3] Including software

also layered on as a level-of-effort cost [39]. The fact that two M/PA factors are multiplied together accounts for the overlap between both subcontractor and prime contractor's activities, as some of the work already performed needs to be re-checked or synthesized by a team that is unfamiliar with the system, for example during final integration by the prime [83]. In this way, the manufacturing costs are determined.

Equation (4.1) shows all cost components for one launch vehicle manufactured, including manufacturing learning factor L_m, First Flight Model Cost $FM1$ and Management & Product Assurance ($M/PA\%$) costs as a percentage of FM1. Also included is the subcontractor profit reduction factor, a concept developed in Section 3.4.4 and demonstrated in Equation 3.10.

$$MAN = c_p \cdot (MAIT + M/PA\%) = c_p \cdot (FM1 \cdot L_m + M/PA\%) \tag{4.1}$$

For a batch or lot, the total lot manufacturing effort is naturally a function of the lot size N, which is included in the cumulative learning factor L_c[4], and explained in Section 4.1.1. It also depends on the FM1, as well as the M/PA% and c_p, as shown in Equation (4.2).

$$MAN_b = c_p \cdot (MAIT_b + M/PA\%) = c_p \cdot (FM1 \cdot L_c + M/PA\%) \tag{4.2}$$

This approach of using the T1 as a basis for manufacturing costs along with development T1 equivalents has been proposed by the Space Systems Cost Analysis Group (SSCAG) professional cost engineers organization [58, 82], applied throughout tools such as NAFCOM [71] and *TruePlanning*, and a concept applied in an agency context at ESA and NASA [69]. A new contribution will be made to this approach by proposing adjustments made to the M/PA and I&T factors relevant to commercial rocket development, and showing the potential of estimates made with this novel way of estimating.

Now the general methodology to determine manufacturing single and batch unit costs has been described, it is time to clarify the elements that make up the manufacturing cost parametric relationships in Equations (4.1) and (4.2), after which the estimating methodology is applied to the liquid methane launch vehicle .

4.1.1. Learning Curve

The learning curve is a tool for estimating recurring costs. It is based on the consideration that repetition of a task means it can be completed in shorter time periods. Even though other factors contribute to learning such as production improvements, the dominant factor in this theory is direct labour. [4]

There are two main learning theories, *cumulative average theory* and *unit theory*. The cumulative average theory is attributed to T.P. Wright in 1936 [45], and was developed while studying WWI airframe production costs [106]. This can in fact be considered as one of the first examples of a parametric cost estimate [11]. The unit theory is credited to J.R. Crawford, who developed it while studying WWII aircraft production costs [4]. It has been demonstrated on launch vehicle production ata for the Lockheed AGENA rocket upper stage, the Ariane 4 liquid propellant strap-on boosters and others [45].

The first type of learning theory, cumulative average theory, states the *average cost of a batch* of units will decrease with a certain percentage once production is doubled. For example, average unit cost of a batch consisting of units 1 through 4 at a learning rate of 80% will be $0.8^2 = 0.64$ of the first unit cost. This approach is appropriate when there is substantial variability in the unit costs early in production due to for example inadequate supplier bases or short lead times, because the total batch cost is averaged. As this is less the case for the production of launch vehicles, the second type of learning theory, unit learning theory, will be used in this research.

Unit learning theory says that with each doubling of production, the costs to manufacture a *specific unit* decreases with a fixed percentage. For example with 80% learning, the second unit would cost 80% of the first unit produced. The fourth unit would cost 80% of the second unit, in total $0.8^2 = 64\%$ of the first unit cost [45].

Unit Learning Theory or Crawford Learning Curve

The unit learning theory or "Crawford Unit Learning Curve" was used extensively in World War II when there was little knowledge of the benefits of production scale and learning [11]. In the post-war period it was sub-

[4] Throughout this chapter, the phrase "learning factor" will be used often. The percentage cost reduction at production doubling will be referred to simply as the *learning factor*, and is constant p. Single n-th unit costs normalized w.r.t. T1 are called *manufacturing learning factor*, L_m. Batch costs from 1 to n are labelled *cumulative learning factor*, where batch costs are also normalized w.r.t. T1, L_c

sequently validated by the Stanford Research Institute [11], and has successfully been applied to estimating costs of launch vehicle production in series [44, 45, 97].

To revisit the concepts explained earlier, the unit learning theory states that each doubling of production means the costs to manufacture a specific unit decreases with a constant percentage.

This means that the cost of the n-th unit U_n in equivalent T1 units is [22, 25]:

$$U_n = T1 \cdot n^b \tag{4.3}$$

Where the learning exponent b is a function of the learning factor p, the factorial cost decrease associated with the production doubling [22, 25]:

$$b = \frac{ln(p)}{ln(2)} \tag{4.4}$$

The n-th unit costs normalized with respect to T1, $\frac{U_n}{T1} = n^b = L_m$, of units 1 up and until 50 is shown in Appendix F, along with the learning cost reduction factor illustrated up to 1000 units.

The amount of learning assumed is subject to the estimators interpretation, and can be based on for example the type of system to be produced, the expected quantities to be produced [22], the system's complexity or the company's experience. In any case, the learning factor for space systems is between 1.0, which means no learning, and 0.75 [45]. The latter implies a cost reduction of 25% per doubling of production. Some suggested values from literature are listed in Table 4.1.

Table 4.1: Learning factors in literature

Source	**learning factor p (%)**
Lockheed Agena [45]	85
EADS Les Mureaux [45]	88
EADS Bremen [45]	85
Complete Vehicle [45]	90
Space Systems Costing Rule of Thumb [22]	95
Program Quantity Dependent [22]	85-95
Airframes [25]	87
Electronics [25]	90-95
Missiles/Launch Vehicles, Aerojet Survey [58]	82-97

Fox et al. [22] mention a standard 95% slope is frequently used, due to its inclusion in the Unmanned Space vehicle Cost Model (USCM), a model based on NASA reference missions. However, Fox also admits that even though 95% appears to be a reasonable default value, it is primarily based on expert judgment instead of empirical data. However for larger quantities Fox proposes a steeper learning factor according to Table 4.2. Koelle suggests stages exhibit a learning factor of approximately 0.85 based on Ariane 4 liquid propellant boosters' and Lockheed's AGENA-A upper stage's cost improvement rates, and that complete launch vehicles show learning of 90% [45].

Table 4.2: Learning factors or cost improvement slopes that are dependent on total program quantity [22]

Total Program Quantity	**Cost Improvement Slope (%)**
1-10	95
11-50	90
>50	85

Considering the nature of the estimate made in this research is for an entire vehicle including all stages, and that total production quantities are expected to at least reach 11 launches but possibly not 50 [5], based on Table 4.2 and 4.1, and because Koelle and Fox indicate it is an appropriate learning factor for these types of production numbers of entire vehicles, a learning factor of 90% was selected that will remain constant throughout this text. This value at a production quantity of ≤ 50 seems appropriate to assess the concept

[5] Some flight numbers: Ariane 5 - 86, Atlas 5 - 52, Soyuz 1700+, Vega - 6, Pegasus - 42, Falcon 9 - 28

launch vehicle's profitability within 50 launches in Chapter 6. Also, the reference cases of Falcon and Pegasus have production numbers in this range, which allows the results of the Price per Flight estimate to be compared to their commercial price quotes at this rate of cost improvement as well.

However, at this point it should be noted that although historical data might indicate a strong cost improvement trend, that in fact labour improvement estimates may have an error rate of ± 25%. This makes it clear that if the methodology suggested here is applied to a program, forecasts should be continuously updated to reflect changes in the current program status, data and assumptions. [22]

The implications of this choice for a learning rate mean the following relationship is assumed between the T1 costs determined in Chapter 2, and the subsequently manufactured units.

- 2nd unit costs are 90% of T1 costs
- 4th unit costs are 81% of T1 costs
- 8th unit costs are 72.9% of T1 costs
- ...

This section has been solely devoted to selecting a proper learning curve slope, and rightly so: Fox identified that misspecifying a learning factor by ±10% can lead to overestimating production costs by 62%, or underestimating them by as much as 35% for production quantities up to 20 units [22]. This means that the selection of the learning factor p has a great influence on the manufacturing cost end result. The effect of this sensitivity, especially since learning plays such a crucial role in the proportionally large share of engine costs and their cost reduction on the liquid methane concept, will be explored later in the sensitivity analysis in Chapter 4.2.1.

Cumulative Learning Factor, Batch Costs and Average Unit Costs

As discussed before, launch vehicles are often ordered in batches, as opposed to per unit. It is therefore that the cost per batch is a meaningful quantity to determine here. Total costs for a batch are approximated by utilizing the cumulative learning factor L_c to derive batch production costs. L_c is the total T1 equivalent cost to manufacture units 1 through n. It is determined with Equation (4.5).

$$L_c = \sum_{1}^{n} L_m \tag{4.5}$$

If the batch in question does not include the first unit, e.g. production cost from unit m to unit n are desired, subtracting the cumulative learning factor $L_{c_{m-1}}$ of units 1 through $m-1$, from the cumulative learning factor L_{c_n} of units 1 through n, will yield the total production T1 equivalent of units $m \rightarrow n$ [6] [25, 58] .

$$L_{c_{m\rightarrow n}} = L_{c_n} - L_{c_{m-1}} = \sum_{1}^{n} L_{m_n} - \sum_{1}^{m-1} L_{m_{m-1}} \tag{4.6}$$

The average T1 normalized unit cost for this specific batch is then the normalized batch cost, divided by the total number of units produced in the batch.

$$L_{a_{m\rightarrow n}} = \frac{L_{c_{m\rightarrow n}}}{n-(m-1)} \tag{4.7}$$

The cost reduction factors discussed here are shown in tabular form and graphically in Appendix F.

After integration and test considerations are discussed in Section 4.1.2, the philosophy and choices outlined for the learning curve will be applied to the liquid methane launch vehicle example in Section 4.2 so that its effects can be shown [4, 45].

[6] The batch includes m

4.1.2. Integration and Test

The subject of Integration and Test (I&T) has was briefly touched upon before in Chapter 3 while producing an estimate for the development phase. It will be elaborated here. The purpose of such activities is threefold [40]:

1. Integrate a space system from components all the way to subsystems
2. Validate program requirements are met through HW/SW testing
3. Document performance and system compliance

As explained, the choice is made to approximate these costs as a percentage of hardware costs, as is common practice for indirect labor cost [81]. This is called level-of-effort costing [39]. NASA and ESA both differently report I&T costs at various levels in the WBS, and it can therefore be difficult to compare them [36]. The choice for this research fell on the ESA practice of allocating all equipment in the launch vehicle breakdown with subcontractor integration and test efforts through the standard MA**IT** support function, and adding onto that an overhead prime contractor I&T factor for system level integration and test work.

In Space Mission Engineering: The New SMAD, the successor to the seminal Space Mission Analysis and Design (SMAD), Wertz et al. [101] suggest the I&T factor should lie between 1% and 33% of hardware costs, averaging 15%. The variations depend on qualitative observations such as identifying many components or conflicting requirements. An approximation should surely fit within such an extensive range. At least Wertz adheres to the approach of wrapping all hardware costs with this I&T overhead, while the ESA approach chosen splits these between system-level and subsystem-level I&T. It is therefore that the applied factor at a system level will be lower than suggested by Wertz. With an eye on the early parametric scope of the estimating work in this text, a choice is made to adhere to an average level-of-effort I&T cost. The reasoning above requires the approximated I&T overhead to be at least less than 15% based on the average set out by Wertz [101].

Delving into further detail, and examining some sample values of this support function cost throughout the space industry, Table 4.3 lists sample values for spacecraft integration and test efforts reported by NASA in its 2009 and 2015 budget estimates [1, 3].

Table 4.3: Integration and Test (I&T) efforts and their relation to hardware costs [1, 3]

Project	I&T [$M]	Hardware [$M]	I&T (%)	Year	Current/Base Year
Mars Science Laboratory "Curiosity"	49.8	579.9	8.6	2009	CY
Lunar Reconnaissance Orbiter	8.7	202.4	4.3	2009	CY
Glory Mission	2.7	102.5	2.6	2009	CY
ICESat-II	18.5	166.4	11.1	2013	BY
Soil Moisture Active and Passive - SMAP	21.8	182.4	12.0	2014	CY
James Webb Space Telescope	295	3994.2	7.4	2014	CY
Magnetospheric Multiscale - MMS	48.8	466.7	10.5	2014	CY
Global Precitipation Measurement - GPM	12.2	342.3	3.6	2014	CY
OCO-2	5.5	127.7	4.3	2014	CY
OSIRIS-Rex	24.9	220.2	11.3	2014	CY

The average I&T effort is approximately 7.6% of hardware costs for these programs. Unfortunately NASA has not listed similar costs for launch vehicles, but as Figure 4.2 - produced with the data in Table 4.3 - shows, I&T cost percentages are spread independently from hardware costs[7], which makes them scalable to launch vehicles as well. This makes sense because many well-known companies such as Boeing or Airbus integrate both satellites and launch vehicles according to the same standards set out by governmental organizations, such as ESA's ECSS standards [17].

Also in Figure 4.2 are the total I&T costs set out against hardware costs[8]. This analysis confirms a dependency between the two, a similar one as was also described on a different dataset for points of integration by Powers [81].

[7] Dataset: I&T, % of HW
[8] Dataset: I&T Cost

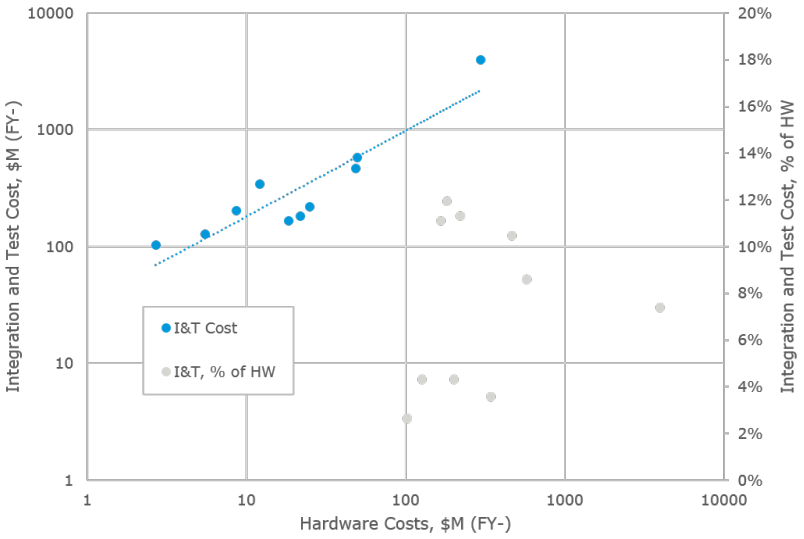


Figure 4.2: Integration and Test (I&T) costs as a function of hardware cost [1, 3]

All in all, the determined average of 7.6% was considered a guideline figure to base the integration and test approximation for this research on. After EJ consultation[9], the I&T factor was adjusted slightly upwards to 9%, reflecting experience in the Ariane and Vega launch vehicle programs [83]. The effects of this choice on the final manufacturing costs will be discussed in the sensitivity analysis of the results in Section 4.2.1. At any rate, these effort costs will be scaled below for applicability to commercial rockets.

As the integration and test efforts are level-of-effort costs that depend on hardware costs, and the 50 unit hardware batch costs in the estimates in Tables 4.5and 4.6 are subjected to learning, also the I&T costs decrease over time and are subjected to the learning effect. This is to be expected from production in series as opposed to single unit production. However, the *percentage* of integration and test effort as a function of hardware costs remain constant under this approximation.

ROM I&T Check

A Rough Order of Magnitude (ROM) check for these I&T values can serve as a sanity check on the approximation. The New Horizons mission, including launch and operations, educational outreach etc... cost round about $700M. In 2010 the Atlas launch vehicle cost roughly $180M to launch, which in 2006 would have been $163M. The total hardware costs would have therefore needed to be around or just below $500M considering all other costs included in the cost figure. If this hardware cost was anywhere between $450M and $500M, and the I&T effort for the mission was roughly k$35,000 [81], it implies the I&T share was between 7.5% and and 8.4%. This confirms the order of magnitude of I&T costs proposed.

I&T Scaling

Finally, the I&T fractions derived previously will be subjected to a key concept in this research, outlined in detail in Section 3.3.2. This is the reduced Management, Integration and Testing effort associated with a reduced scope of work subcontracted out. This tactic was found to be characteristic of commercial companies' effort to reduce cost, as found during preparatory work of this research [13]. For example SpaceX contracts only 20% of total manufacturing out [12], while 60% can easily be subcontracted under traditional government development [83].

According to Table 3.2, the reduced I&T costs as a percentage of hardware costs will be lowered to approximately 3.2%. This keeps it in line with the amounts proposed by Wertz [101], while also taking into account the described reduction in management effort.

With the I&T effort now described, it is time to apply all the discussed concepts in this chapter to the cost estimate of the liquid methane launch vehicle under study.

[9] EJ Georg Reinbold, ESA TEC-SYC

4.2. Methane Launch Vehicle Manufacturing Costs

The learning curve and the approximations made for the launch vehicle's integration and test work have a profound effect on the cost estimate made on the liquid methane LV concept. Just as in Chapter 3, the cost estimate for this concept will be outlined in this section.

The main influencer of the learning curve will be the number of times a hardware element is re-used on the launch vehicle. This holds especially true for the cost driver, the engines. This LV features 12 of them to be able to easily replace them when a single engine fails, and to optimally profit from a fast cost reduction by increasing the number produced in the learning curve.

Table 4.4: Engine development and manufacturing cost of the liquid methane launch vehicle concept with equivalent weight single engine, compared to standard 12 engine configuration

			Total Mass	**Development Cost** [k€]	**Manufacturing Cost** [k€]	**Total Cost** [k€]
Single Large Engine	**Engine Mass**	3,000	3,000	120,000	540,000	660,000
	Number of Engines	1				
Standard Config.	**Engine Mass**	250	3,000	37,000	630,000	667,000
	Number of Engines	12				

The methodology described previously in this chapter is applied by adding the MAIT to M/PA support functions, with an overhead I&T and second M/PA contribution relating to the prime contractor also present. Results for manufacturing a batch of 50 launch vehicles are shown for two stages in Table 4.5 and Table 4.6. This amount was chosen to show how Return on Investment (ROI) affects a decision for a Price per Flight (PpF) in Chapter 6. The entire vehicle manufacturing costs including M/PA overhead are shown in Table 4.7.

Table 4.5: Liquid methane concept 1st stage and payload, avionics and attitude control module manufacturing cost estimate for 50 units

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Total FU [k€]	FM1	MAIT	M/PA	Manufacturing Cost [k€]
Stage 1	*Liquid Stage*			**5,778**		**36,867**		**848,275**	**47,002**	**867,940**
	Solid Casing		S-SC-	-	-	-	-	-	-	-
	Pressurizant Tank		S-PT-	103	1	543	515	16,549	917	16,933
	Fuel Tank		S-FT-	727	1	2,187	2,072	66,604	3,690	68,148
	Oxidizer Tank		S-OT-	873	1	2,492	2,361	75,880	4,204	77,640
	Stage Structure									
		Thrust Cone	S-SS-TRC	180	1	319	302	9,716	538	9,941
		Skirt	S-SS-SKI	656	1	1,038	983	31,599	1,751	32,332
		Thermal Control	S-SS-THM	24	1	51	48	1,547	86	1,583
	Engine(s)		S-EN-	250	12	29,315	2,315	618,284	34,258	632,617
	Thrust Vector Control		S-TV-	113	1	606	574	18,445	1,022	18,873
	Pressurization System		S-PS-	0	1	0	0	0	0	0
	Pipes & Valves									
		Pipes	S-PV-PIP	65	1	158	150	4,825	267	4,936
		Valves	S-PV-VAL	30	1	93	88	2,834	157	2,900
	Stage Harness		S-SH-	7	1	65	62	1,992	110	2,038
Payload				**250**		**1,365**		**41,571**	**2,303**	**42,534**
	Payload Adapter		P-PA-	50	1	402	381	12,252	679	12,536
	Payload Fairing		P-PF-	200	1	963	912	29,319	1,625	29,998
Avionics				**67.10**		**2,412**		**73,456**	**4,070**	**75,159**
	Avionics									
		Comms	A-AV-COM	26	1	696	660	21,211	1,175	21,702
		Power	A-AV-PWR	28	1	599	568	18,250	1,011	18,673
		Data Handling	A-AV-DHL	13	1	1,116	1,058	33,996	1,884	34,784
		GNC	A-AV-GNC	0	1	0	0	0	0	0
		Avionics Harness	A-AV-HNS	0	1	0	0	0	0	0
Attitude Control				**51**		**4,921**		**149,859**	**8,304**	**153,333**
	ACM		C-AC-	51	1	4,921	4,662	149,859	8,304	153,333
I&T				**3.2%**		**1,440**		**43,850**	**2,430**	**44,867**
	Stage I&T		I&T	-		1,165	1,104	35,480	1,966	36,302
	PAA I&T		I&T-P-	-		275	260	8,370	464	8,564

Table 4.6: Liquid methane concept 2nd stage and payload, avionics and attitude control module manufacturing cost estimate for 50 units

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Total FU [k€]	FM1	MAIT	M/PA	Manufacturing Cost [k€]
Stage 2	*Liquid Stage*			**1,740**		**6,955**		**211,824**	**11,737**	**216,735**
	Solid Casing		S-SC-	-	-	-	-	-	-	-
	Pressurizant Tank		S-PT-	45	1	300	284	9,144	507	9,356
	Fuel Tank		S-FT-	611	1	1,932	1,831	58,840	3,260	60,204
	Oxidizer Tank		S-OT-	168	1	770	730	23,452	1,299	23,995
	Stage Structure									
		Thrust Cone	S-SS-TRC	50	1	100	95	3,043	169	3,113
		Skirt	S-SS-SKI	516	1	834	790	25,400	1,407	25,989
		Thermal Control	S-SS-THM	8	1	19	18	594	33	608
	Engine(s)		S-EN-	250	1	2,443	2,315	74,399	4,122	76,124
	Thrust Vector Control		S-TV-	49	1	365	346	11,109	616	11,367
	Pressurization System		S-PS-	0	1	0	0	0	0	0
	Pipes & Valves									
		Pipes	S-PV-PIP	20	1	70	67	2,144	119	2,194
		Valves	S-PV-VAL	15	1	58	55	1,759	97	1,800
	Stage Harness		S-SH-	7	1	64	60	1,941	108	1,986
Interstage				**25**		**60**		**1,825**	**101**	**1,867**
	Interstage Structure		I-IS-	25	1	60	57	1,825	101	1,867
Stage I&T				**3.2%**		**222**		**6,751**	**374**	**6,908**
	Stage I&T		I&T			222	210	6,751	374	6,908

Increasing the number of hardware elements on the launch vehicle means learning for that specific equipment element will progress faster during the manufacturing phase. This conceptual launch vehicle has been designed to profit from this fact by using 12 reference engines.

In this case, from Table 4.5, the reference engine has an estimated cost of 2,315 k€ excluding Management or Product Assurance, the so-called FM1. The cost for the batch manufacture of these engines, 600 in total, which is listed in Equation (4.2), coupled with the cumulative learning factor in Equation (4.5) is then:

$$MAN_b = c_p(FM1 \cdot L_{c_{1\to600}} + M/PA\%) \to c_p(FM1 \cdot \sum_{1}^{600} L_m + M/PA\%) = 0.970 \cdot (2{,}315 \cdot 267.112 + 5.3\%) = 633\text{M€} \tag{4.8}$$

This result is also shown under the last *Manufacturing Cost* column in Table 4.5.

Table 4.7: SOLSTICE calculated total manufacturing costs of the liquid methane launch vehicle concept under study, for a total of 50 units produced

		Flight Unit Cost[k€]	**Manufacturing Average Unit Cost** [k€]	**Manufacturing Costs**[k€]
		54,242	**29,612**	**1,480,615**
M&PA			**1,425**	**71,272**
5.3%	**M/PA**		1,425	71,272
Stage 1	**Total**	**47,005**	**23,677**	**1,183,833**
	Stage	36,867	17,359	867,940
3.2%	**Stage I&T**	1,165	726	36,302
	Payload Module	1,365	851	42,534
	Avionics	2,412	1,503	75,159
	Attitude Control	4,921	3,067	153,333
3.2%	**PAA I&T**	275	171	8,564
Stage 2	**Total**	**7,237**	**4,510**	**225,509**
	Stage	6,955	4,335	216,735
	Interstage	60	37	1,867
3.2%	**Stage I&T**	222	138	6,908

The cumulative learning factor illustrates that the total cost to manufacture 600 engines with cost improvement, is equivalent to manufacturing 267 of the T1 engine. Hence the nomenclature *"T1 Equivalent"*. Without learning, 600 equally priced units would cost $600 \cdot FM1 + M/PA\% = 1{,}400$M€, which is more than twice the cost. All of this is the case assuming no changes take place to the manufacturing line over production, and learning is therefore constant with no unlearning taking place [4, 95].

An added benefit of using multiple engines is also that a smaller engine will have lower development costs than a larger one, and those are non-recurring costs that need only to be suffered once. In Table 4.4 a rough approximation of engine development costs and manufacturing costs for 50 launch vehicles is shown, both for the case where there would theoretically be a 3,000 kg engine mounted to the thrust frame, and for the standard 12 engine configuration at 250 kg a piece.

From Table 4.4 it appears that at first glance the decision to incorporate multiple smaller engines instead of a larger engine would be slightly uneconomic. However the decision is never that simple. Adding multiple engines together will increase the total assembly weight as extra struts are needed. On the other hand this effect is also offset somewhat by the scrapping of a roll control system that is needed with a one engine system. Leaving the roll control system out will decrease the multi-engine concept's cost again. Because of so many influencing factors, a more in-depth tra studiesde-off study between these examples is needed before outright stating costs benefits of one concept over the other. The developed methodology and tool will be able to aid in making these trade-offs. [45]

4.2.1. Sensitivity of the Manufacturing Costs

Learning Curve Sensitivity

As identified by Fox et al.[22], the manufacturing costs are sensitive to variations in the selection of the learning curve slope, the learning factor. By assuming a learning factor of 95%, and thereby misspecifying it 10% from its true value, errors of up to 62% can occur.

In the case of the liquid methane rocket, a 90% learning curve was chosen. In this section the effect that variations in the "true" cost improvement have under this assumption will be explored. This is especially crucial since the cost improvement curve plays such an important role in the batch costs of the main cost driving element, the engines. Out of the 900 million first stage hardware production costs, 600 million is made up of the engines' cost alone, so large variations of final cost are expected when modifying the assumed learning curve.

To explore such variation, the learning factor of 90% is varied between its minimum and maximum observed values in Table 4.1. This will coincidentally be the same range as suggested by a survey by Aerojet on cost improvement for missiles and launch vehicles [58], namely between 82% and 97%. Similar to Fox' [22] theoretical approach, only incorporated in an applied estimate to a launch vehicle, the percentage error in the estimate introduced by assuming 90% learning is illustrated relative to differing values of "true learning", the true percentage of cost improvement experienced during manufacturing. The results of this analysis are listed in Table 4.8.

Table 4.8: Error introduced by assuming a 90 % cost improvement rate learning factor p, compared to the "true learning" experienced during manufacturing, after [22]

"True Cost Improvement (%)"	**Total Cost [k€, 50u]**	**Average Unit Cost [k€]**	**Percent Overestimated/ Underestimated (%)**
82	909,783	18,196	39
86	1,159,099	23,182	22
assumption: p = **90**	**1,480,615**	**29,612**	**0**
94	1,893,392	37,868	-28
97	2,277,090	45,542	-54

If the true cost improvement in the manufacturing process would be 82%, as is possible according to Meisl [58], the total 50 rocket batch manufacturing costs would be overestimated by 39% compared to their actual cost. If however every doubling of production would cause a cost decrease of only 3% - an equivalent learning curve of 97% - the actual manufacturing costs would be underestimated by almost a factor two. This magnitude of error was to be expected considering the previous work of the think tank RAND on the subject [22]. However, this sensitivity to the cost improvement slope emphasises the need to take great care in selecting its value, and to keep the reasons for selecting it in mind when making investment decisions such as those outlined in Chapter 6.

Integration and Test Sensitivity

Because there is some ambiguity on the applicable Business As Usual (BAU, unscaled percentages) Integration and Test (I&T) level-of-effort percentages between on the one hand ESA expert judgment opinion[83] (I&T=9%), and data gathered on reference missions in Table 4.3 (I&T = 7.6%), a short sensitivity study on this parameter will feature here. As a range to vary this I&T effort over is chosen the maximum and minimum values found for the found reference missions, which is [2.6;12]. The results of these variations is shown in Table 4.9 compared with the assumed 9%. Note, all three values are initially unscaled and are reduced with the scale factor S_m = 2.85 from Section 3.3.2. This will result in a low/nominal/high considered commercial I&T level-of-effort of 0.9/3.2/4.2 percent respectively.

4.3. Validation

The validation cases presented in the previous chapter on the development cost estimation process are regrettably not usable here. Orbital ATK and SpaceX do not publish pure manufacturing costs figures to compare the estimates made through this proposed methodology with. However, a short discussion on Falcon 1

Table 4.9: Sensitivity of the manufacturing cost estimate to changes in Integration and Test (I&T) factor through scaling with the proposed commercial scaling factor S_m

	Low I&T	**Nominal I&T**	**High I&T**
Business As Usual I&T	2.6%	**9.0%**	12.0%
Commercial Scaled (S_m^{-1}) I&T	0.9%	**3.2%**	4.2%
Average Unit Manufacturing Cost [k€]	28,876	**29,612**	29,957
50 Unit Manufacturing Cost [k€]	1,443,788	**1,480,615**	1,497,827
Percentage Difference	-2.5%	-	1.2%

manufacturing costs will follow in Section 4.3.2. Finally, CERs outlined by Christopher Frank [23] which are derived from Graver [29] will be compared to the same estimate for the Solid Rocket Motor of the Pegasus XL launch vehicle, in order to assess the degree to which costs match for the two.

Notwithstanding, the total estimates for the Falcon 1, Falcon 9 and Pegasus XL vehicles show an example application of the model, and may be of interest to the reader. Therefore the manufacturing cost estimates of these vehicles is included in Appendix J, Tables J.1 & J.2 for Falcon 1, Tables J.5 & J.6 for Pegasus and Tables J.3 & J.4 for Falcon 9.

4.3.1. Maxus 9 Manufacturing Validation

A dataset that is available, is that of the Maxus sounding rocket, which is manufactured by ADS for ESA and is used to perform microgravity experiments with at an altitude of up to 790km. Manufacturing data is available for the 9th mission, Maxus 9. This mission serves as a good validation case because the exact recurring unit costs are known explicitly from an industrial proposal, which allows for the learning curve cost improvement assumption to be tested and validated.

As it is driven by a Castor 4 engine, one of which was planned to be a first stage of the Capricornio rocket (itself a three stage orbital launch vehicle) a cost estimate of a sounding rocket featuring such a stage will be deemed representative for an orbital system. A sketch of the vehicle configuration is shown in Figure 4.3.

Obviously this case can not be considered as pure commercial production, as it is performed in name of a space agency. Rather than it posing a restriction, this fact will prove to be a chance to test the methodology employed nominally, in a non-commercial approach.

This approach will be free from the adaptations proposed in the research, namely excluding the profit sharing cost reduction factor c_p found in Section 3.4.4, and also excluding the scaling of Management, Product Assurance and Integration and Test contributions by the reduced management effort scaling factor c_s, which means they are set at 15% for the first two and 9% for the latter respectively.

The tests will be performed at three levels. First, the costs are determined for the total vehicle. Afterwards, the M/PA + I&T, as well as the hardware (HW) costs only will be compared between the industrial proposal and the estimate.

The purely hardware estimate comparison will serve as a test of the learning curve approach itself, without the proposed commercial adaptations to level-of-effort costs to distort the comparison. The M/PA + I&T comparison will serve to indicate how well these assumptions on level-of-effort costs hold during traditional development.

Due to sensitivity of the underlying data, the validation is included in the confidential Appendix L. From this validation, it was concluded that the estimate performed on the Maxus 9 rocket was in line[10] with its 2011 industrial proposal by ADS[11].

[10] Within ± 10%

[11] Then EADS Astrium

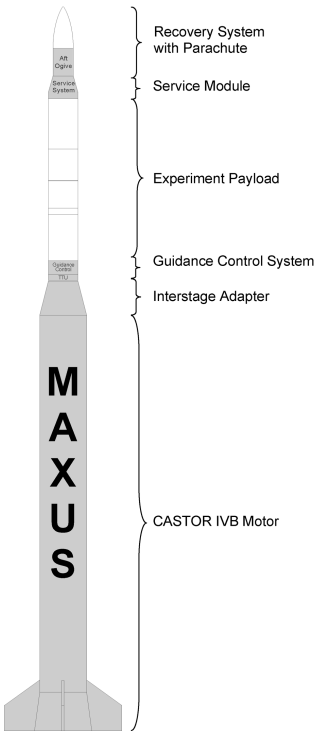


Figure 4.3: Maxus vehicle configuration, including Castor 4B engine and payload section [85]

Table 4.10: Manufacturing cost estimate validation using the Maxus 9 EADS industrial proposal, redacted. Full figures found in Table L.6

	EADS Proposal [k€]	**SOLSTICE ESA** [k€]	**Delta Cost** (%)
Top-level Costs	*redacted*	*redacted*	5.9
M/PA and I&T	*redacted*	*redacted*	-2.4
Hardware Only	*redacted*	*redacted*	8.1

The differences in cost between the estimate and proposal are highlighted in Table 4.10, which is a redacted version of Table L.6 for confidentiality reasons.

The Cost Modeling Accuracy (CMA) for this estimate's FU cost, derived in an analogous fashion to the liquid methane rocket's CMA in Chapter 2 and based on the data available, lies at 7.9%.

4.3.2. Falcon 1 Manufacturing Validation

Because the Maxus rocket example was used as a validation of the manufacturing estimate, it was not possible to test the proposed I&T and M/PA commercial scaling adjustments to the estimation methodology. In order to validate this proposed adjustment on a commercial rocket, the Falcon 1 manufacturing cost estimate including scaling was compared to its actual commercial production effort. Even though the Falcon 1 launch vehicle's costs are not widely publicized, in a news update issued by Elon musk in 2005 [68], the company says the vehicle's production cost is $5.9M (2005). The average unit manufacturing cost estimate derived from Tables J.1 and J.2 is shown in Table 4.11. Estimated production costs are 8,620 k€ (2015), which translates to $6,1M (2005). The manufacturing estimate overestimates actual costs by 3.4% and is within the target accuracy of ±10%

Table 4.11: Average unit manufacturing cost estimate for the Falcon 1 launch vehicle, based on Tables J.1 and J.2

Manufacturing Average Unit Cost [k€]		**8,620**
M&PA		**418**
5.3%	**M/PA**	418
Stage 1	**Total**	**6,233**
	Stage	5,440
3.2%	**Stage I&T**	172
	Payload Module	471
	Avionics	131
	Attitude Control	-
3.2%	**PAA I&T**	19
Stage 2	**Total**	**1,968**
	Stage	1,866
	Interstage	42
3.2%	**Stage I&T**	60

4.3.3. Pegasus XL Manufacturing Validation

Finally, the way a manufacturing cost estimate is built up for an equipment-level element in this research will also be tested with a CER that was developed specifically for solid motors by Graves [**?**]. The example launch vehicle that will be used is the first stage solid rocket motor on the Pegasus XL vehicle, the Orion 50S XL. This motor has a burn time of t_c = 69.1s, and a thrust of T = 626.3kN. The total impulse for this engine TI is 43.3MNs, but the CER is described in thousands of pound seconds, which equals TI = 9728klbss. Now the equation for the total cumulative average batch cost $CAC(Q)$ of Q = 50 units in 1988 dollars is [29]:

$$CAC(Q)77.595Q^{-0.3597}TI^{0.5081} = 2,019\text{k\$(1988)} \tag{4.9}$$

This CER assumes the Pegasus has one nozzle and is not manufactured from titanium or carbon fiber. The $CAC(Q)$ means that the average manufacturing cost of one unit out of the batch of 50 is 2,019 k$ (1988). This may be converted to a theoretical first unit ($C_{1,S}$) cost with Equation (4.10), where p is the learning factor at 90%.

$$C_{1,S} = \frac{CAC(Q)}{Q^{\frac{ln(p)}{ln(2)}}} = 3,658\text{k\$(1988)} \tag{4.10}$$

Converting this to 2015 euros yields 7,401 k€. Compared to the SOLSTICE cost estimate for the solid casing of the Pegasus rocket in Table J.5 of 7,095 k€, the theoretical first unit methodology used for this research's manufacturing cost estimate underestimates the production costs approximated by this previous research by 4.1%.

Because of the age of the CERs developed in 1993 by Graver [29], the CERs may not be up to date with current knowledge of manufacturing solid rocket engines. Costs are likely lower than higher due to technical prowess made between 2015 and 1993, and therefore closer to the SOLSTICE estimate.

Comparing that same vehicle's estimate to that of another resource, Van Kesteren [97] employs a CER which yields a lower estimate of about 4 M€. However, each phase estimate is not validated individually in this research. Subsequently, Van Kesteren combines that underestimate with a higher development cost which is not in line with the $50M (1988) it would have cost to develop this specific rocket [31, 51, 79]. In this way a reasonable cost per flight is achieved nonetheless.

4.3.4. Manufacturing Validation Summary

Validation of the estimate was performed on the Maxus 9 sounding rocket case, by comparing these costs to the industrial proposal for that rocket. Also, costs for the Falcon 1 were estimated and compared to the manufacturing costs reported for that vehicle. Finally, an estimate for the first stage solid casing *S-SC-* of the Pegasus XL rocket was compared to results from a parametric relationship developed previously [23, 29], in order to show its consistency within the existing field of cost estimates. The results of this validation are shown in Table 4.12.

The results of both vehicle's estimates are summarized in Table 4.12; for the unredacted results refer to Appendix L.

Table 4.12: Manufacturing cost estimates by the SOLSTICE model on two reference cases, compared to actual reported costs [68]. Consult Appendix L, Table L.6 for redacted Maxus 9 validation data and Airbus proposal. *Estimate from Graver [29]

Launch Vehicle	**SOLSTICE ESA Manufacturing Estimate**	**Reported Manufacturing Costs**	**Accuracy**
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) [68]	+3.4%
Pegasus XL Solid Casing	7,095 k€ (2015)	7,401*k€ (2015)	-4.1%

4.4. Conclusion, Accountability, Method Shortcomings and Limitations

In this chapter, a method was presented to determine manufacturing costs for a launch vehicle. These costs make up the first part of the total *recurring costs*, operations costs being the second part. The manufacturing costs were determined for the liquid methane rocket, as well as on three levels of a validation case for which an industrial proposal was available for consultation.

4.4.1. Accuracy Discussion

As suggested in the research proposal in Appendix K, the manufacturing cost estimate was expected to lie within ±10% of actual costs, while the development phase estimate should be less predictable at ±20%. This

has so far been the case; all manufacturing costs featured in Table 4.10 lie within the predefined expected accuracy.

Concerning the I&T and M/PA costs, the estimate made on the validation case is -2.4% (below) the proposed industrial price. It can be concluded that the management overhead or the I&T overhead, or both, are higher at EADS than their approximated values at 15% and 9% respectively. Because these costs are not reported separately by EADS, there is little transparency as to where cost excesses are incurred.

The hardware costs of the validation case were overestimated slightly, with a delta cost between the proposal and the estimate of 8.1%. The accountability for this was traced back to the Castor 4B solid rocket engine, whose costs is lower than sample data regression curve employed for this element's cost. This curve is outlined in Figure 2.4 and can be compared to the reference data in the industrial proposal provided in Appendix L.

If this FU accuracy is extrapolated to the manufacturing phase, the variations of the estimates outlined above can be explained with the CMA. As discussed before, this CMA most likely also includes Design Maturity Margin (DMM), External Project Events (EPE) and Project Owned Events (POE) risks because these were included initially in the data-points used to build up the CERs.

Of course the method itself also unavoidably includes inaccuracies in the process of estimation, for example through rounding of level-of-effort percentages included (9% and 15%) and the learning curve assumptions made (why not a learning curve of 89.99% instead of 90%). This means the costs risks described here, as well as rounding effects on the part of the estimator, will also be applicable to the liquid methane launch vehicle cost estimate.

4.4.2. Method Limitations

At the basis of the cost improvement curve lies the assumption that production takes place continuously, at a constant number of units produced over a set period of time, and that production costs can be deterministically modeled; this is never the case [57]. If any of these assumptions changes, for example when production is halted for some time due to waning demand or assembly line modifications, the method will need to be adapted. As an illustration, when production is ceased the learning effect is partially undone by a phenomenon dubbed "unlearning" [95]. Staff on the production line simply "forget" how to produce efficiently, and experience "negative learning" [55]. These changes can be incorporated in the method when actual production intervals are known in a later phase estimate.

Currently, the cost improvement curve depends solely on the unit number produced. In reality, the rate at which the rockets are produced, i.e. how many are produced per year or per month, is also something of an influence on the learning factor p. In the current method for example, rocket number 2 is assumed to cost 90% of rocket number 1, irrespective of whether the second is produced a week or ten years from the first. Actually, the improvement will be far less unless a higher production rate is maintained. In essence the result of this loss of cadence will be the same as that of the unlearning effect. Obviously, a more complex model can be constructed that takes into account this production rate, making it applicable to low- and extremely high-volume production. However the current assumptions currently made hold for rates typical of launch vehicle production, especially with little production data known at an early estimate.

Design improvements, i.e. engineering work or non-recurring costs in the production phase, are also not accounted for in the applied method, because they are not foreseen at the time of an early stage estimate. This additional work can undo learning by halting production such as described above, or could undo cost improvements because assembly line workers are unfamiliar with a new design or how to assemble a new product. In this research, the generalizing assumption is made that this type of engineering work does not take place, in order to be able to generate an early parametric cost estimate.

Finally, but possibly most importantly, the main simplification made in this method is that production costs are wholly dependent on the number of units produced, while *indirect construction costs* are included in the unit labour cost. Indirect construction costs are costs that do not become part of the final product, including: facilities, field administration, tools, direct supervision etc... [39]. Capital expenditures of this type are fixed costs that are incurred irrespective of the number of units produced. However, in this approach all costs are allocated to a specific unit in order to quantify a per-unit-cost. As with most of the assumptions made, the basis for such an approximation lies in the early nature of the estimate performed. Certainly once a project matures through phases C/D and the assumptions make way for production data, the methods employed should be calibrated at the very least, or wholly replaced by detailed bottom-up estimates.

5

Operating Cost Estimate

The last of the three main activities that make up the Cost per Flight, and the second part of the *recurring costs*, is the launch operations campaign. Absolutely crucial to a successful launch [56], it encompasses the work performed after manufacturing to get the vehicle ready for launch, and all launch operations up and until successful splashdown/disposal of all stages, and satellite launch. The methodology of estimating operations costs will be illustrated using the main thread of this research, the liquid methane launch vehicle case. After the methodology is outlined, it will be validated by comparing the values of operating costs to examples in literature, and again by comparing the total development, manufacturing and operations costs in a cost and price per flight estimate in Chapter 6 to those found for two reference cases. The definition of operations throughout the research only applies to NASA's definition of *Launch Operations*, which does not include management of payload/crew on orbit, which is considered *Mission Operations* [45, 96]. Therefore mission operations is not included in the cost estimate.

Included in the launch operations activities are [96]:

- Processing and integration of the launch vehicle, which includes launch vehicle testing as well as electrical, mechanical and fluid integration
- Processing and integration of payloads
- Launch management and control: preparation and operation of the launch pad and control centre, as well as other facilities, and countdown systems monitoring
- Logistics, which is scheduling and coordination activities
- Post launch responsibilities such as clean-up and optional retrieval of stages

TRANSCOST by Dietrich Koelle [45] is the only publicly available model for estimating space transportation operations cost [13], and sources of historical operations and support costs are not readily available because the private space industry guards this data closely [46]. It is therefore that the parametric method supplied by Koelle will be applied here in Section 5.1.1 and Section 5.1.2, where first the assumptions and inputs made will be outlined, and afterwards the results will be shown per subsection.

The method has been applied to small launch vehicles before in [97], who suggested Koelle's method overestimates costs for small launch vehicles. With no clear indication of where this overestimate stems from, there is no way to test whether the operations estimate will be too high for this particular research vehicle. Luckily, some resources such as a U.S. Congress report [96], a RAND study into launch vehicles' life-cycle costs [15], studies into reduced launch costs for small satellites [48], and a short discussion on the economic model of usable and expendable launch vehicles by Wertz [100] can shed light on whether or not the estimate made with the TRANSCOST method is representative for small vehicles. This discussion is outlined in Section 5.2. Because the estimate was performed before, the focal point of this chapter will lie on the method results and if this is in line with publicly available resources, and whether the estimate can be considered applicable to small launchers. Finally, Section 5.3 will feature a sensitivity analysis of the operating costs on the launch rate and the operations cost improvement factor.

5.1. TRANSCOST Operating Costs

The method proposed by Koelle is based on CER's which require certain assumptions on the part of the vehicle configuration and operations procedures. These assumptions will be discussed briefly, before they are applied in the sections that follow.

One assumption that lies at the basis of the estimate is that a launch pad is leased, and not owned by the launch service provider. This entails that the direct operations costs include a launch site user fee, instead of having it accounted to the indirect operations costs as a company cost if it wás owned by the provider itself. Another is to assume a constant operations cost, by estimating an average cost improvement factor L_o for launches 1 through 50. The average and total costs for the 50 total units will be representative of actual operations cost, but initially they will be underestimated and with higher number of units they will be overestimated. Section 5.3, Table 5.4 will show the difference this assumption makes is only in the order of a few percent.

The main distinction in operations costs made by Koelle is between *Direct Operations Costs* and *Indirect Operations Costs*, and these will be treated here separately. The main Ground Rules and Assumptions and input parameters for the TRANSCOST model are listed in Table 5.2. To facilitate referencing, most symbols have been kept analogous to the work of Koelle, with some exceptions. With these GRA's set, the parametric CER's described by TRANSCOST listed in Table 5.1 and Equation (5.1) are enough for an initial estimate of the operations cost.

It is here that necessary assumptions inherent to an early phase estimate (Section 1.2.5) play a role. It is thinkable that standard hourly rates and therefore work-year costs W in a commercial company could be lower than those proposed by Koelle. However, because of a lack of publicly available data on company-specific work-year costs, other values for these costs are not used. Even though the estimator might know better, this reference number is kept as standard. This allows the CER's with commercial correction factor f_{11} to be used in the PpF estimate, and to check whether the proposed commercial correction factors in Chapters 3 and 4 hold within the desired accuracy that is the research goal.

5.1.1. TRANSCOST Direct Operating Costs

Direct operations costs (DOC) are cost 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.

Table 5.1 shows the Direct Operations costs of the liquid methane vehicle example with all individual segment cost CER's adapted from TRANSCOST 8.2 [45] and the results of the applied estimate. The propellant costs are simply the oxidizer, fuel and pressurizant masses combined with the specific costs-per-kilogram (c_{ox},c_f and c_{pres} respectively) listed in Appendix G, Table G.1.

Table 5.1: Direct Operations Costs based on TRANSCOST model [45], with learning factor L assumed constant for an average 50 units

Segment	**CER**	**Costs** [k€]
Ground Operations	$W \cdot 8 \cdot M_0^{-0.9} \cdot N^{0.7} \cdot f_v \cdot f_c \cdot L \cdot f_8 \cdot f_{11}$	2,738
Propellant Cost [111]	$\frac{M_p}{r+1} \cdot c_f + (M_p - \frac{M_p}{r+1}) \cdot c_{ox} + M_{pres} \cdot c_{pres}$	36
Flight and Mission Operations	$W \cdot 20 \cdot Q_N \cdot LpA^{-0.65} \cdot f_v \cdot f_8$	762
Transportation Costs	$T_s \cdot M_0$	465
Fees and Insurance Costs	$I/1000 + F + c_{payl} \cdot P$	1,332
Direct Operating Costs		**5,323** k€

Table 5.2: TRANSCOST operations cost model ground rules and assumptions (GRA) [45]

Parameter	GRA	Units	Symbol	Justification
Launches per Year	8		LpA	SpaceX average incl. 2016 full year
Assembly and Integration factor	0.85	-	f_c	Vertical and transportation to launch pad, requirement from customer
Country productivity factor	1	-	f_8	Nominal value for first estimate
Vehicle type factor	0.8	-	f_v	Liquid storable propellant
Vehicle complexity factor	0.8	-	Q_N	Number of stages times 0.4 for ELV's
Commercial factor	0.55	-	f_{11}	Commercial operation multiple, suggestion by Koelle
Average learning factor operations	0.64	-	L_o	Constant over 50 launches at 90% learning
Work year costs	286.425	k€	W	Based on inflation, linearly extrapolated from Koelle
Number of stages	2	-	N	Given in vehicle design, Appendix B
Fuel and oxidizer mass	78,780	kg	M_p	Given in vehicle design, Appendix B
Gross Lift-off Weight (GLOW)	86.69	Mg	M_0	Given in vehicle design, Appendix B
Pressurizant Mass	49	kg	-	Given in vehicle design, Appendix B
Mixture ratio	3.15	-	r	Given in vehicle design, Appendix B
Public damage insurance	100	M€	I	Typical range, smaller than smallest russian launchers (2000 data, Koelle)
Payload capacity	300	kg	P	Given in vehicle design, Appendix B, linked to fee per maximum LEO payload
Payload charge site fee	5.51	€kg^{-1}	c_{payl}	Suggested in TRANSCOST
Launch site fees	1,220	k€	F	Inflation and exchange of "Virginia Space Port" costs
Specific transportation cost to launch site	5.365	€kg^{-1}	T_s	ESA internal cost-per-kilogram reference
Percent of work subcontracted out	20%	-	S	SpaceX reference example [12]

5.1.2. TRANSCOST Indirect Operating Costs

Indirect operations 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 [45], all of which are also termed "commercialization costs". An indication of the magnitude of IOCs per launch was developed by Koelle graphically, and repeated in Figure 5.1. Here, the costs of a single man work-year for a dedicated launch provider company with 100% of procurement costs contracted to one or more companies, is shown on curve A. Curve B shows the reduced personnel effort required when prime contractor and service provider work more closely together compared to curve A. Finally, curve C is an example of reduced costs if the launch vehicle producer is also the launch service provider, as is the case with SpaceX. [45]

Examining this figure, it is clear the IOCs per flight depend on the launch rate per year. This is to be expected as the costs of administrative personnel is constant if hired on a full-time basis. Divided over a higher number of flights means the personnel cost per flight will decrease. However, a fixed cost per flight at the asymptote is also visible, and these are most likely the costs attributed to marketing effort per flight or related to the technical program/procurement [45].

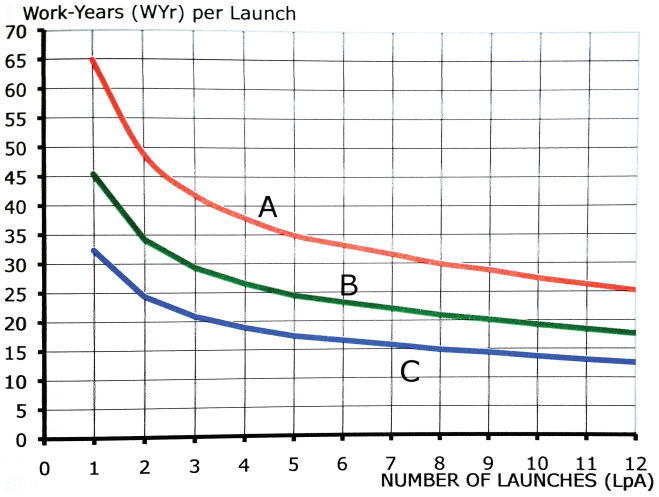


Figure 5.1: Indirect operating costs as a function of Launches per Annum [45], from which the CER Equation (5.1) was derived

A CER for the IOCs was developed specifically for this research from the graphical interpretation Koelle has made in the TRANSCOST method, the relationship of which is shown in Equation (5.1)[1]. For 20% subcontracted out, S will be a decimal 0.2 in this relationship. It is critical while applying this relationship to note that this is no replacement for an estimate which takes into account a team size for program administration. CERs such as this, which are based on reference companies such as Arianespace and SpaceX, should be replaced by bottoms-up estimates once requirements have crystallized [94], and the fact that it is applied in this research as an ICE is only because the exact commercialization activities have still to be defined.

$$\textbf{IOC} = 40 \cdot S + 22.5 \cdot LpA^{-0.379} \cdot W = \textbf{4,168}\ \text{k€} \tag{5.1}$$

5.2. Results Discussion and Validation

The liquid methane launch vehicle's operation cost estimate made with the TRANSCOST method are presented in Table 5.3.

Table 5.3: TRANSCOST operations cost per flight, as a share of recurring costs

	Cost [k€]
Direct Operations	5,323
Indirect Operations	4,168
TRANSCOST Operating Cost	**9,491**
First production unit	48,717
Average production unit	29,600
Operations' share of total RC	24%

Also shown is how these operations costs relate to the production costs, and what percentage they make up of total recurring costs. As mentioned before under the assumptions, these operations costs will be underestimated initially because an average learning factor for operations will be assumed. This means that the first launch operations costs will be slightly higher than the estimate of 9,491k€, and later on they will likely be lower.

The results obtained show that the TRANSCOST operations costs are 16% of theoretical first unit costs. However solely comparing it to the first unit costs would be unfair as the operations costs are averaged. It therefore makes more sense to compare them to the average unit costs of 29,600 k€, against which both IOC and DOC combined make up 24% of the total recurring costs, see Figure 5.2.

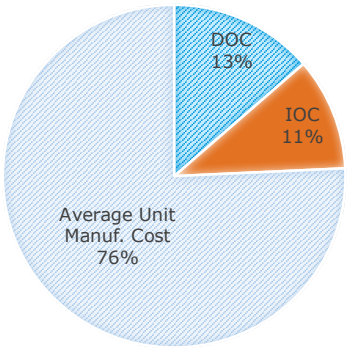


Figure 5.2: Operations cost determined with the TRANSCOST [45] method, compared to the manufacturing cost estimate for the liquid methane launch vehicle - as a percentage of recurring costs

[1] CER in k€

5.2.1. Validation

To check the results of the estimate, first the operations cost contribution to the total recurring costs will be compared to values typically found for launch vehicles and described in literature. Further validation will be provided in the form of estimates on the Pegasus XL and Falcon 1 launch vehicles, simultaneously with the Cost per Flight in Chapter 6.

Reported Operating Costs

First off, Koelle [45] himself sketches a remarkably similar ratio to the one shown in Figure 5.2 between production and operations costs, and even between DOC and IOC. According to his research, DOC lies in the range of 10-20% of combined costs - this research finds a figure within that range of 13%. Indirect operations costs should be slightly lower, averaging at between 10-15%, where this research finds 11% - within this proposed range.

Operations costs evolve to become a large percentage of total costs, as was found out during the Space Shuttle era, with values reaching up to 45% of recurring costs according to the report by Congress. However typical values for these costs of around 20% were identified for expendable launch vehicles [96]. The estimate made in this research is 4% higher than this.

In a 2005 study into alternatives for space exploration systems performed by NASA, titled *NASA's Exploration Systems Architecture Study* [73], a life-cycle cost estimate is made for various alternative launch systems. Production costs are estimated with the NAFCOM database, and a subsequent reserve factor is employed to estimate operations cost. This reserve factor was set at 10%. The difference between the full operations costs fraction of 24% determined here and this figure is evident but explainable. A governmental deep space exploration architecture does not include commercialization costs, as the launches do not need to be marketed and sold. It is therefore more appropriate to compare this figure only with the DOC of launching this small rocket, which stands at 11% and is therefore close to the averages NASA proposes. These resources suggest that the fraction of operations costs belonging to the recurring costs is correct. The available evidence suggests that the operations cost model proposed by Koelle is valid for small launch vehicles.

Validation on Commercial Small Rocket: Pegasus PpF

Operating costs are validated together with the later Pegasus Price per Flight (PpF) estimate of Section 6.2.4. Estimated Pegasus PpFs at varying launch rates (LpA) are compared to the rocket's true pricing throughout its life-cycle. The impact on pricing of changing LpA is visualized in Figure 6.6. The trend the model shows is similar to that of real price points. Because the operations cost was the only part of the estimate that is a function of the LpA (and therefore influenced by this change), the trend means that the doubling of launch prices seen in Figure 6.6 is accurately[2] reflected by differences in model results that stem *specifically* from the operations part of the estimate. It also proves high operations costs are not part of the TRANSCOST overestimate identified in previous research [97]. The estimate is also applied to the Falcon 1 PpF reference case in Chapter 6, and confirms this.

5.3. Sensitivity Analysis

Two central issues will be explored in the sensitivity analysis of the liquid methane launch vehicles's cost estimate results, with the aim of clarifying differences arising from the assumptions made in this chapter.

The first is the effect of averaging the learning during operations, which is a simplifying assumption that neglects taking into account cost decreases per unit by considering one average degree of cost improvement L_o. The difference this assumption makes on the end result is explored in Table 5.4. Initially, the operating costs will be underestimated because the average learning factor is lower than the true improvement. The initial first unit operations costs will be closer to 11,000 k€ than the roughly 9,500 k€ assumed as an average. Total recurring costs will be underestimated by 2.4%. Later units, such as the 50th unit illustrated, will have lower operations costs than the assumed average. This results in an error of 0.6% in the recurring cost estimate determined with T1. Both errors are less than the CMA outlined in Chapter 2, and are therefore indistinguishable from the variation expected in the estimate stemming from the spread of the data used.

The second effect that will be explored is that of varying the key cost driver of operations cost, the launch rate LpA [45, 100]. It was assumed that this number of Launches per Annum (LpA) was 8 as a target for the liquid methane vehicle concept. However, because this parameter has such a large effect on the estimates

[2] ±20%, research goal

Table 5.4: Error induced in the TRANSCOST method by assuming an average learning factor in the operations phase estimate, instead of applying a learning curve to the *Ground Operations Segment*, after [45]

	No Improvement	**Average Improvement**	**50th unit**
Learning factor	1.000	0.640	0.552
Total Operations Cost [k€]	11,000	9,491	9,100
Error in T1 + Operations Cost (%)	-2.4%	-	0.6%

in this chapter, the sensitivity of the final results to changes in the parameter need to be outlined. It is clear that higher launch rates result in lower operations costs per flight, but exactly how much this is will be shown here.

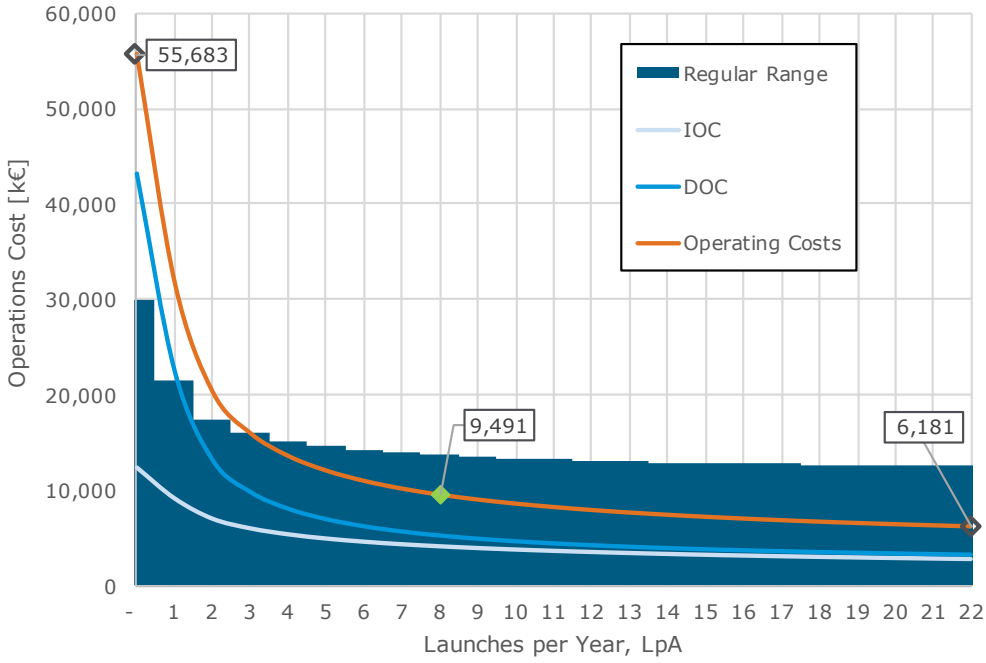


Figure 5.3: Average operations cost of the liquid methane launch vehicle concept as a function of the Launches per Annum (LpA), with the expected range maximum of 35% of recurring costs [45]

Operations costs will be determined for a range of LpA figures, for which the maximum and minimum amount of launches belonging to the analysis need to be determined. The highest amount of LpA ever to be achieved was that of the Soyuz rocket at 47 launches a year in 1979 [13]. However, since the fall of the Soviet Union the highest LpA achieved by that same vehicle was 22 in 2014; this seems a more reasonable higher bound of the sensitivity analysis. 1 launch per year would be the lowest amount imaginable, but the reference case of the Maxus rocket is launched even less, at an average of 0.45, which will be considered the lowest bound. The resulting analysis of operations cost per flight as a function of launch rate is presented in Figure 5.3.

A launch rate as low as 0.45 a year, such as is the case with the Maxus rocket, will yield a total operations cost per flight for the liquid methane concept that is roughly equivalent to 100% of T1 costs at 54,000 k€, or almost twice the average manufacturing unit cost at 29,000 k€. Only after launch rates rise higher than 4 LpA does the fraction of operations cost approach typical values of lower than 35% [45] of recurring costs. The design point of 8 launches per year falls within the expected amount of operations effort, at 9,500 k€ or

24% of total recurring costs per launch. Further cost reduction at higher rates is possible, until 6,200 k€ per launch.

5.4. Discussion and Conclusions

5.4.1. Discussion

An interesting discussion may be had about the results of the operating cost estimate with the TRANSCOST method, especially the one performed on the Pegasus reference case.

The low number of launches per year has an extreme influence on the operating costs, making them roughly twice as high as the total manufacturing costs of the rocket, as illustrated in Figure 6.8. This high estimate is driven specifically by higher indirect operating costs. Clearly this high estimate has either or both of two implications:

- The source of the previously identified TRANSCOST overestimate for small launch vehicles in [97] stems from a gross overestimation of IOCs, which would explain a phenomenon which was not directly identified in previous research
- At very low launch rates, small vehicles become more expensive to operate due to increasingly high indirect operating costs per flight

The first hypothesis is immediately rejected, as the IOCs were never included in the basic cost model employed in [97] because they were considered negligible in that work. Moreover, the validation in Chapter 6 proves that the results of the operating cost estimate are valid. However, clearly the fact that about *a tenth* [45, 73, 96] (see also Figure 5.2) of recurring costs are usually attributable to IOCs raises the question of whether these could be considered negligible. At least it will not be considered so for this study. In any case, the overestimation of Koelle's method more likely comes from the development cost instead of in the IOC estimate, as evidenced by previous work by the RAND Corporation performed by Eisman [15] and Gonzales [27], who employ the TRANSCOST method and subsequently overestimate development costs of the Pegasus launch vehicle.

This same Pegasus launch vehicle's flight history also reveals that the second implication is correct: lower launch rates for small vehicles drastically increase prices and make the launch service more expensive. This is clearly evident from Figure 5.4 which shows Pegasus launch rates and prices. In its heyday in the year 1998, a total of 6 Pegasus flights took place from its Lockheed L1011 TriStar carrier aircraft. From 2005 onwards, the company has only managed a single year[3] where more than 1 flight took place, with no flights at all since 2013. The price increases have been steady since its 1990 price of $11M (1990), which is currently $22.5M (2015), to $30M in 2008 [84], which is currently $34M (2015), to its latest launch with a total cost of $56.3M [61, 86].

As a component of the final Cost per Flight, DOCs also increase at lower launch rates, but not as significantly as IOCs for small rockets, see Figure 6.8. This is because operations expenses on hardware can be scaled back, especially with a flexible launch platform such as a carrier aircraft in the case of Orbital's Pegasus. However, the indirect operations costs will be higher per flight because the plane is expensive to maintain, as is keeping a sufficiently trained crew and having the launch vehicle's entire commercialization program active. The size of this commercialization team is independent of the launch vehicle's size, and will therefore make up a larger amount of the Cost per Flight for smaller rockets than for larger ones. These inflated indirect operating costs for small systems are also reflected in the IOC's CER in Equation (5.1)[45], which does not depend on mass. In other words, small launch systems are particularly at risk of larger cost increases because of lower launch rates, something that can directly be attributed to higher indirect operating costs.

5.4.2. Conclusions

It can be concluded from the analysis that the operations costs are sensitive to variations in LpA especially at a launch rate of lower than 4 per year up to 100% of T1 costs, or roughly twice the average manufacturing unit costs. However, there is only a 30% difference in total operations costs between 8 and 22 launches per year, which on the total average recurring costs is reduced to 8%. Yet again this illustrates the importance of maintaining a high launch rate, but now this analysis reveals a minimum launch rate of at least 4 LpA for this specific launch vehicle to keep operating costs within acceptable bounds.

[3] 2008, 2 launches

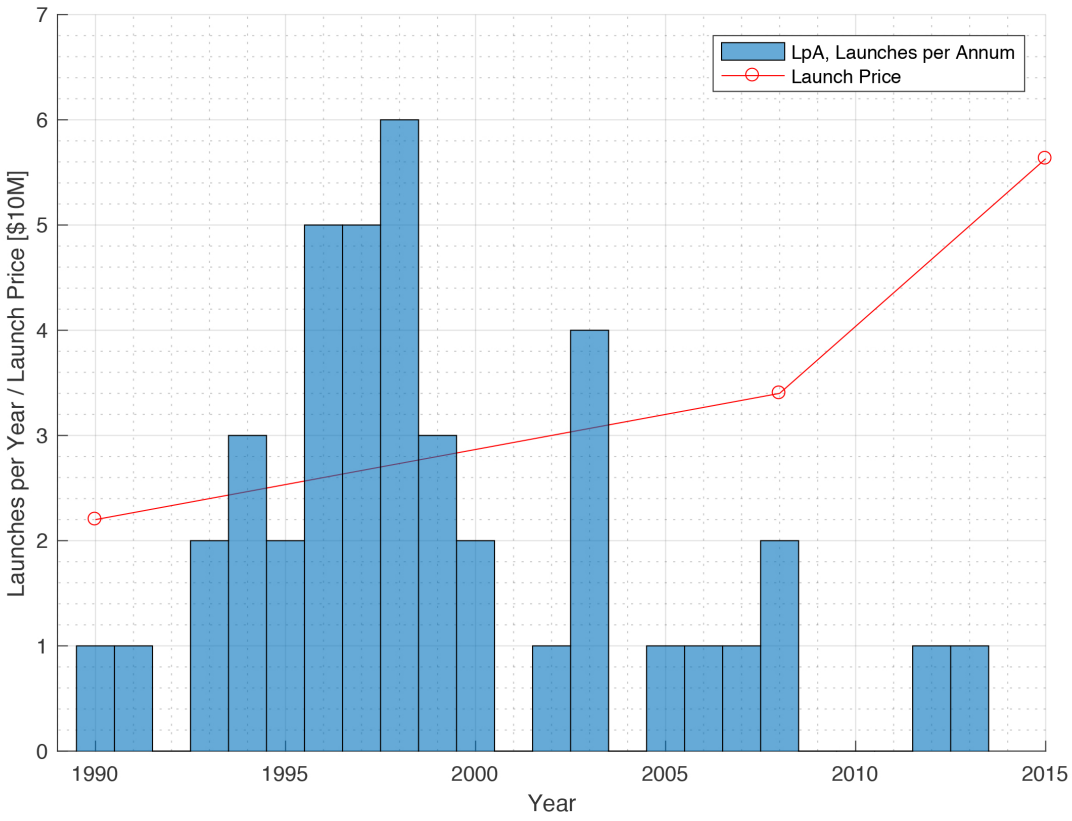


Figure 5.4: Declining Pegasus launch rates, amid a backdrop of increasing price per flight [61, 84, 86], in 2015 dollars

Compared to the liquid methane launch vehicle at the same low LpA point, the smaller Pegasus XL rocket has reduced DOCs, as these are (at least partially) dependent on GLOW, see Table 5.1. The IOCs however will remain constant according to Equation (5.1) *ceteris paribus*, and will therefore have a greater impact on the cost per flight. This effect is shown graphically in Figure 6.8, and means there is more risk of disproportionate operating costs, and specifically IOCs, at lower launch rates for smaller launch vehicles. This should be a serious consideration for any (aspiring) small rocket operator.

It can also be concluded that future small rocket launch service providers should *at least* **maintain a high launch rate** sufficient enough to keep IOC's contribution to the launch price low. This is in addition to employing other cost-saving strategies, see [13, 98] for further examples. Whether or not this high launch rate can be maintained also depends on the market demand for small satellite launches, which has been identified to grow in the coming years [61]. Conversely, the FAA reports that no such future market yet exists, but that supply of launch services could just as easily create an previously unforeseen demand [20].

These market effects and the high launch rate requirements for small launch vehicles allow us to draw conclusions on this industry's potential. Low-cost commercial launch service providers need one of two things to be successful. Either higher market demand will spur lower prices through higher launch rates and reduced indirect[4] operating costs. Otherwise, sufficiently low-priced rockets are needed to create a market demand themselves, thereby anticipating an attainable LpA schedule to keep the costs (especially IOCs) low and prices attractive. This depends on price elasticity of demand E_d, a concept explored further in Chapter 6. Wertz notes that it will be difficult to find funding organizations that will forgo their initial investment to create demand in the market for their own launch vehicles and their competitors [100]. This means it will be difficult for a new rocket to create market demand itself by pricing. Therefore it seems existing market demand must be met with high launch rates to spur lower prices. This sees dedicated small satellite launches compete directly with existing ride-share piggyback opportunities, and prices can be compared between the two in Section 6.3.

[4] And to a lesser extent DOCs

6

Price & Cost per Flight

Now that the basis for the development cost, as well as the manufacturing and operations cost per flight are established, these can be combined to form a Cost per Flight (CpF) figure in Section 6.1. This CpF represents the total cost to a company to launch a single rocket. Even though the development cost is incurred beforehand, it is attributed to - and spread out over - the launch vehicles separately. It is included in the per-vehicle-cost because in the launch price, the development costs need to be earned back for the launch service provider to be profitable.

Attributing the development cost to single units through this so-called *amortization* makes it more straightforward to establish a cost-based Price per Flight (PpF) in Section 6.2, the launch price charged by a service provider to a customer. The PpF figure for launch vehicles is something that is often publicized and therefore available for comparing an estimate to. Also, in addition to the cost-based PpF laid out in Section 6.2.1, a constant pricing strategy and its impacts on profitability will be explored in this chapter as well. This constant pricing will be rooted in a break-even analysis, explained in Section 6.2.2, and a Net Present Value analysis, discussed in Section 6.2.3.

Finally, because these PpF figures are publicized, a comparison can be made between those prices obtained through the SOLSTICE model and those officially listed. This will be done in Section 6.2.4, and a discussion on the results of the study will follow in Section 6.3.

The methodology applied here is based on experience gained at ESA's Cost Engineering Section *TEC-SYC*, with small influences from Koelle's 1984 paper [43], and work by Wertz [100]. Also, the life-cycle cost curve is inspired by suggestions of the space industry's commercial workings by Peeters [78] and Trivailo [94]. Again, the methodology will be explained by applying it to the liquid methane rocket concept, and it will subsequently be applied to reference cases in order to assess its validity.

6.1. Cost per Flight

Parts of the cost per flight, i.e. the costs per rocket launched, were established throughout this report. Three major contributors were identified: the development cost, the manufacturing costs and the operations cost. The first is a single non-recurring charge, and the latter two are recurring costs that were determined per launch vehicle in previous chapters. What remains is to amortize the development costs over a certain amount of flights in order to arrive at a development charge per unit. Later on, this will enable the conversion of the CpF into a unit PpF that also includes development costs. Then, PpF results can the be compared to freely available launch price quotes. It should be noted that government-funded development, such as is the case with SpaceX as well as the Ariane/Vega vehicles, development amortization charges are not incurred by the launching company, but rather are absorbed by the mandating agency [2, 53]. This fact is also discussed in Chapter 3.

6.1.1. Development Cost Amortization

There are no figures available on how commercial spaceflight companies (and these are few as of yet) might amortize their development costs into their pricing and repay the debt built up during initial start-up and development phases. Regardless, after the amortization phase period, the CpF will be the same for any amortization scheme. Also, the average CpF of all units in the amortization range will always be the same. It is

therefore trivial to set an arbitrary range of flights to which development costs are charged, in order to compare the costs and resulting pricing with public launch price quotes. Specifically, the average launch cost will be an important metric to determine launch pricing with.

For the amortization estimate, a number of 50 flights is chosen to amortize the development costs over. This does not mean the company operating the vehicle will be profitable in 50 flights. The *break-even-point*, where a return is made on investment, occurs sooner than this (refer to Section 6.2.2). This choice was made to avoid major discontinuities in the CpF that occur at a lower amortization range, when the amortization charge suddenly drops to zero. As an example, the CpF may halve suddenly for the 10th flight when the amortization period stops at the 9th flight. It is not expected for this research that a cost-based PpF would change drastically as well, so to reflect a more moderate and realistic pricing strategy, the amortization will be kept to this larger range. It is also a convenient number of flights to add the average manufacturing costs to, which were already determined for 50 flights in Table 4.7. Again it is emphasized that on the average CpF this choice has no influence[1]. At this point the amortization charge value can be derived, starting with the total development costs.

The liquid methane vehicle concept's development costs are shown in Table 3.6, with the total non-recurring effort being 218,555 k€. The amortization charge over 50 flights is then shown in Equation (6.1), where A is the per flight amortization charge, and N_a the number of flights over which the charge is spread. DEV is the total of non-recurring development cost.

$$A = \frac{DEV}{N_a} = \frac{218{,}555}{50} = 4{,}371\text{k€} \tag{6.1}$$

6.1.2. Average Cost per Flight

The average cost per flight for 50 units of the methane concept is determined by combining all average costs determined before. These are:

Average Manufacturing Costs The average unit production cost (MAN_a), found by averaging the decreasing estimate of the true manufacturing costs. This was done in Section 4.2, Table 4.7, and amounts to **29,612** k€

Average Operations Costs Operations costs (OPS) were assumed to stay at a constant average, a simplification that had little effect on the final result, as was shown in Table 5.4. The cost estimate stems from Table 5.3 and is **9,491** k€ for the concept rocket

Amortization Charge The development costs (DEV) are amortized as the final element of the cost per flight. Above, the amortization charge (A) was shown, which is **4,371** k€

The total average cost per flight CpF_a is determined by combining these different costs-per-flight estimates together, according to Equation (6.2).

$$\mathbf{CpF_a} = MAN_a + OPS + A = 29{,}612 + 9{,}491 + 4{,}371 = \mathbf{43{,}474}\text{k€} \tag{6.2}$$

How these three contributions to CpF relate to each other is shown in Figure 6.1.

By far the largest contribution to Cost per Flight is the manufacturing cost, with 68% of costs stemming from production alone. Operations costs are 22% of the CpF total and the last contribution, the development costs, make up 10% of total average CpF.

From the average cost per flight in Equation (6.2) it can at least be concluded that the average launch service price for this particular batch of 50 LVs should be higher than the average launch cost estimate of 43 M€, in order to make a profit.

6.1.3. Unit Cost per Flight

In addition to determining an average Cost per Flight, it is also interesting to perform a detailed analysis of the *per-unit* cost per flight. Doing so will shed light on the evolution of these costs as the program progresses. Unsurprisingly, if the unit CpF is a function of both the constant operations cost and constant amortization charge, as well as a decreasing manufacturing cost (because of the cost improvement outlined in Section 4.1.1), the CpF will naturally decrease as well. Combining these contributions in a single overview results in Figure 6.2.

[1] Also note that amortization is assumed constant; while other amortization schemes are thinkable such as amortization proportional to *recurring costs*, the end result is the same

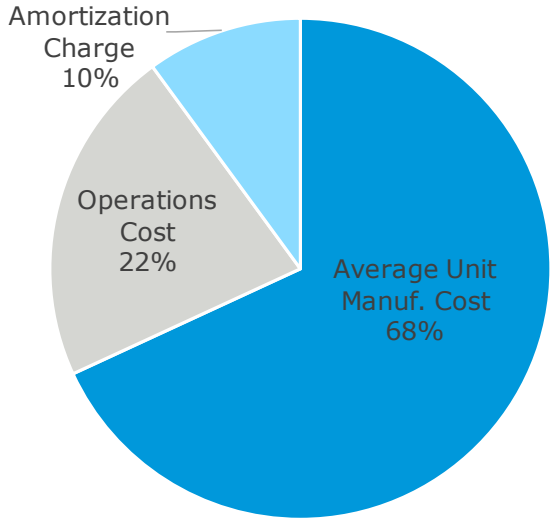


Figure 6.1: Average Cost per Flight contributions of manufacturing and operations effort, as well as development amortization charge per flight, 50 production units

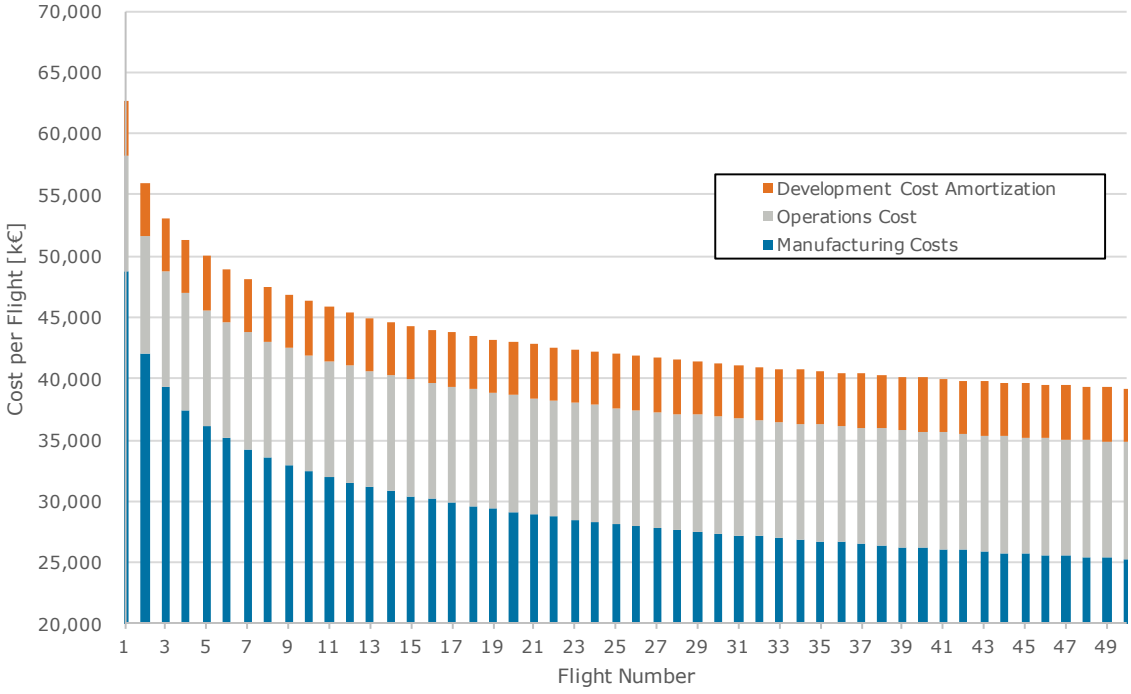


Figure 6.2: Cost per Flight for units 1 up and until 50, with the main influence the decreasing manufacturing costs due to learning

Launch costs are estimated at 63 M€ for the first flight. These costs decrease to roughly 43 M€ for the 20th flight, and improve further to 39 M€ towards the 50th flight. These results are shown in Table 6.1.

If the launch vehicle was produced for agency payloads or goals, this estimate of the CpF in Figure 6.2 would be sufficient. Even the development costs would not need to be included. However, because it is of interest to compare commercial pricing to the results obtained with this research, the analysis is taken a step further by translating cost into price.

Table 6.1: Sample of unit Cost per Flight for the liquid methane LV concept, for all unit CpF refer to Figure 6.2

	Unit 1	**Unit 20**	**Unit 50**
Development Amortization Charge [k€]	4,371	4,371	4,371
Manufacturing Costs [k€]	48,717	29,127	25,315
Operations Costs [k€]	9,491	9,491	9,491
Unit Cost per Flight [M€]	62.6	42.0	39.2

6.1.4. Cost per Flight Validation

Although no CpF values for commercial rocket reference cases are known, it is possible to compare the ratios of development, manufacturing and operations costs to those found in literature to assess the correct order of magnitude of the estimates performed. These contributions were compared to those found in a study by Larch [50] for MT Aerospace into a next-gen low-cost launcher for Europe. The concepts under study there are meant to fill the gap between the 3,000 kg GTO payload capacity of the Soyuz launch vehicle and the 10,000 kg GTO payload of the Ariane 5. This means that Larch's proposed launch vehicles are significantly larger than the one investigated for this study, which has a 300 kg to LEO capacity. While development and production costs are primarily mass-dependent, operations costs are only partially so (see Table 5.1 and especially Section 5.1.2, Equation (5.1)). It is therefore to be expected that the hardware production and development costs of Larch's launchers will make up a larger share of their total costs, compared to the liquid methane concept. This is indeed the case: ratios of life-cycle cost contributions are 78/5/17 percent for manufacturing/operations/development respectively.

On the other hand, according to Hertzfeld [33] the DoD concluded in an economic study on launch vehicles that development and manufacturing costs typically make up 30% and 50% of overall costs respectively. However, Hertzfeld notes that non-traditional entrepreneurial firms engaged in developing launch vehicles have manufacturing costs around 75% of total costs, accounting for overhead cost reductions [33]. This realistically reflects the manufacturing costs found for the liquid methane launch vehicle.

6.2. Price per Flight

Compensation paid by satellite operators for a launch is seen by them as a "cost", but in reality what is charged is a fee to cover costs, plus a profit margin. In other words, there is a distinction between the Cost per Flight and Price per Flight (PpF), where the first are the expenses incurred by the launch service provider, and the latter the amount for which a launch is sold to a customer.

To be able to compare launch quotes advertised commercially to prices derived from launch vehicle cost estimates, the latter costs need to be translated into price. Doing so requires an understanding of which prices a launch service provider would charge a customer, i.e. there is a need to understand pricing decisions. Pricing decisions are important for every company's profitability and long-term survival, and prices are the most flexible elements of a marketing strategy [5]. It is therefore that numerous pricing strategies have been explored and documented in literature.

Three main categories of strategies were identified [5]: *cost-based pricing, competition-based pricing* and *demand-based pricing*. To limit the scope of this research, which is primarily based on cost-estimating, pricing strategies in the cost-based category will primarily be explored. After the results in this category have been found, the outcomes can be compared to competitors' prices and viewed in light of market demand. In doing so the other two categories will also be touched upon briefly as well.

As a cost-based pricing method, by far most service organizations[2] employ a *cost-plus pricing strategy* [5] - where a profit margin is added onto the service's average cost. This is the first strategy that will be explored, and is detailed in Section 6.2.1.

Also, a *break-even* analysis, where at a certain number of rockets produced the sales revenues will equal the costs, is deemed appropriate [5]. This is mainly because a service provider could realistically wish to recoup their investments within a certain period. In turn, this is something that a target price can be based on. For this second analysis performed, this fixed price-target will be established in Section 6.2.2 based on life-cycle expenditure profiles, which describe investments (in particular the development phase) as a function of time.

[2] To which launch service providers will be counted

Finally, a *Net Present Value* (NPV) analysis of the launcher program will be performed. Even though this also uses the same life-cycle expenditure profiles developed in the *break-even* analysis, it will be considered here separately in Section 6.2.3. By comparing the NPV of the program at different launch prices, a simple go/no-go investment decision on the LV can be made at various prices. This is the primary use of the NPV metric. However, by reversing this reasoning, one can discover at which price point a program is worth investing in. In other words, the lowest possible prices for the program to still be realistically profitable can be identified.

All three analyses will clarify what considerations commercial launch companies might have while setting their services' prices, and facilitate translating the already determined costs into prices comparable to those set by the market.

6.2.1. Cost-based Price per Flight

In this section, a the *cost-based pricing* strategy will be explored. This means that the PpF charged by a launch service provider will be based on the system's cost. Previously, the CpF was estimated in Section 6.1, so what remains for this analysis is to determine the profit margin applied to the service.

In order to stay consistent with previous reasoning on the development cost build-up in Chapter 3, as well as to maintain transparency on the part of the cost engineer towards the ESA propulsion section customer, a standard profit margin of 8% assumed throughout ESA's tender system *"emits"* will be maintained [14]. This is done while keeping in mind the profit margin may actually vary between 4% and 14% [45], see Section 3.4.4 for details.

Combined with the unit CpF in Figure 6.2, the unit Price per Flight - which includes a profit margin - is illustrated in Figure 6.3. The price of a launch follows the cost of the launch but at a point that lies 8% higher. The average cost based $PpF_a^{\%}$ is also trivial to compute in Equation (6.3).

$$\mathbf{PpF_a^{\%}} = CpF_a + 8\% = \mathbf{46{,}952}\text{k€} \tag{6.3}$$

Also shown in Figure 6.3 is the a-priori-set fixed launch price of 45 M€ that will be the subject of the *break-even* and *NPV* analyses to follow.

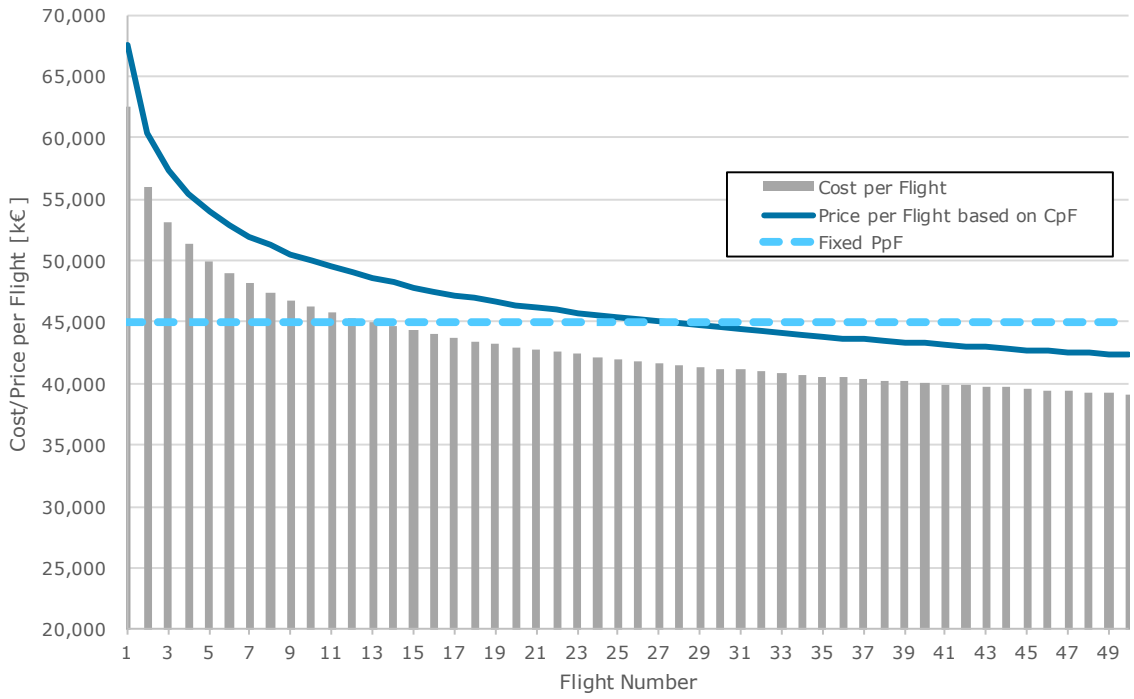


Figure 6.3: Cost per Flight for units 1 up and until 50, with cost-based Price per Flight. Includes fixed launch price for break-even and NPV Price per Flight analysis

The Price per Flight estimate for the first flight of the liquid methane launch vehicle is 67.5 M€, which

decreases to 46 M€ for flight number 20. The 50th rocket's price is estimated at 42.5 M€.

6.2.2. Break-even Fixed Price per Flight

The *break-even* analysis centers around the point where costs equal revenues [5]. For a single product all else equal, the price will then equal the cost. In the launch market however, expenditures on for example development have to be done before production and operation can start, after which revenues are made by selling the launch. What has changed fundamentally is that time has been introduced as a variable. To estimate at which point in time and at which launch number the revenues of the service will equal the costs, first the way costs are spent over time must be characterized. It is not the aim of the study to define this to the most detailed extent possible. Therefore some simplifications are made.

Realistically, a rocket manufacturer invests in factories and tooling before production starts. It means total production costs are spread over time. However, the first simplification made is that the production costs of a single launcher are all incurred at one instant, together with the operations cost and revenue from selling the launch. This allows easily attributing the manufacturing and operating costs to a single launch vehicle, and the same holds for the positive cash flow due to sales. The spread of costs per year is then only a function of the number of launches per year (LpA). The total life-cycle costs and revenues are then only a function of the LpA and the number of years the program lasts for. Further assumptions made on the life-cycle of the liquid methane launch vehicle are listed in Table 6.2.

Table 6.2: Parameters for the life cycle expenditure estimate used in the *break-even* and *NPV* analyses

Assumption	**Value**	**Justification**
Duration of Development	3 years	Based on Falcon 1 development
Manufacturing and Ops. Duration	10 years	Minimum length long term investment [105]
Inflation rate	2.8%	Average EU inflation rate 1995-2015, Appendix C

While the revenues and recurring costs can be attributed to single launch vehicles, the expenses incurred during development need to be spread out over the assumed duration of the development phase. In this case that is 3 years, see Table 6.2. Without any vehicles produced during that period, it is not possible to allocate this cost to a hardware element. However, cost engineering standard practice can be of help. The so-called *"Beta Curve"* can be used for spreading parametric cost estimates.

Beta Curve Development Cost Expenditure Profile

The *Beta Curve* is a Probability Density Function that is frequently used to describe expenditure profiles during project phases. This curve can be modified by setting two parameters of the PDF relating to cost fraction and peakedness (α and β). The curve is frequently used for R&D-type contracts [69]. While NASA utilizes the Phasing Model available via the ONCE Model portal, ESA has similar capabilities in the form of the PCS tool.

The PDF of the *Beta Curve* on the normalized range $x = [0;1]$ is shown in Equation (6.4) [21], where $\Gamma(t)$ is the gamma function $\Gamma(t) = \int_0^\infty x^{t-1} e^{-x}\, dx$.

$$f(x;\alpha,\beta) = \frac{\Gamma(\alpha+\beta)}{\Gamma(\alpha)\Gamma(\beta)}\, x^{\alpha-1}(1-x)^{\beta-1} \tag{6.4}$$

Typical space projects expend about 45%-55% of their funds within the first 50% of time. The general cost engineering rule of thumb for flight hardware or software development cost spreading, is to assume a more front-loaded distribution of 60:40, that is 60% of resources spent in the first half of development and the remainder afterwards. For ground systems the reverse is typically true, i.e. they have a spending distribution more akin to a 40:60 beta curve. [69]

Because the conceptual vehicle is actually flight-hardware, the aforementioned 60:40 spread will be assumed. This corresponds to a curve with $\alpha = 2$ and $\beta = 2.5$ However, based on the amount of technology needing pre-development (such as the liquid methane propulsion system, a propulsive technology which is completely new terrain for the European space industry) one could argue for a more front-loaded curve of for example 70:30.

The proposed expenditure profile of 60:40 is illustrated in Figure 6.4, alongside a 2-2/α-β symmetric profile as an illustrative example. Also shown is the cumulative expenditure, which reaches 60% at the mark halfway through development.

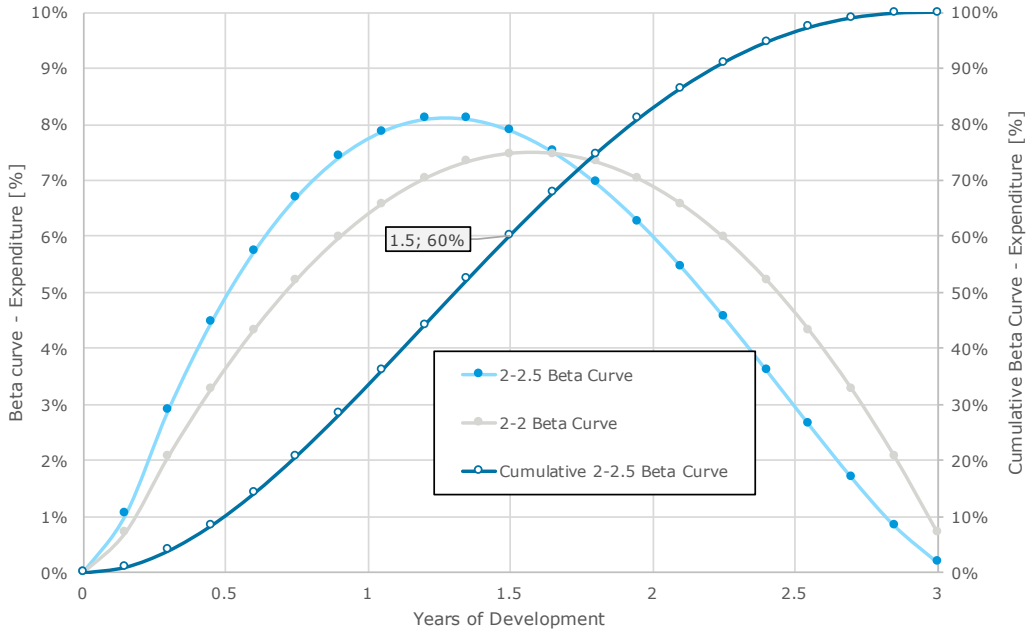


Figure 6.4: Beta distribution of the expenditure profile during the three year development phase; the curve is front-loaded with a 60:40 expenditure ratio between the first half of development and the last. $\alpha = 2, \beta = 2.5$

Break-even Pricing

The development effort was distributed over time with the 2-2.5 beta curve, and it is now possible to incorporate its cumulative effect into the sum of overall expenses and sales revenues. In this way the cumulative cash flow curve can be constructed [63], which resembles the classic J-curve frequently encountered in private equity. This curve is characterized by increasing debt, and later by accelerated returns. Using this curve it is possible to set a launch price based on a desired break-even period.

Shown in Figure 6.5 are calculated returns in the form of a cumulative cash flow curve for the entire liquid methane launch vehicle program, starting with development, which in this example kicks off in the year 2017. Returns were calculated for three fixed launch price points, as well as for the cost-based price per flight with 8% profit margin outlined in Section 6.2.1. All values are adjusted by an annual 2.8 percent of inflation, the Eurozone average over 1995-2015.

The J-curve shows that first, negative returns are realized by investing in the development of the rocket. This development spending profile is modeled by the cumulative beta distribution. Afterwards, simultaneous expenses are made in the form of manufacturing and operations costs, and revenues are also generated through sales. Because in the manufacturing and operations phase initially the launch price will be lower than the costs (which are roughly 56 M€, consult Figure 6.3), a negative rate of return will be realized initially. Afterwards profits are made until a break-even point is reached at $Returns = 0$. The subsequent period of positive returns is called the Profit Generation Potential (PGP) [52]. By setting a target break-even year in the future, i.e. an intersection of the J-curve with the abscissa, the required launch price can be varied so that desired break-even period is achieved. For example to accomplish a break-even in 10 years, the launch price must be set to $PpF^{10} = 41{,}250$k€ or higher. In a similar fashion Figure 6.5 reveals that at a launch price of 45,000 k€ the launch service provider will be debt-free starting 2024, equivalent to a break-even period of 7 years. Additionally, the strategy of selling the launch at a cost-based price (including margin and amortization) will have a break-even period of 5 years, $PpF^{\%} = PpF^{5}$. It is this way that starting with the launch costs and their spread, a pricing strategy based on break-even requirements can be determined.

6.2.3. Net Present Value Analysis

The disadvantage of the break-even analysis as presented above is that it does not account for the time-value of money. "Money in hand today is more valuable than an identical amount of money received in the future" [69] goes the old adage, which reflects the idea that money today can earn interest and is more worth today than over any period in the future, even in the face of interest. This concept is called the Present Value (PV)

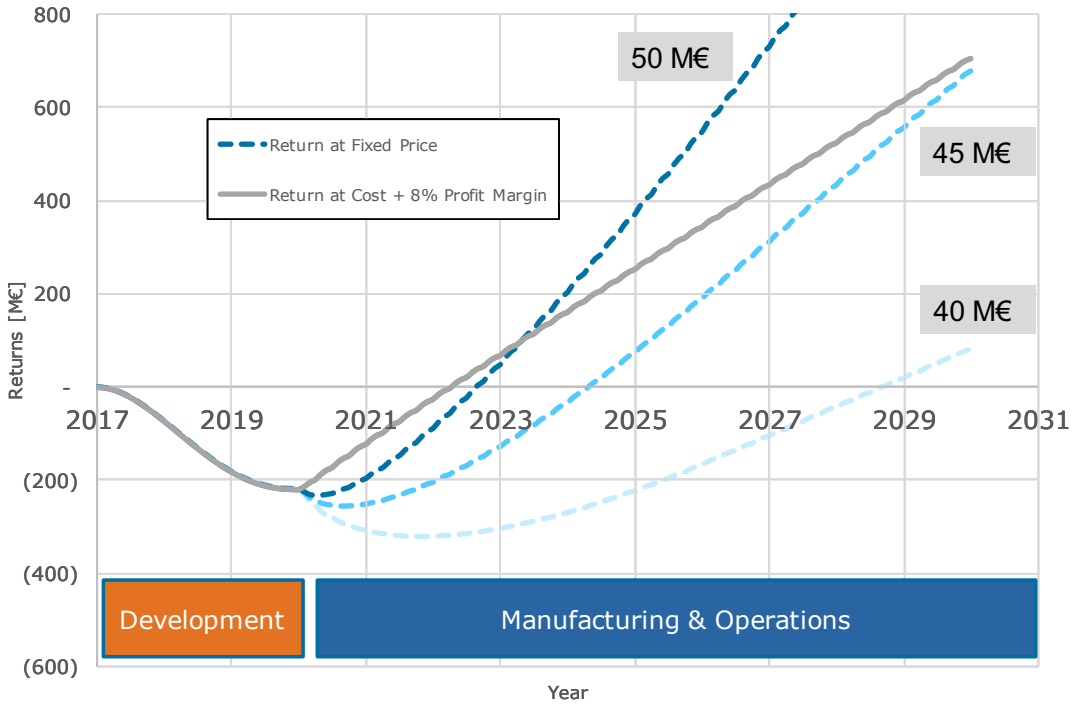


Figure 6.5: Cumulative cash flows of the liquid methane launch vehicle program over a three year development period with beta curve spending profile, and subsequent manufacturing and operations phase at various launch price target points. A break-even year may be selected by varying the launch price

of costs and benefits, and is an approximation of what future cash flows are worth today. The PV of benefits minus the PV of costs is the Net Present Value. In practical terms a launch vehicle program will be worth investing in if the NPV is positive. [69]

$$NPV > 0 \longrightarrow Invest$$
$$NPV < 0 \longrightarrow Reject$$

The NPV of the program is derived by applying a discount rate k per period, to the cash flows at period t, and subtracting the subsequent present value of the sum of benefits, which is the sales price PpF, from the sum of costs DEV, MAN, OPS over all periods n. This principle is shown in Equation (6.5). [67]

$$NPV = \sum_{t=1}^{n} \frac{PpF(t)}{(1+k)^t} - \sum_{t=1}^{n} \frac{DEV(t) + MAN(t) + OPS(t)}{(1+k)^t} \tag{6.5}$$

By comparing the NPV of the program at different launch prices and a fixed schedule, a simple go/no-go investment decision on the rocket can be made that depends solely on launch price. Such use is the primary purpose of the NPV metric. However, by reversing this reasoning, one can discover at which price point a program has a positive NPV, and is therefore worth investing in. In this way the minimum fixed launch price can be found at which the entire defined program is feasible[3].

The only value not yet set in Equation (6.5) is the discount rate k. It discounts future cash flows on the basis of assumed attainable return on funds held today, and is typically approximated by a firm's cost of capital [67], the weighted cost of debt and equity financing combined. Typical discount rates for three sources of financing are listed in [45]:

- Government loan: 7%
- Commercial lender: 15%

[3] Of course this feasibility depends on the market need at a certain price point as well, but such a market study can be performed after the minimum price is set

- Equity financing: 25%

These financing conditions are standard values in the work of Koelle, however with interest rates lower in 2016 than in 2013, a more conservative custom cost of capital value could be researched which includes a lower risk-free premium on government bonds. It is assumed that as a default, commercial companies will attract funds primarily from commercial lenders - the case for SpaceX, funded by Google and Fidelity at $1Bn [109] - which would justify a rate of 15% annually, or $k = 0.15$. However for all three types of financing and varying PpF, the corresponding NPV values are estimated, and shown in Table 6.3. Also shown are the NPVs of programs involving cost-based pricing, as outlined in Section 6.2.1.

Table 6.3: Net Present Value (NPV) of the entire liquid methane launch vehicle program under different financing conditions and varying Price per Flight. A positive NPV is required for a worthwhile investment

	Government	**Lender**	**Equity**
Applied discount rate k	7%	15%	25%
Price per Flight M€		**NPV** M€	
35	-423	-346	-279
40	-69	-36	-158
45	284	74	-37
50	638	284	83
55	991	495	204
60	1345	705	352
Cost-based Price, $PpF^{\%}$	350	148	28

A positive NPV is means the proposed launch vehicle program is worth the investment. Negative NPV, values marked in red in Table 6.3, are launch vehicle programs that have a negative value today which means these are not worth investing in. From Table 6.3 the price per flight requirements under different financing schemes can be derived. Equity financing requires a $PpF^{NPV}_{25\%} > 50$M€ for a non-negative NPV, and a Government and Lender financed enterprise requires a $PpF^{NPV}_{7\%,15\%} > 45$M€.

With the NPV metric defined at various price points, it has proven possible to derive a minimum required selling price for a launch service as a function of the funding that is secured. It is currently assumed that commercial lender funding applies to the methane launch vehicle's program. However, based on future developments the PpF should be adjusted to reflect profitability under the prevailing cost of capital.

Liquid Methane Concept Price per Flight Summary

All possible pricing strategies for the liquid methane concept are summarized in Table 6.4.

Table 6.4: Required methane concept Price per Flight summary, at different pricing strategies and conditions: *cost-based* $PpF^{\%}$, *break-even* PpF^{Y} and Net Present Value PpF^{NPV}

	Condition	**Required Price per Flight**
$PpF^{\%}$	8% profit	47 M€
PpF^{Y}	7 years break-even	45 M€
	10 years break-even	41 M€
PpF^{NPV}	7% government financing	45 M€
	15% commercial lender financing	45 M€
	25% equity financing	50 M€

6.2.4. Price per Flight Validation

Since the conditions under which a price point was established are not made public, a straightforward *cost-based* Price per Flight will be selected to perform a validation on. This will be done by comparing the cost estimate performed on two reference cases, namely the Falcon 1 and Pegasus XL rockets, to their advertised launch prices.

However, launch prices and kilogram-to-orbit prices are not only a function of program costs, but in fact service rates that have been set according to a pricing strategy. In this chapter it was shown that various launch price strategies are possible in addition to cost-based pricing. Applied pricing can also include other economic considerations, such as return periods and investment value under certain financing conditions. Surely these types of issues will also be of influence on an actual commercial price quote. That means the validation estimate performed with solely a cost-based PpF is expected to exhibit some deviation from the actual quoted launch price. This is of course in addition to variance expected within the CMA, which is explained in Chapter 2.

Falcon 1 Price per Flight Estimate

Again, just as in Chapter 3, the Falcon 1 mass breakdown is approximated by scaling the mass fractions of the Ariane 4 second stage. This mass breakdown was complemented with publicly available mass data; especially the Merlin engines are a critical point, because engine development and manufacture is a major cost driver of the entire system. Both phases' cost estimates applied to the Falcon 1 are found in Table J.1 and Table J.2 for the first and second stage respectively. However, the development of the Falcon 1 was fully covered by NASA funding [2, 53, 72]. What this means for the estimate is that development costs should not be amortized and included in the PpF during the estimating process.

The operations cost determined through the outlined method in Chapter 5 amounts to an average of 6,690k€, assumed to be set at a target launch rate of 10 per year [89]. The manufacturing (8,623k€ average) and operations costs together make up the CpF, and adding on an 8% profit nominal profit margin results in the estimated average cost-based Price per Flight:

$$PpF_a^{\%} = (MAN_a + OPS) \cdot 108\% = 16{,}538\text{k€}(2015) \tag{6.6}$$

The average price per flight is estimated at 16,538 k€, which is $13.1M (2008), and contrasts starkly with the $7.9M (2008) [13, 86] launch price of the Facon 1. The estimated average price is more than 50% higher than the listed price.

The source of this overestimate can be traced back to the operations phase estimate, as the manufacturing phase estimate is accurate to within a few percent, see also Section 4.3.2. The estimated operations costs are around 45% of the total recurring cost. It was already established previously in Section 5.4, and in particular Figure 5.2, that operations costs should typically lie around 25% of recurring costs.

However, the assumptions that lie at the basis of operations estimate do not hold for the Falcon 1 case. An adjustment to the cost estimate should be included to reflect the actual expenses incurred. First, it should be noted that Kwajalein range costs were negotiated by SpaceX and include an unknown component of public subsidy, and also that the first few manifested flights carried uninsured government payloads [41]. Because the early flights were set up under the U.S. Government umbrella, they also logically require no commercialization.

Ignoring commercialization IOCs, and building up the DOCs listed in Section 5.1.1, a subsidized average Cost per Flight can be derived:

- Launch range fees and Ground Operations Costs according to Elon Musk [89]:$0.8M (2008).
- Launch, flight and mission operations cost according to TRANSCOST [45] equal to 660 k€ (2015), or $0.522M (2008)
- Propellant cost according to TRANSCOST and Zandbergen [45, 111] of 4 k€ (2015), or $0.0032M (2008)
- Manufacturing Costs, determined with the method outlined in Chapter 4, of 8,623 k€ which equals $6,826M (2008)

The total Cost per Flight estimate adjusted for subsidies will then be the sum of the costs listed above, namely $8.1M (2008). Including 8% profit, the Price per Flight estimated is **$8.7M** (2008). This is a more reasonable approximation to the advertised $7.9M PpF [86], and is within the accuracy required of ±20%.

Eventually, the Falcon 1 was scrapped due to limited demand; the target launch rate of 10 per year was never achieved, which made costs higher than the price asked.

The basis of the cost estimate is a simple combination of development amortization, average operations and decreasing manufacturing costs, along with an assumed profit margin. While apparently straightforward,

the Falcon 1 reference case required the amortization charge to be neglected, and adjustments to be made to the operations estimate in order to reflect truly incurred costs. That these changes were necessary reflects the fact that any application of a cost model will always require additional judgment on the part of the estimator on a case-by-case basis [94]. A cost model is therefore automatically not a device with which to blindly convert a system's mass into a monetary value, or something to apply directly without questioning its outputs. It can be seen more as a tool to quickly apply a certain developed methodology, which needs to be fully understood in order to make a reasonable judgment on the results obtained. The SOLSTICE tool is therefore inherently limited to the user's understanding of the methods applied, and the conditions under which the methodology was developed.

Pegasus XL Price per Flight Estimate

As a second reference case, the average Cost per Flight and Price per Flight of the Pegasus launch vehicle will be estimated. Again, the PpF is built up of all phase cost estimates, the development cost estimate, manufacturing cost estimate and operations estimate. Contrary to the Falcon 1 PpF estimate, the development costs are amortized over each single flight in order to reach a final launch price.

From Tables J.5, J.6 and J.7 in Appendix J, the average manufacturing costs are determined for 50 launch vehicles in Table 6.5.

Table 6.5: Estimate of the average unit manufacturing costs for the Pegasus XL launch vehicle, for 50 units, based on Tables J.5, J.6 and J.7

Manufacturing Average Unit Cost [k€]		**10,339**
M&PA		**502**
5.3%	**M/PA**	502
Stage 1	**Total**	**6,110**
	Stage	4,422
3.2%	**Stage I&T**	140
	Payload Module	369
	Avionics	1,131
	Attitude Control	-
3.2%	**PAA I&T**	47
Stage 2	**Total**	**2,442**
	Stage	2,368
	Interstage	-
3.2%	**Stage I&T**	75
Stage 3	**Total**	**1,285**
	Stage	1,245
	Interstage	-
3.2%	**Stage I&T**	39

The development amortization charge and operating costs are combined with the average manufacturing cost and profit margin to reflect the total $PpF^{\%}$, all of which are shown in Table 6.6.

The average Price per Flight was estimated at 20,008 k€. Because over the entire life-cycle of the Pegasus the advertised price per flight has been so variable, it is difficult to compare it to the estimated PpF [97]. However, at a target target launch rate of 12 per year [110], the initial price of the launch vehicle was set at 20,300 k€ (2015), converted from the $22.6M (2015) price in Figure 5.4. SOLSTICE overestimates the initial price by 1.5%, which is within the established research goal of ±20%, see Appendix K, and also falls within the Cost Modeling Accuracy found in Chapter 2. This means that this type of variation in the result was to be expected.

Table 6.6: Pegasus cost-based average Price per Flight

	Amount [k€]
Development Amortization Charge	2,284
Manufacturing Cost	10,339
Operations Cost	5,903
Profit Margin	8%
Price per Flight	**20,008**

A special type of validation that explains the price-swings for this rocket relative to its launch rate *LpA* is added as an ancillary supplement to this report, in order to illustrate the flexibility and accuracy of the tool developed in this research.

First, the historical launch rates as shown in Figure 5.4 were smoothed out into a three-year centered average[4] to reflect the fact that prices are not updated continuously. This amount was chosen because it is assumed the current, next-year's, and of course previous year's launch manifest (and therefore LpA) will be known and available to base pricing on in a specific reference year[5]. For each year in operation, a Price per Flight value based on LpA was estimated using the SOLSTICE model. These estimates are shown in Figure 6.6 alongside an interpolation of known historical price points. When the difference between actual price and estimated price is more than 20%, the estimate is marked red. On the other hand, if it is within the target ±20%, the estimate is marked green. Finally, if the estimate falls within the CMA expected but outside the target range, the estimate is marked yellow.

Out of 24 points evaluated, the model estimated launch prices within the acceptance margin 17 times. This is a success rate of roughly 70%. It should be kept in mind that this result was already obtained by comparing the estimate to a a simple linear interpolation of only three actual launch price data-points. The number of points that lie within the combined accuracy target and expected CMA of 28.47%[6] is actually higher, at 20 points - a score of 83%. These 20 points are considered within the variance expected in the data used to build up the Flight Unit estimate, as well as most likely other cost risks identified in Figure I.1.

Out of the 10 years where the model did not score within ±20% intended, 7 had no launches that year or in the year either preceding or succeeding it. None of the prices in the years estimated lying out of the target range of ±20% had a three-year average LpA of above $2\frac{1}{3}$. However, to say the model is more sensitive at lower LpA would be incorrect, as many other low launch rate years correctly show an increase in the estimate where there was also a rise in prices, particularly clear in latter years.

Interestingly enough, when examining points that lie within the expected CMA but outside the target accuracy range, it is obvious these are exclusively latter-year estimates, in years where the program has matured. These estimating errors are not as extreme as ones made for the early stages of the rocket's program. Errors are possibly larger initially because pricing early on is based on an optimistic target maximum achievable launch rate of 12 LpA [110] - something which is corroborated by comparing the 12 LpA price estimate in Table 6.6 of 20 M€ (2015) to the advertised 20 M€ (2015) price at the time of its introduction - 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 that lowered price-point. Initial prices could be set lower to capture market share (Section 6.3.3), or prices may be otherwise influenced by investment value decisions and return-period requirements such as those explained previously in this chapter.

6.2.5. Price per Flight Reference Results

The price per flight estimates on the reference Falcon 1 and Pegasus XL vehicles are collected into an overview of launch vehicle prices in the 100-700kg payload class in Figure 6.7. Actual prices are within the estimates' arithmetic Relative Standard Error (RSE) or Cost Modeling Accuracy.

It would naturally be desirable to have more estimates to compare the prices in Figure 6.7 to. Mass data however, at least in the level of detail in which costs are modeled parametrically and built up in this research, is not available on other rockets. This is because on the one hand this data is company confidential and not

[4] Two-year centered average for the end-points 1990 and 2015

[5] Launch preparation activities with Orbital ATK can start as early as 24 months in advance, so the applied smoothing is still conservative [77]

[6] 20% required accuracy, and 8.47% CMA variance expected on the input data, refer to Section 2.3.2

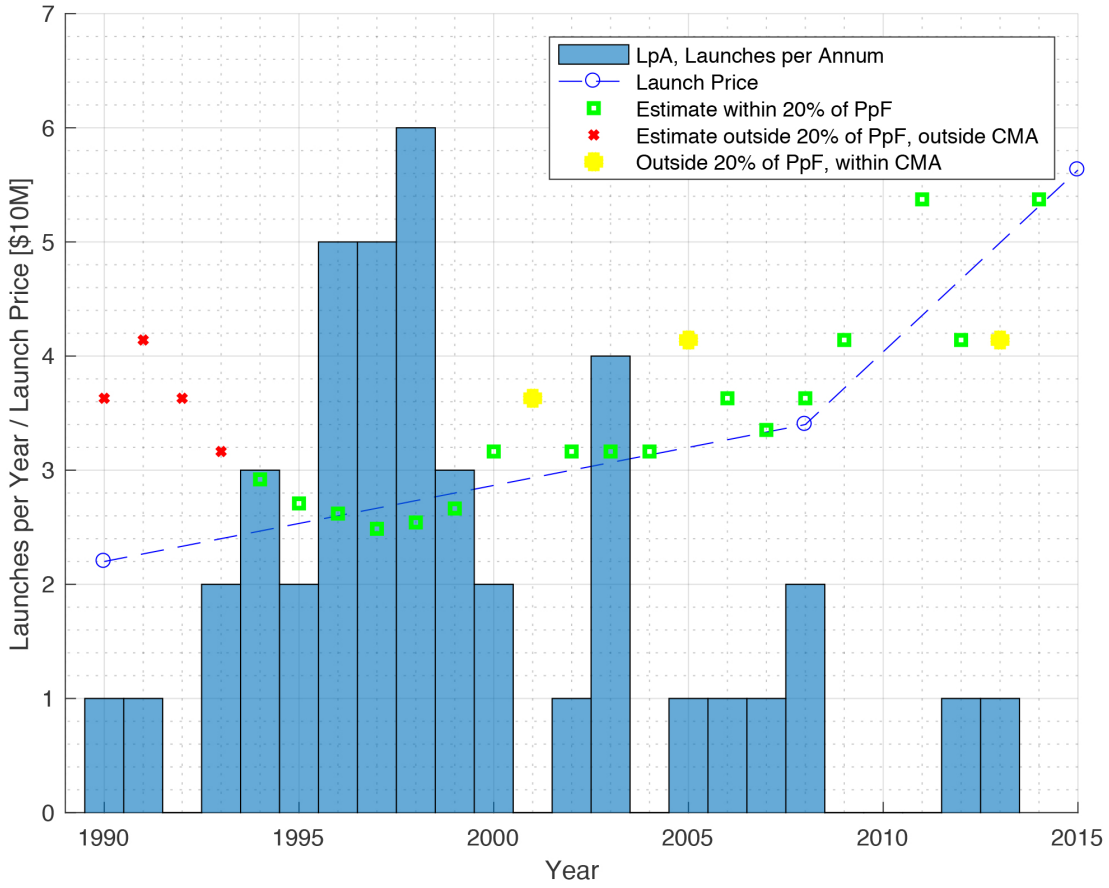


Figure 6.6: SOLSTICE estimated launch prices on a 3-year smoothed launch rate LpA, compared to the interpolated actual launch prices in blue circles. Green estimates are within the acceptance margin; the model scores 70% within the target ±20% range, and 83% within the CMA variance expected. 2010 is excluded due to a singularity resulting from a zero in the smoothed launch rate. All prices are in 2015 dollars

public knowledge, and on the other because most small rockets have not yet entered production. When more vehicles come to market is recommended to keep updating and refining the estimate made in lieu of this research. This suggestion will also feature in the recommendations in Section 7.2. For now, there are no price quotes or data to suggest the estimates made in this work do not hold. A summary of the validation cases for the PpF are shown in Table 6.7.

Table 6.7: Price per Flight estimates by the SOLSTICE model on two reference cases, compared to actual reported costs [61, 84, 86]

Launch Vehicle	**SOLSTICE ESA PpF Estimate**	**Reported Price**	**Accuracy**
Falcon 1, 10 LpA	$8.7M (2008)	$7.9M (2008) [86]	+10%
Pegasus XL 12, LpA [110]	20.0 M€ (2015)	20.3 M€ (2015) [61, 84]	+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

6.3. Results Discussion, Method Critique and Limitations

In this chapter a number of different ways to construct the Cost per Flight (CpF) and Price per Flight (PpF) were presented. The CpF per unit was determined by combining two recurring costs, the manufacturing costs and the operations costs, with a fraction of the development cost that is amortized over a set number

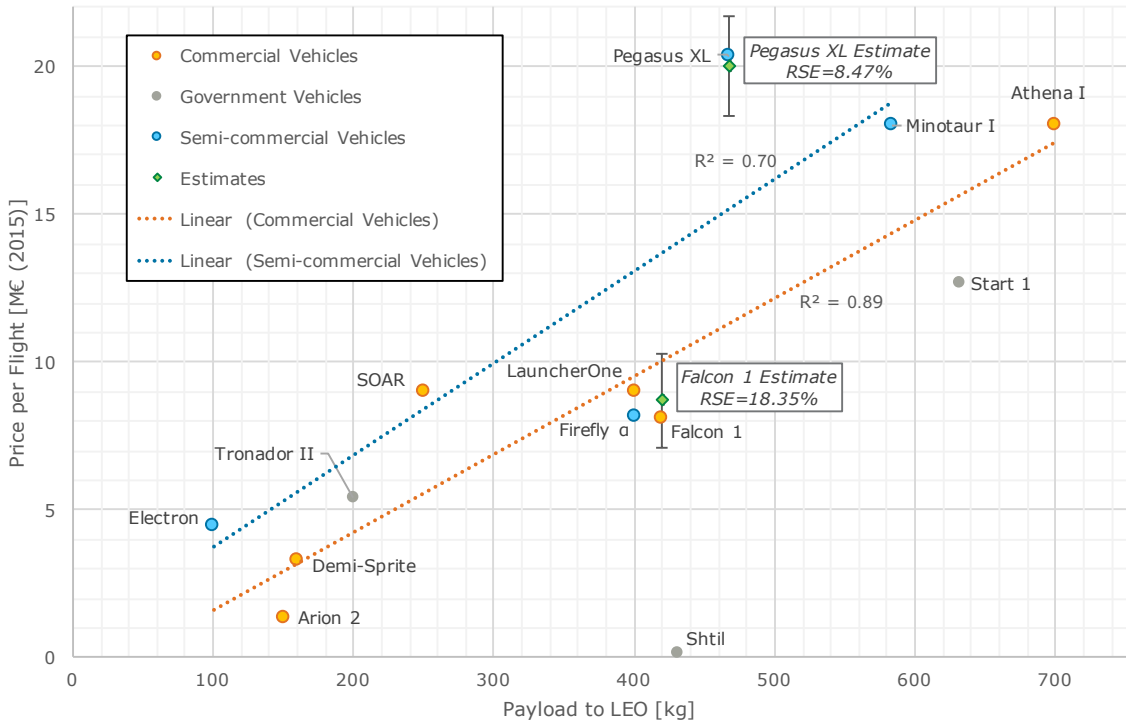


Figure 6.7: Advertised Price per Flight of small launch vehicles in the 100-700 kg payload class, as a function of payload to LEO mass [74], along with estimates made by the SOLSTICE model and their arithmetic Relative Standard Error (RSE) or Cost Modeling Accuracy

of launches. This was a simplification made to be able to attribute certain long-term program costs to a specific launch vehicle. The main advantage is that the CpF figure can be converted into a PpF, in order to set out an expected flight price. Such an approach also facilitates a comparison between results of the study and publicly available launch price quotes, as was done for the validation cases of the Falcon 1 and Pegasus launch vehicles. Of course realistically, program overhead costs, manufacturing costs on a continuous assembly line and launch facilities costs that are incurred throughout the year can not be attributed to a single rocket. However, this simplification was made in lieu of a simplified initial cost estimate for the launch program.

Even though a cost-based Price per Flight has been the focal point of this chapter, a handful of other relevant pricing strategies were outlined on which a PpF could be based. Not all these strategies could be discussed in this report, as it was never its intended purpose to explore pricing strategies to the extent that others such as Avlonitis [5] have done. Even if these strategies were explored more in-depth, their accuracy would be difficult to verify in the face of the often confidential business practices employed by commercial aerospace companies. In a launch vehicle manufacturing and operator company, such a discussion on pricing would be more at home. In such a context, not only the price but also the market demand explained in Section 6.3.3 plays a key role.

6.3.1. Launch Rate Trap for Small Rockets

One of the most important findings in this research is that small rockets are susceptible to extreme operations cost increases at low launch rates.

These proportionally high costs were first observed by estimating the Pegasus PpFs at varying launch rates (LpA), and verifying these against the rocket's true pricing throughout its life-cycle. The impact on PpF of changing that *LpA* was visualized in Figure 6.6 and corresponds to actual price increases witnessed in the Pegasus' price quotes. Because the launch price increase was also evident in the liquid methane concept and the Falcon 1, its source was researched. Operations costs were suspect because under approximately 4 launches per year, these costs will be out of the ordinary expected range of 35% of recurring costs as seen in Figure 5.3

As a matter of fact, the increases for small vehicles can be directly attributed to the *Ground Operations Costs* part of the Direct Operating Costs, as well as the Indirect Operating Costs, as these do not scale with

vehicle size (GLOW) to reduce costs for small vehicles[7]. At low launch rates these costs combined become proportionally larger. The effect is compounded for smaller rockets that have lower hardware costs than larger ones; operations costs will make up a disproportionate share of total cost per flight at lower LpA. The total operations costs will have a larger impact on the Cost per Flight (CpF) for small vehicles mainly because of the indirect operations cost increase, as can be seen from Figure 6.8. This is a problem that is particularly relevant to small vehicles, and constitutes a major cost-risk. It should certainly make keeping up a high launch rate a priority for small rocket operators that wish to run their business profitably.

The exceptional susceptibility of small launch vehicles to this cost risk is shown in Figure 6.8, where the disproportionate increases in indirect operating costs at lower launch rates for the smaller Pegasus XL rocket and Falcon 1 rocket are compared to the lower impact these costs have on the larger liquid methane (CH4) concept at, and the much larger Falcon 9 vehicle. Direct operations costs increase similarly as a proportion of the CpF, and these also influence the CpF in a major way. However, the differences between small and large rockets in the way costs are distributed stem primarily from the Indirect Operating Costs (IOC) increases.

This makes sense intuitively: direct operations costs are only partially made out of labor costs, and further consist of hardware-related expenses. These other expenses can be scaled back when not launching frequently, so direct operations costs are easily controlled. Commercialization costs, which are program administration and marketing & contracts management [45], are purely labor costs that can not be scaled back at low launch rates. It can be concluded that these size-independent and launch-rate-independent costs pose a threat to small rocket programs.

What is more, the launch service provider can choose between leasing a launch pad, and acquiring and operating this itself. The latter would render the facilities' costs under Indirect Operations Costs, which were prone to cost increases. Facilities costs per flight would be at risk of becoming disproportionately large with a low launch rate. Small rocket operators would therefore be advised to mitigate this risk by leasing their launch pads, in order to stay flexible and scale back operations in the face of limited demand.

6.3.2. Methane Concept Price per Kilogram Disparity

Something that has not yet been addressed in this chapter is how the price of the proposed liquid methane rocket concept will be in relation to competitors in the market. The average cost-based price per flight was estimated at 46,952 k€, and with 300 kg payload capacity to LEO the kilogram-specific user cost is:

$$\frac{PpF_a^{\%}}{P} = \frac{46,952}{300} = 156\text{k€}\,\text{kg}^{-1} \tag{6.7}$$

This is significantly more than for example the larger Falcon 9 rocket, which boasts a 2.72 k€ kg^{-1} payload cost. But the question is how the vehicle per-kilogram-costs stack up against its closest competitors in the small launcher market. Table 6.8 shows data gathered by Niederstrasser [74] on kilogram-specific LEO prices of future planned launch systems in the considered 100-700kg payload range, and whose prices have been converted to Euros at the 2015 exchange rate in Appendix D.

Table 6.8: Price per kilogram LEO payload of the methane launch vehicle's competitors between 100-700 kg [74]

Vehicle Name	**Specific Cost to LEO** [k€ kg^{-1}]
Firefly α	22
Demi-Sprite	26
SOAR	44
LauncherOne	49
Super Strypi	53
Electron	54
CH4 Launcher	**156**

It is clear that the methane concept has a cost-per-kilogram payload price that is too high to be able to directly compete with its nearest competitors, being almost three times as expensive as the most costly comparable rocket concept, the GO Launcher. A caveat should be mentioned alongside the cost per kilogram quotes in Table 6.8: none of the launch systems has demonstrated flown hardware in production as of yet. It is therefore wholly possible these prices are based on severely underestimated costs, which could be due to

[7] As can be seen from the CERs in Table 5.1 and Equation (5.1), the relationships that do not contain M_0 (GLOW) as a parameter

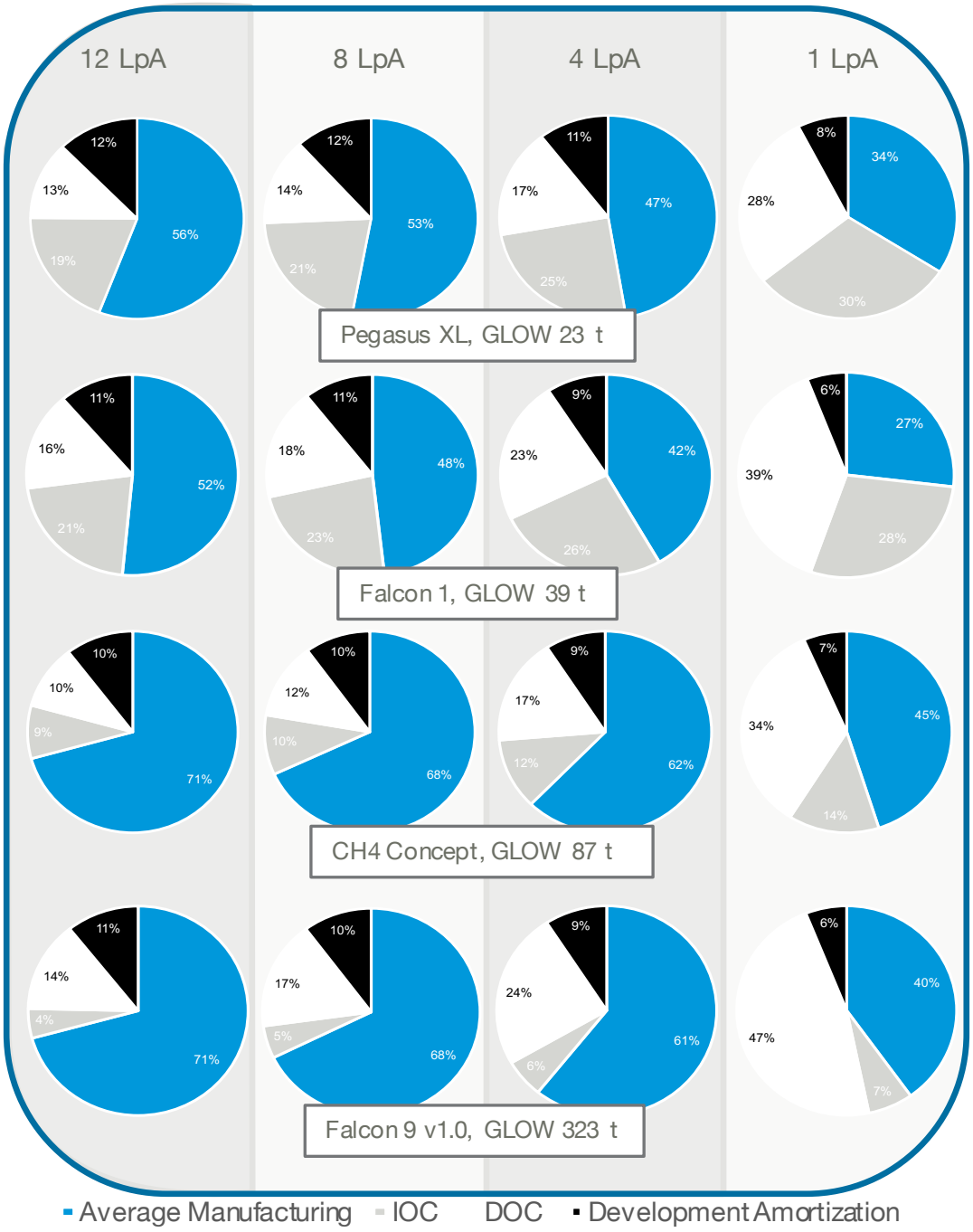


Figure 6.8: Cost per Flight composition for various sizes of launch vehicles: the Indirect Operations Cost (IOC) becomes more prominent with lower Gross Liftoff Weight (GLOW) vehicles, and total operations costs becomes a larger percentage of costs at a low number of launches per year (LpA) for small rockets

for example optimistic launch rate projections that will eventually result in high Indirect Operations Costs per flight, as suggested in Chapter 5. For example the Electron rocket is targeting a launch rate of 52 to possibly 100 launches per year, and LauncherOne could see 30 launches per annum.

Compared to existing dedicated launch offerings such as the Athena Ic at 28.6 k€kg^{-1} and the Pegasus XL at 45.1 k€kg^{-1}, the methane concept is still in the order of three times as expensive as other systems per kilogram [10]. When contrasted to available ride-share opportunities for launching small satellites, the liquid methane concept fares little better. It's price-per-kilogram is still significantly above the 27.5 k€kg^{-1} offered

by the Falcon 9.

6.3.3. Launch Market Price Elasticity of Demand

The demand for a smallsat launch service is currently low[8], but if dedicated launches were offered at competing prices a market for this type of service could be created [20]. This is called price elasticity of demand: the amount demand changes with a change in prices. This elasticity is defined in the case of the launch vehicle market as a function of demand q:

$$E = \frac{PpF}{q}\frac{dPpF}{dq} \tag{6.8}$$

NASA led a study into commercial space transportation along with industry partners [49] that explored how demand for various types of launches, including *Annual LEO Payload* market demand, changes with decreasing price. Also identified was the relationship between the potential for market capture and dollars per pound to orbit charged. The results of this study are found in Figure 6.9 as published in [52].

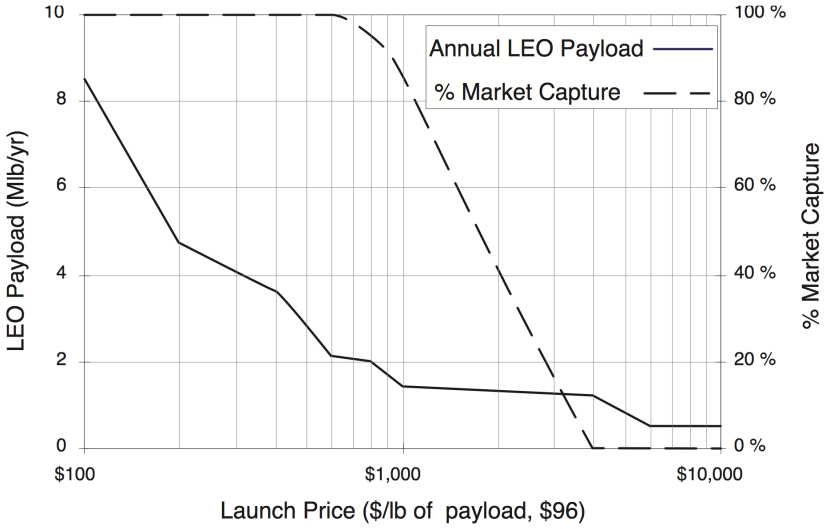


Figure 6.9: Price elasticity of demand of the launch to LEO market, and market capture based on launch price per pound payload, as in [52]

$4,000 (1996 dollars) per pound of payload is the point at which a launch vehicle can start to gain a share of the LEO launch market, which corresponds to roughly 16 k€kg^{-1} (2015). Most vehicles in Table 6.8 have higher prices per kilogram than would ideally be needed to capture a LEO market share. Clearly SpaceX does have this capability with the Falcon 9 at 2.7 k€kg^{-1}. The liquid methane launch vehicle's 156 k€kg^{-1} price-per-kilogram should be reduced either by making the rocket more performant and increasing payload capacity, or by lowering its costs to increase its competitiveness.

In this research it was assumed that all subsystems required development before production. However, in reality costs can be reduced by potentially using pre-developed hardware such as an engine. To provide a truer picture of possible price-per-flight and kilogram-to-orbit price, the estimates outlined in this chapter were redone without the engine's development charge. The development cost is reduced in this case to 162 M€, the CpF will be 42.3 M€. The average price-per-flight is estimated at:

$$PpF_a = 45.7\text{M€} \longrightarrow 152\text{k€kg}^{-1} \tag{6.9}$$

The minor change in price-per-kilogram is entirely logical considering that the development cost's amortization charge makes up the smallest share of the total CpF, evident from Figure 6.1. A reduced development effort will therefore only have a minor impact on the cost-per-kilogram to orbit. The conclusion holds that this launch vehicle will be uncompetitive.

[8] According to launch manifests for the coming years [20]

7

Conclusions and Recommendations

This chapter will explore what can be concluded from this research first in Section 7.1, along with the way it reached the goals it set out to achieve. It will also discuss additional findings uncovered that hold for the economics of small launch vehicles. Finally, recommendations will follow in Section 7.2 that outline further research to be conducted in follow-up to this work.

7.1. Conclusions

7.1.1. Answer to the research question

The concluding answer to the research question is:

> **Yes, it possible to estimate the price per flight of a 100-700 kg payload capacity commercial launch vehicle within 20% of actual prices, through costing of individual rocket design elements.**

It has proven possible to estimate costs for the different phases of launch vehicle development, manufacturing and operations, and construct with these elements a Price per Flight for small rockets. The development costs and manufacturing costs were modeled with the theoretical first unit T1 costs, and combining these with so-called T1 equivalent units. The operations phase cost estimates were made with TRANSCOST [45].

The T1 equivalents method was adjusted to make this estimate possible, and in doing so, a meaningful contribution to that way of estimating has been supplied with this research. Adjustments were made as follows: it was first identified that in TRANSCOST [45], Koelle successfully argues that commercial companies reduce management costs and increase profit retention by having a lower share of work allocated to subcontractors, and developing more of their systems in house [13]. The factors corresponding to these cost savings in the T1 equivalents method were identified. These were the Business As Usual (BAU) Management and Product Assurance (M/PA) and Integration and Test (I&T) level-of-effort overhead costs. To model commercial cost improvements, these two factors were scaled by almost a factor 3 to account for reduced subcontractor management effort. 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 under commercial circumstances.

For these three phases individually, the validity of the results was proven by estimating costs of 4 reference launch vehicles. The development phase estimates were within the 20% target accuracy expected compared to reference cases. Manufacturing phase estimates were within the target accuracy of 10% of reference costs. The phase estimates were combined into a cost- and price per flight, and were again within the 20% combined accuracy expected with respect to the reference cases. With this combined estimate, the contribution of the operations costs were indirectly validated. The price per flight estimated has also proven to follow actual observed changes in cost and price per flight due to varying launch rates.

All findings indicate the T1 equivalents method, with its new suitable adaptations developed, as well as Koelle's work on operations costs, hold for small commercial launch vehicles. It was proven that it is possible to estimate price per flight of small commercial launch vehicles by costing individual elements for the T1 estimates to arrive at a price per flight.

7.1.2. Research Activities

The original research goals were set out in the research proposal attached in Appendix K. Each of these goals was linked to an activity. The following overview will indicate whether these activities were performed successfully ✓, partially completed ✤ or not completed ✗.

- *Construct a price per flight model for cost estimating commercial rockets with a payload range between 100-700 kg within ±20% of reported prices* ✓
  A model was constructed that is able to perform a *point estimate* on the price per flight for all launch vehicle tested, within the desired ±20% accuracy set out beforehand. Furthermore, the approximation made for the CMA stemming from the input data-spread indicates that estimates for certain types of launch vehicles, such as liquid propellant rockets, have a 1σ variation outside this target range. Therefore, even though the point estimate accuracy was achieved for all considered reference cases, it is expected that actual prices for these liquid rockets will be considerably more variable. It has also been shown that the expected variation (1σ) of the mean (point estimate), combined with the required nominal accuracy of 20%, is able to account for *all* observed cost variations in the costs of the launch vehicles available to base this research on, barring those prices belonging to a vehicle program's 4 year start-up. It is suggested these early prices are not based on costs, but on other considerations.

- *Model uncertainties of the PpF model* ✤
  The uncertainties of the PpF based on the underlying data were approximated with the Flight Unit CMA variation, and because the equivalents method contains only linear multipliers on the theoretical first unit T1 this uncertainty should hold for the development and manufacturing estimates. However, the same CMA found for the T1 was only assumed to hold for the CpF and PpF as well, and was not directly modeled in the operations phase estimate. This is therefore left as a refinement that should be incorporated in future work on the subject, and the objective is considered partially complete.

- *Validate the PpF model* ✤
  The price per flight was modeled and validated for each of its three constituent phases of development, manufacturing and operations separately. The price per flight itself was also validated as a whole. However, it is recognized that the amount of available reference cases is not enough to ensure the approaches' validity over the full spectrum of launch vehicles considered in the 100-700 kg payload range. Data about these launch vehicles that may be used to base other reference estimates on are not publicized (yet). It would be ideal to further refine the developed methodology on the basis of more cost estimates for actual flight hardware. Nonetheless, all available vehicle data and price quotes suggest the estimates made in this work are valid.

- *Determine the CpF/PpF range of the conceptual launch vehicles under study* ✓
  As constructed with the CMA stemming from the flight unit, the liquid methane's costs were combined into a Cost- and Price per Flight estimate with corresponding uncertainty range.

- *Amalgamate cost estimates into a cost range per kilogram launched corridor* ✤
  This goal was only partially achieved. Even though the cost estimates made could be amalgamated into a cost range per kilogram launched overview in Figure 6.7, rockets have such varying uncertainties stemming from the chosen amount of test models, the size of teams, the differing launch rates, the materials used in each rocket, the launch facilities employed... that establishing a coherent corridor would have been impossible form the start. This signifies that this goal was initially inappropriately set, with not enough regard for this potential outcome.

- *Optionally add a learning curve to the operations phase estimate, or add a sensitivity analysis of the model to a change in technical input parameters* ✓
  The learning phenomenon was not only introduced in the operations phase alone, it was employed in all three phases: learning while manufacturing System Test Hardware (STH) in the development phase was implemented, cost improvement shaped the production phase estimate, and finally the operations cost was approximated with a learning component as well. The second suggested goal was achieved as well; the cost effects of changing the number of engines on the launch vehicle, and its impact on manufacturing costs, were determined with the newly developed method. Even though there are many more technical input parameters to vary that might warrant further exploration, a first step was made that has shown the possibilities of cost estimating in this way.

7.1.3. Cost Findings for Small Rockets and the Liquid Methane Concept

Listed here are other major findings relating to cost estimating small launch vehicles. These do not directly involve the research goals as proposed and are therefore listed separately.

- Engines are traditionally a large system cost driver [45], and the same holds for small launch vehicles as well, with for example roughly 60% of the liquid methane's flight unit's first stage costs stemming from the engines. The sensitivity to this cost driver means that selecting reference data for the engine's Cost Estimating Relationship warrants extra attention.
- The value selected for the cost improvement slope due to learning has a major influence on the manufacturing cost estimate. Cost improvement values of between 82% and 97% are typical, but may lead to overestimating or underestimating manufacturing costs by as much as +39% or -54% respectively. Therefore, care needs to be taken in selecting this value while performing the estimate. As a project goes through its stages of development, instead of solely comparing it to similar systems and setting a cost improvement value based on this comparison, actual manufacturing data can be used as inputs to re-assess the estimated learning effect. In this way the uncertainty on the estimate decreases in later phases.
- Small launch vehicles are susceptible to high Indirect Operating Costs (IOCs) at low launch rates, even more so than larger launch vehicles. This is because indirect costs do not scale with the vehicle's size as much as direct costs do. These indirect costs lead to cost increases of up to a factor 2, and in small rockets can make up almost three quarters of the Cost per Flight, if a launch rate of at least 1 per year is not achieved. Operations costs will be within a typical range of ≤ 35% of recurring costs at 4 launches per year or more. To partially offset this risk, leasing launch facilities instead of acquiring them is recommended for small rocket operators.

In this research, the most important conclusion concerning the liquid methane concept vehicle studied in Section 6.3.2 is that currently, costs are too high to gain a share in the launch market. Estimated costs result in kilogram-to-orbit prices that are three times higher than its nearest competitors. Also, the market is not elastic enough at the price point of 150 k€ kg^{-1} to accommodate this new launch option.

7.1.4. Application of SOLSTICE in the Concurrent Design Facility

While the SOLSTICE tool was being developed, the methodologies formed throughout this research successfully supported a Concurrent Design Facility (CDF) pre-Phase A study on small, air-launched rockets at ESA-ESTEC. The concepts studied boasted a payload capacity of 120 kg to SSO. Costs were estimated for both solid, as well as liquid propellant options of a trimaran rocket configuration that could be launched from underneath a Tornado fighter aircraft. This provides an example of the flexibility, and wide applicability, of the proposed way to synthesize an early stage cost estimate for small launch vehicles.

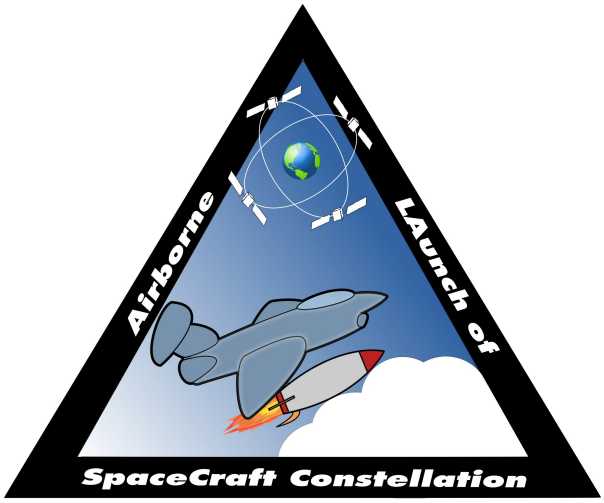


Figure 7.1: *Airborne Launch of SpaceCraft Constellation* - ESA Concurrent Design Facility study where the methodologies developed were applied

7.2. Recommendations

This final section features recommendations for future work to be performed in the domain of costing launch vehicles, and specifically small commercial ones. There are two main recommendations that hinge on two goals that have not been fully achieved yet.

Firstly, proper continuation of this research work would aim to assess the degree of accuracy with which the newly developed methods approximate costs, by contrasting additional rocket reference cases (that are currently unobtainable) to their freely available launch price quotes. The examples explored throughout this study, while each representative in their own right, are only a limited subset of the broader range of 100-700 kg payload rockets in or entering the launch market. As more companies participate, estimates applied to newly developed small launch systems are valuable steps towards fully understanding the estimating potential and refinements needed to the developed costing framework.

A second major recommendation worth considering is to link the uncertainties belonging to the input data, which were meticulously derived for the Flight Unit, to the overall Cost Modeling Accuracy (CMA) of the Cost per Flight and Price per Flight figures. Because the current build-up of these final estimates features the TRANSCOST method, which does not supply an accuracy range for its CERs, the spread of the input data could not be connected directly to the expected CpF spread. While the CMA surely does hold for the T1 equivalents approach taken in the development and manufacturing cost estimates, as these approaches are just linear multipliers on the Flight Unit cost, a possible solution for the entire framework could be to in due course replace TRANSCOST with a tool or method that provides more insight into its own accuracy range.

Apart from these two major recommendations, a number of other issues might be worthwhile investigating.

- It will not be possible to generate a payload/cost curve with this model. This is because payload mass can not be directly related to system mass without incurring inherent uncertainties on that part. To do so requires an extensive study on launch vehicle sizing, which does not lie within the cost estimating scope of this research. However, a first step was made towards this goal by supplying a new method to estimate the costs of commercial rockets. Other work will link a mass model to such a tool. The result will be a cost point estimate such as that featured in Figure 6.7 with corresponding cost variance, and on the abscissa the uncertainty in mass would be featured, which stems from technical risk [70]. A combined cost modeling accuracy and technical risk profile can then be constructed that can lead to better understanding of the payload-cost curve.

- A potentially interesting application of these methods at the TU Delft, is to incorporate them into the in-house Multidisciplinary Optimization (MDO) tool to optimize rocket designs, which was developed by Van Kesteren [97] and Miranda [65]. In this way, costs of solid as well as liquid rockets could be treated as an independent variable in the design process.

- The Cost Modeling Accuracy determined for the Flight Unit in Chapter 2 most likely includes influences to the spread in input data due to Project Owned Events development risk, and to a lesser extent External Project Events such as company politics. It would be beneficial to separate these risks in a further study so that a clearer cost-risk picture for a specific launch vehicle configuration can be constructed.

- It is recommended more cost engineering work be done with the supplied methodology and tool to support optimum design decisions for small rockets. This research has started to explore the power of doing trade-studies with the tool developed. A brief assessment was made whether the liquid methane launcher concept would be more economic with a single larger engine, or several smaller ones. Another example of such a trade study is this research's valuable support in ESA's Concurrent Design Facility. Such trade studies are important decision-making aids in space projects [69], and more rigorous assessments in the future would provide a valuable insight into cost drivers and key choices to be made in a program involving these novel types of small commercial launch vehicles.

Bibliography

[1] National Aeronautics and Space Administration. Fiscal Year 2009 - Budget Estimates. www.nasa.gov, 2008.

[2] National Aeronautics and Space Administration. Commercial Market Assessment for Crew and Cargo Systems. Technical report, NASA, April 2011.

[3] National Aeronautics and Space Administration. Fiscal Year 2015 - Budget Estimates. www.nasa.gov, 2014.

[4] Timothy P. Anderson. Learning Curve Primer, Part 1 - Unit Theory. *The National Estimator*, pages 12–16, Fall 2011. Society of Cost Estimating and Analysis.

[5] George J. Avlonitis and Kostis A. Indounas. Pricing objectives and pricing methods in the services sector. *Journal of Services Marketing*, 19(1):47*57, 2005.

[6] Daniel N. Baker and S. Pete Worden. The Large Benefits of Small-Satellite Missions. *EOS, Transactions, Americal Geophisical Union*, 89(33):301–302, August 2008.

[7] Andrew Chaikin. Is SpaceX Changing the Rocket Equation? Air & Space - Smithsonian, January 2012.

[8] Raymond P. Covert. Correlations in Cost Risk Analysis. Annual SCEA Conference, June 2006.

[9] Raymond P. Covert and Timothy Anderson. Correlation Tutorial. The Aerospace Corporation, Cost Drivers Learning Event, November 2005.

[10] Nicholas Crisp, Katharine Smith, and Peter Hollingsworth. Small Satellite Launch to LEO: A Review of Current and Future Launch Systems. *Transactions of the Japan Society for Aeronatical and Space Sciences, Aerospace Technology Japan*, 12(ists29):Tf_39–Tf_47, 2014. doi: 10.2322/tastj.12.Tf_39.

[11] R. Curran, S. Raghunathan, and M. Price. Review of aerospace engineering cost modelling: The genetic causal approach. *Progress in Aerospace Sciences*, 40(8):487 – 534, 2004. ISSN 0376-0421. doi: http://dx.doi.org/10.1016/j.paerosci.2004.10.001.

[12] Dustin Doud. Designing for the Future by Testing Today: A Summary of SpaceX System Management Practices. In *International Astronautical Congress*, volume IAC-12,D3,4,1,x15878. SpaceX, International Astronautical Federation, 2012.

[13] Nigel Drenthe. Identifying Factors influencing Cost per Flight of Small Commercial Launchers. *Literature Research*, TU Delft, 2016.

[14] ECOS Team. ECOS 5 Training - Self Training Manual. Technical report, European Space Agency, Accessed: August 2016.

[15] Mel Eisman and Daniel Gonzales. Life Cycle Cost Assessments for Military Transatmospheric Vehicles. RAND Corporation, 1997. MR-893-AF.

[16] ESA Cost Engineering Team. *TEC-SYC Cost Risk Procedure*. European Space Agency, Keplerlaan 1, Noordwijk, February 2010.

[17] European Cooperation for Space Standardization (ECSS). *Space Project Management - Project Planning and Implementation*. ESA, Noordwijk, The Netherlands, draft 14 edition, July 2007.

[18] European Cooperation for Space Standardization (ECSS). *Space Project Management - Cost and schedule management*. ESA, Noordwijk, The Netherlands, draft 14 edition, July 2008.

[19] European Space Agency. Vega evolution concept. esa.int, Space In Images, November 2012.

[20] FAA Commercial Space Transportation (AST) and the Commercial Space Transportation Advisory Committe (COMSTAC). 2015 Commercial Space Transportation Forecasts. Technical report, FAA, April 2015.

[21] Catherine Forbes, Merran Evans, Nicholas Hastings, and Brian Peacock. *Statistical Distributions*. John Wiley & Sons, Inc., 4 edition, 2011.

[22] Bernard Fox, Kevin Brancato, and Brien Alkire. *Guidelines and Metrics for Assessing Space System Cost Estimates*. Number ISBN 978-0-8330-4023-7. RAND Corporation, Santa Monica, CA, United States, 2008.

[23] C.P. Frank, C.M. Tyl, O.J. Pinon-Fischer, and D.N.Mavris. New design framework for performance, weight and life-cycle cost estimation of rocket engines. In *6th European Conference for Aerospace Sciences*. EUCASS, June 2015.

[24] Futron Corporation. Space Transportation Costs: Trends in Price Per Pound to Orbit 1990-2000. *Futron*, 2002.

[25] Galorath. Modeling Cost Improvement with SEER-H, Accessed: August 2016.

[26] Paul R. Garvey, Stephen A. Book, and Raymond P. Covert. *Probability Methods for Cost Uncertainty Analysis*. Number ISBN: 978-1-4822-1976-0. CRC Press, 2015.

[27] Daniel Gonzales, Mel Eisman, Calvin Shipbaugh, Timothy Bonds, and Anh Tuan Le. Proceedings of the RAND AIR FORCE Workshop on Transatmospheric Vehicles. In *Project AIR FORCE*, 1997.

[28] William Sealy Gosset. The Probable Error of a Mean. *Biometrika*, 6(1):1–25, March 1908. Student's t-distribution.

[29] Charles A. Graver and Damon C. Morrison. CAC(Q) CERS FOR SOLID ROCKET MOTORS. Technical report, Department of Defense, June 1993.

[30] D. Greves. Engineering Costing Techniques in ESA. *ESA Bulletin*, (81), February 1995.

[31] Walter Edward Hammond. *Space Transportation: A Systems Approach to Analysis and Design*. AIAA Education Series, 1999.

[32] Florence Hauss. Data relating to Flight VA213. arianespace & Astrium, June 2013.

[33] Henry R. Hertzfeld, Ray A. Williamson, and Nicolas Peter. Launch Vehicles: An Economic Perspective. Space Policy Institute, September 2015.

[34] Jr. Humboldt C. Mandell. Cost-Estimating Relationships for Space Programs. In Joel S. Greenberg and Henry R. Hertzefld, editors, *Space Economics*, volume 144, pages 57–87. AIAA, January 1992.

[35] Charles D. Hunt. FY14 NASA New Start Inflation Indices (NNSI). Cost Analysis Division, Online NASA Publication, February 2014.

[36] Charles D. Hunt and Michel O. van Pelt. *Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars*. BiblioGov, Noordwijk, The Netherlands, 2004.

[37] Instituto Nacional de Pesquisas Espaciais. Plano diretor 2011-2015. inpe.br, July 2011.

[38] Ralph-Werner Jaeger. *Ein Beitrag zur Analyse der Fertigungskosten von Raketenzellen*. PhD thesis, Fachbereich 12 der Technischen Universität Berlin, January 1976.

[39] William A. Janda and Thomas A. Taylor. Estimating Construction Labor and Indirect Costs. In *The Engineer's Cost Handbook*, pages 153–187–. CRC Press, February 1997. doi: 10.1201/9780203910016.ch6.

[40] Gail Johnson-Roth. Mission Assurance Guidelines for A-D Mission Risk Classes. aerospace.org, report no. TOR-2011(8591)-21, June 2011.

[41] John Jurist, Sam Dinkin, and David Livingston. When Physics, Economics and Reality Collide: The Challenge of Cheap Orbital Access. *AIAA*, 2005.

[42] D. E. Koelle and R. Janovsky. Development and transportation costs of space launch systems. Presentation DGLR, 2007.

[43] Dietrich E. Koelle. The Transcost-Model for Launch Vehicle Cost Estimation and its Application to Future Systems Analysis. *Acta Astronautica*, 11(12):803–817, March 1984.

[44] Dietrich E. Koelle. *TRANSCOST "Statistical-Analytical Model for Cost Estimation and Economical Optimization of Space Transportation Systems"*. Number TCS-TR-140A(98). TransCostSystems (TCS), Ottobrunn Germany, 6.2 edition, October 1998.

[45] Dietrich E. Koelle. *Handbook of Cost Engineering and Design of Space Transportation Systems*. Number TCS-TR-200. TransCostSystems (TCS), Ottobrunn Germany, 8.2 edition, October 2013.

[46] Zachary Krevor and Alan Wilhite. An approach for calculating the cost of launch vehicle reliability. In *SPACE Conferences and Exposition*. American Institute of Aeronautics and Astronautics, September 2007. doi: 10.2514/6.2007-9920.

[47] H. H. Ku. Notes on the Use of Propagation of Error Formulas. *Journal of Research*, 70C(4):263–273, October 1966.

[48] Theresa Kuennen, Horst D. E. Knorreck, Mitchell W. Elson, and Steven J. Buckley. Reducing the Cost of Launching Small Satellites: A Perspective From the Field. In *18th Annual AIAA/USU Conference on Small Satellites*, number SSC04-X-1, 2009.

[49] Langley Research Center, Hampton, Virginia. Commercial Space Transportation Study (CSTS) - Executive Summary, April 1994.

[50] S. Larch, P. Perczynski, O. Kunz, and R. Ernst. Proposal for a European Low Cost Next Generation Launch vehicle Family, Based on the Common Core Booster Architecture. Space Access Conference, 2011.

[51] Roger D. Launius and Dennis R. Jenkins. *To Reach the High Frontier: A history of U.S. Launch Vehicles*. Number ISBN: 978-0-8131-2245-8. The University Press of Kentucky, 2002.

[52] H. Lee and J.R. Olds. Integration of Cost Modeling and Business Simulation into Conceptual Launch Vehicle Design. In *AIAA Defense & Space Programs Conference and Exhibit*, number 97-3911. Georgia Institute of Technology, September 1997.

[53] Alan Lindenmoyer. Commercial Orbital Transportation Services. Technical Report SP-2014-617, NASA, February 2014.

[54] Alan Lindenmoyer and Dennis Stone. Status of NASA's commercial cargo and crew transportation initiative. *Acta Astronautica*, 66(5–6):788 – 791, 2010. ISSN 0094-5765. doi: http://dx.doi.org/10.1016/j.actaastro.2009.08.031.

[55] Jonathan D. Linton and Steven T. Walsh. Extracting Value from Learning Curves: Integrating Theory and Practice. *Creativity and Innovation Management*, 22(1):10–25, 2013. ISSN 1467-8691. doi: 10.1111/caim.12013.

[56] John M. Logsdon, Ray A. Williamson, Roger D. Launius, Russell J. Acker, Stephen J. Garber, and Jonathan L. Friedman. *Exploring the Unknown*, volume IV: Accessing Space. Library of Congress Cataloguing-in-Publication Data, 1999. NASA SP-4407.

[57] Joseph B. Mazzola and Kevin F. McCardle. The Stochastic Learning Curve: Optimal Production in the Presence of Learning-Curve Uncertainty. *Operations Research*, 45(3):440–450, 1997. doi: 10.1287/opre.45.3.440.

[58] Claus Meisl. Rules of Thumb Compendium - Programmatic and Cost. In *SSCAG Meeting*. Space Systems Cost Analysis Group, February 1994.

[59] Claus J. Meisl. Techniques for cost estimating in early program phases. *Engineering Costs and Production Economics*, 14(2):95 – 106, 1988. ISSN 0167-188X. doi: http://dx.doi.org/10.1016/0167-188X(90)90112-U.

[60] Doug Messier. Spacex subcontractors revealed. Online, June 2011. SpaceX Subcontractors.

[61] Doug Messier. SpaceWorks Review Shows Sharp Growth Expected in Nano- and Microsat Market. www.parabolicarc.com, February 2013.

[62] Doug Messier. Updated List of Smallsat Launch Vehicles. www.parabolicarc.com, October 2015.

[63] Thomas Meyer and Pierre-Yves Mathonet. *Beyond the J Curve: Managing a Portfolio of Venture Capital and Private Equity Funds*. John Wiley & Sons, Inc., February 2011.

[64] Charles Miller, A Wilhite, Dave Cheuvront, Rob Kelso, Howard McCurdy, and E Zapata. Economic assessment and systems analysis of an evolvable lunar architeture that leverages commercial space capabilities and public-private-partnerships. *NexGen Space LLC under flagrant from NASA*, July 2015.

[65] Francisco Miranda. Design Optimization of Ground and Air-Launched Hybrid Rockets. Master's thesis, TU Delft, Delft University of Technology, 2015.

[66] Julio Miravalls. Cohetes reciclables 'made in Spain', December 2015.

[67] R. Charles Moyer, James R. McGuigan, and Ramesh P. Rao. *Contemporary Financial Management*. Number ISBN: 9781285198842 1285198840. Cengage Learning, 2014.

[68] Elon Musk. *"Falcon 1 is Really Important"*. spacex.com, 2005.

[69] NASA. *2008 NASA Cost Estimating Handbook*. National Aeronautics and Space Administration, Washington, DC, 4.0 edition, February 2015.

[70] NASA. *NASA Cost Estimating Handbook*, chapter Appendix G. NASA, February 2015.

[71] NASA and Air Force Cost Model. *NAFCOM 96 Manual*. Science Applications International Corporation (SAIC), 1996.

[72] NASA Associate Deputy Administrator for Policy. Falcon 9 Launch Vehicle NAFCOM Cost Estimates. Presentation, NASA, August 2011.

[73] National Aeronautics and Space Administration. NASA's Exploration Systems Architecture Study. Technical Report NASA-TM-2005-214062, NASA, November 2005.

[74] Carlos Niederstrasser and Warren Frick. Small Launch Vehicles - A 2015 State of the Industry Survey. *Orbital ATK*, (SDC15-II-7), August 2015.

[75] OANDA. Historical eur/usd exchange rates. www.oanda.com, March 2016.

[76] OECD. OECD Consumer Price Index Inflation Figures. www.oecd.com, February 2016.

[77] Orbital ATK. Pegasus User's Guide. orbitalatk.com, October 2015.

[78] Walter Peeters. From suborbital space tourism to commercial personal spaceflight. *Acta Astronautica*, (66):1625–1632, 2010.

[79] Nancy J. Perry and Andrew Erdman. We're Losing the New Space Race. Fortune Magazine, April 1990. Pegasus Development Cost Quote.

[80] Giorgio Petroni and Stefano Santini. Innovation and change? The evolution of Europe's small satellite manufacturers. *Space Policy*, 28(1):25 – 32, 2012. ISSN 0265-9646. doi: http://dx.doi.org/10.1016/j.spacepol.2011.12.008.

[81] Nicole Powers. A parametric approach to nasa mission operations costing. In *SPACE Conferences and Exposition*. American Institute of Aeronautics and Astronautics, August 2014. doi: 10.2514/6.2014-4398.

[82] Georg Reinbold. Parametric Estimation of Development Cost. EADS Presentation, April 2007.

[83] Georg Reinbold. Expert Judgment Consultation - Personal Communication, August 2016.

[84] Ed Rogers. Pegasus XL-HESSI: Last-Minute Decisions in Flight-Based Launch. http://gsfcir.gsfc.nasa.gov/casestudies, November 2015. GSFC-1019C-1.

[85] Andreas Schütte. Texus and Maxus - An overview of the latest developments for the future. Proceedings of the 19th ESA Symposium on European Rocket and Balloon Programmes and Related Research, June 2009. ESA SP-671.

[86] E. Seedhouse. *SpaceX: Making Commercial Spaceflight a Reality*. Number E-ISBN 978-1-4614-5514-1 in Springer Praxis Books. Springer New York, 2013.

[87] Dale Shermon. *Systems Cost Engineering: Program Affordability Management and Cost Control*. Number ISBN: 978-0-566-08861-2. Gower Publishing, 2009.

[88] Christian Smart. Bayesian Parametrics: How to Develop a CER with Limited Data and Even Without Data. *Missile Defense Agency*, April 2014.

[89] Space Exploration Technologies. U.S. Space Launch Market: Crisis or Opportunity. Presentation SpaceX at dls.virginia.gov, July 2007.

[90] Alan Stern. Commercial space flight is a game-changer. *Nature*, 484(7395):417, April 2012.

[91] Sherry Stukes and Henry Apgar. Systems Engineering Desk Reference - An Aid for Cost Estimators. Presentation at 25th International Forum on COCOMO and Systems Software Cost Modeling, November 2010. SSCAG.

[92] Space Exploration Technologies. Falcon 9 user guide. www.spacex.com, August 2016.

[93] Duncan D. Thomas. *Joint Agency Cost Schedule Risk and Uncertainty Handbook*. Naval Center for Cost Analysis, March 2014.

[94] O. Trivailo, M. Sippel, and Y.A. Şekercioğlu. Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning. *Progress in Aerospace Sciences*, 53:1 – 17, 2012. ISSN 0376-0421. doi: http://dx.doi.org/10.1016/j.paerosci.2012.02.001.

[95] Erik W.K. Tsang and Shaker A. Zahra. Organizational unlearning. *Human Relations*, 61(10):1435–1462, October 2008.

[96] U.S. Congress, Office of Technology Assessment. Reducing Launch Operations Costs: New Technologies and Practices, September 1988. OTA-TM-ISC-28.

[97] MW Van Kesteren. Air Launch versus Ground Launch: A Multidisciplinary Design Optimization Study of Expendable Launch Vehicles on Cost and Performance. Master's thesis, TU Delft, Delft University of Technology, 2013.

[98] Mark Ventura. *The Lowest Cost Rocket Propulsion System*. American Institute of Aeronautics and Astronautics, 2016/09/12 2006. doi: doi:10.2514/6.2006-4782.

[99] Ronald L. Wasserstein and Nicole A. Lazar. The ASA's Statement on p-Values: Context, Process and Purpose. *The American Statistician*, 70(2):129–133, June 2016. p value.

[100] James R. Wertz. Economic Model of Reusable vs. Expendable Launch Vehicles. In *Symposium IAA.1: Economics and Commercialization of Space Activities*, October 2000.

[101] James R. Wertz, David F. Everett, and Jeffery J. Puschell, editors. *Space Mission Engineering: The New SMAD*. Number ISBN: 978-1-881-15-9. Microcosm Press, 2011.

[102] Westview Special Studies in Science, Technology, and Public Policy. *Space Policy Alternatives*. Westview Press, Inc., 1992.

[103] Walter C. Williams. Lessons From NASA - Design reviews, failure analysis, and redundancy are favored over predictions and life testing for spacecraft success. *IEEE Spectrum*, 18(10):79–84, October 1981.

[104] Alexandra Witze. "Rocket-on-a-rail" prepares to launch satellite. *Nature*, October 2015 2015.

[105] World Economic Forum and Oliver Wyman. The Future of Long-term Investing. WEF Report, World Economic Forum, 3 East 54th Street, New York, USA, 2011.

[106] T.P. Wright. Factors Affecting the Cost of Airplanes. *Journal of Aeronautical Sciences*, 3(4):122–128, February 1936. doi: 10.2514/8.155.

[107] Yale University. Tests of significance. Online, 1997.

[108] Obaid Younossi, Mark A. Lorell, Kevin Brancato, Cynthia R. Cook, Mel Eisman, Bernard Fox, John C. Graser, Yool Kim, Robert S. Leonard, Shari Lawrence Pfleeger, and Jerry M. Sollinger. *Cost Estimation of Space Systems - Past Lessons and Future Recommendations*. Number ISBN 978-0-8330-4460-0. RAND Corporation, Santa Monica, CA, United States, 2008.

[109] Ariel Zambelich. SpaceX Lands $1 Billion From Google and Fidelity. wired.com, January 2015.

[110] B.T.C. Zandbergen. Pegasus Fact Sheet, 2000, TU Delft Blackboard.

[111] B.T.C. Zandbergen. Thermal Rocket Propulsion. Class AE4-S01 Handbook, v2.05, February 2016. TU Delft - Faculty of Aerospace Engineering.

[112] George Zyskind and Frank B. Martin. On Best Linear Estimation and a General Gauss-Markov Theorem in Linear Models with Arbitrary Nonnegative Covariance Structure. *SIAM Journal of Applied Mathematics*, 17(6):1190–1202, November 1969.

A

Ground Rules and Assumptions

A cost analysis should always be preceded by a thorough definition of the Ground Rules and Assumptions (GRA) [59, 69]. This appendix features those that are relevant to the estimating process followed in the small rocket cost model SOLSTICE. The GRA's establish the boundary conditions under which the estimate was developed, so that these may be communicated efficiently to stakeholders and the customer, in this case ESA. Keeping communication lines open in this fashion will ensure the estimate is always within the customer's expectations at delivery. Clearly defining the ground rules and assumptions also allows for an estimate to be reproduced, which benefits the academic side of this particular cost analysis exercise.

Economic Conditions All costs will be denominated in Euros (EUR) in the economic conditions (EC) of 2015, unless otherwise stated. This can be deviated from to compare a cost estimate on a reference validation case to price quotes that were made for that rocket in a specific year. In that case, the estimate made with the model SOLSTICE should be adjusted for inflation. The values at which inflation/deflation are approximated stem from NASA's New Start Inflation Indices (NNSI) of 2014 [35], and OECD Eurozone inflation data [76].

When estimates or price quotes are converted between the Euro (€) and the United States Dollar (USD) ($) in the same base year, the exchange rate of that particular year is used. For each year up and until 1998, these exchange rates are listed in Appendix D. The exchange rates between the USD and a "standard European currency" before the creation of the Euro is fixed at a rate of 1.216 $\frac{EUR}{USD}$ for years < 1997, which is the average exchange rate between 1998 and 2015.

An agreement with the customer for the estimate was made to apply local inflation to make up the differences in years between two price quotes, and convert between Euros (€) and United States Dollars ($)(USD) in the same year as the estimate, which is 2015. For example if the estimate yields Euros in 2015, and a comparison was to be made with a price quote in Dollars in 2008, the estimate in Euros would be deflated by using the US inflation indices, and converted at the 2015 exchange rate.

CERs and Variance The data gathered to construct the equipment-level CER's with which the Flight Unit costs are built up, exhibit a certain amount of spread. This variation was analyzed per equipment element, and combined into the estimated variance expected in the FU/T1. Such uncertainty is part of the Cost Modeling Accuracy part of the total cost-risk [70][1]. Ideally, this error should be propagated with T1 Equivalents to estimate the expected CMA in the development and manufacturing estimates, such as was outlined in the research proposal in Appendix K. Due to the fact that TRANSCOST does not provide uncertainties of its operating cost CERs, an uncertainty on the price per flight would not have been attainable within the context of this research. Synthesizing the model with a different operating cost estimate and uncertainty, was left as a recommendation in lieu of developing a new costing methodology for small commercial systems. The FU modeling accuracy is here assumed to hold for the also for the PpF estimate; the Flight Unit uncertainties will be assigned to the final PpF directly

As outlined previously, an equipment element's *mass* will be specified as an independent variable of cost, the dependent variable. Their relationship is assumed to be causal, i.e. not just a statistical artifact [8, 69], and following the typical cost engineering curve of $C = a \cdot M^b$ [45, 69, 82], where C is cost in any unit, and M

[1] For other cost-risk contributions, see Figure I.1

is mass in any unit, without an added constant c. This allows the regression curve a and b values found to be compared to those in the standard NAFCOM database [71, 88].

Correlation Instead of applying a standard $\rho_0 = 0.2$ correlation coefficient between all subsystems, as was described in Section 2.3.2, some systems are excluded to signify that these do not influence each other in the analysis. This is why some correlation coefficients in Table I.3 are set to zero instead of ρ_0.

Logically, the solid stage *S-SC-* does not correlate with elements from a liquid rocket stage because these subsystems are not present within a single stage. Also, the avionics are electronics that are assumed to be of a constant size irrespective of the size of the launcher. Finally, the mass of the payload adapter and fairing are assumed to be independent from the size of the stages underneath them, except for other structural elements these need to be attached to, such as structures of the stage and tank.

Development Costs The amount of System Test Hardware (STH) units assumed to be manufactured and tested throughout the development phase is constant for every cost estimate performed. Of course, if program details become available in later stages the estimate can be revised. Each development program has: 1 Development Model (DM) used for thermal/structural testing, 1 Engineering Model (EM) that is flight representative in form, fit and function, without full redundancy and high reliability parts, and 1 Protoflight Model (PFM) that undergoes qualification tests but is also part of the flight hardware [2].

Manufacturing Costs Integration and Test (I&T) manufacturing percentages derived in Section 4.1.2 are assumed constant. It means these decrease along with the manufacturing costs as more units are produced, which is representative of true I&T efforts which can be improved with learning as well [83].

During this cost improvement, it is assumed that no modifications to the assembly lines take place, and also that manufacturing is not halted: there are no interruptions to the learning process [95].

Operating Costs The estimate made with TRANSCOST [45] assumes the launch service provider does not own a launch pad, it is leased. The direct operations costs include this launch site user fee.

The cost to launch, especially ground operations cost, are subject to learning. An average cost improvement rate over 50 launches is assumed for vehicles 1 through 50. This makes the operations cost an average constant value. If not for this assumption, it would be decreasing slightly like the manufacturing costs.

Other General Assumptions The development and manufacturing of payload will not be included in the cost estimate. Its integration and mating with the launcher in the launch facilities is included in the operations cost however.

In principle, the estimate is developed with a firm-fixed price contract in mind without program support or contingencies, as this results in reduced costs [72] typical of commercial launch service providers.

References

[8] Raymond P. Covert. Correlations in Cost Risk Analysis. Annual SCEA Conference, June 2006.

[2] European Cooperation for Space Standardization (ECSS). *Space Engineering - Verification*. ESA, Noordwijk, The Netherlands, November 1998.

[35] Charles D. Hunt. FY14 NASA New Start Inflation Indices (NNSI). Cost Analysis Division, Online NASA Publication, February 2014.

[45] Dietrich E. Koelle. *Handbook of Cost Engineering and Design of Space Transportation Systems*. Number TCS-TR-200. TransCostSystems (TCS), Ottobrunn Germany, 8.2 edition, October 2013.

[59] Claus J. Meisl. Techniques for cost estimating in early program phases. *Engineering Costs and Production Economics*, 14(2):95 – 106, 1988. ISSN 0167-188X. doi: http://dx.doi.org/10.1016/0167-188X(90)90112-U.

[69] NASA. *2008 NASA Cost Estimating Handbook*. National Aeronautics and Space Administration, Washington, DC, 4.0 edition, February 2015.

[70] NASA. *NASA Cost Estimating Handbook*, chapter Appendix G. NASA, February 2015.

[71] NASA and Air Force Cost Model. *NAFCOM 96 Manual*. Science Applications International Corporation (SAIC), 1996.

[72] NASA Associate Deputy Administrator for Policy. Falcon 9 Launch Vehicle NAFCOM Cost Estimates. Presentation, NASA, August 2011.

[76] OECD. OECD Consumer Price Index Inflation Figures. www.oecd.com, February 2016.

[82] Georg Reinbold. Parametric Estimation of Development Cost. EADS Presentation, April 2007.

[83] Georg Reinbold. Expert Judgment Consultation - Personal Communication, August 2016.

[88] Christian Smart. Bayesian Parametrics: How to Develop a CER with Limited Data and Even Without Data. *Missile Defense Agency*, April 2014.

[95] Erik W.K. Tsang and Shaker A. Zahra. Organizational unlearning. *Human Relations*, 61(10):1435–1462, October 2008.

B

ESA Conceptual Liquid Methane Launch Vehicle

This features the mass breakdown of the conceptual liquid methane launch vehicle which forms the center point of the SOLSTICE cost estimate. The tables featured here show how each subsystem's mass is allocated to a specific equipment breakdown element with which a flight unit cost will be constructed in Chapter 2. The masses of the structural elements of the launcher have been obtained in a rather simple manner and were not the result of a detailed structural analysis.

The concept that will take center stage in the estimate is a two-stage-to-orbit rocket that is propelled by a fuel/oxidizer combination of Liquefied Methane (CH_4) and Liquid Oxygen (LOX). The rocket has a payload to LEO (SSO) capacity of 300kg, and therefore falls within the payload range considered of interest to this study. It is a purely conceptual example of how a low-cost launch vehicle, inheriting much of the necessary hardware from the European space sector, could be constructed. Liquid methane was the propellant of choice for this vehicle as it is only lightly cryogenic, and is not subject to the handling constraints that liquid hydrogen systems have [45, 83]. This is one of the traits that commercial vehicles have been found to exhibit in preparatory work [13]. The engine design could be re-used potentially from a different program. This saves effort developing a new propulsion system, which is the most resource intensive part of a rocket [45]. The vehicle also features contemporary electric thrust vector control powered by batteries.

Table B.1: Stage 1 of the liquid methane launch vehicle concept from ESA, along with mass allocations to subsystem equipment elements in the breakdown used to construct the flight unit estimate

LOX-CH4 Stage 1	**Number**	**Nominal Mass per Unit [kg]**	**Mass with Margin [kg]**	**Allocated Mass [kg]**	**Specification**
PRIMARY STRUCTURE			**2436**		
Tank structure			***2256***		
Aft Skirt	1	224	224	224	S-SS-SKI
Aft Skirt Interface	1	22	22	22	S-SS-SKI
Forward LCH4 Bulkhead		36	0	0	S-FT-
Forward LCH4 Y-Ring	0	7	0	0	S-FT-
LCH4 cylinder	1	684	684	684	S-FT-
Aft LCH4 Bulkhead	1	36	36	36	S-FT-
Aft LCH4 Y-Ring	1	7	7	7	S-FT-
Inter-tank Interface	1	0	0	0	S-FT-
Inter-tank (NOT PRESENT)	1	0	0	0	S-FT-
Forward LOX Bulkhead	1	36	36	36	S-OT-
Forward LOX Y-Ring	1	7	7	7	S-OT-
LOX cylinder	1	787	787	787	S-OT-
Aft LOX Bulkhead	1	36	36	36	S-OT-
Aft LOX Y-Ring	1	7	7	7	S-OT-
Forward Skirt Interface	1	37	37	37	S-SS-SKI
Forward Skirt	1	373	373	373	S-SS-SKI
Equipment Bay structure			***0***		
Thermal cover	0	0	0	0	S-SS-THM
Engine Thrust Frame			***180***		
Thrust cone	1	160	160	160	S-SS-TRC
Engine attachment plate	1	20	20	20	S-SS-TRC
SECONDARY STRUCTURE			**100**	**100**	I-IS-
PROPULSION SYSTEM			**3239**		
– *Reference Engine* –	12	250	3000	3000	S-EN-
Feed system	1	50	50	50	S-PV-PIP
Collector	1	15	15	15	S-PV-PIP
Pressure regulation	1	20	20	20	S-PV-VAL
Check valves	2	5	10	10	S-PV-VAL
He gas for LOX Press.	1	40	40		
He Tanks	6	17	103	103	S-PT-
CH4 gas for CH4 Press.	1	100	100		
AOCS			**0**		C-AC-
THRUST VECTOR CONTROL			**113**	**113**	S-TV-
STAGE SEPARATION SYSTEM			**18**	**18**	I-IS
THERMAL CONTROL			**24**	**24**	S-SS-THM
AVIONICS			**61**		
COMMUNICATIONS				0.0	A-AV-COM
GNSS antenna	0.0	0.2	0.0		
ATN	0.0	0.4	0.0		
GNSS receiver + IMU	0.0	8.0	0.0		
RTC	0.0	1.5	0.0		
DATA HANDLING				0.0	A-AV-DHL
ECU	0.0	3.0	0.0		
POWER				30.2	A-AV-PWR
Pyro battery	2.0	0.8	1.9		
Functional battery	2.0	3.5	8.4		
BDP	2.0	8.3	19.9		
PYROTECHNICS	1.0	20.0	24.0	24.0	S-IS-
HARNESS	1.0	5.0	7.2	7.2	S-SH-
Stage dry Mass			**5991**		
PROPELLANT			**64600**		
Stage Lift-off Mass			**70591**	**kg**	

Table B.2: Stage 2 of the liquid methane launch vehicle concept from ESA, along with mass allocations to subsystem equipment elements in the breakdown used to construct the flight unit estimate

LOX-CH4 Stage 2	**Number**	**Nominal Mass per Unit (kg)**	**Mass with Margin (kg)**	**Allocated Mass (kg)**	**Specification**
PRIMARY STRUCTURE			**1320**		
Tank structure			***1295***		
Aft Skirt	1	366	366	366	S-SS-SKI
Aft Skirt Interface	1	37	37	37	S-SS-SKI
Forward LCH4 Bulkhead	1	26	26	26	S-FT-
Forward LCH4 Y-Ring	1	5	5	5	S-FT-
LCH4 cylinder	1	48	48	48	S-FT-
Aft LCH4 Bulkhead	1	26	26	26	S-FT-
Aft LCH4 Y-Ring	1	5	5	5	S-FT-
Inter-tank Interface	1	46	46	46	S-FT-
Inter-tank (NOT PRESENT)	1	456	456	456	S-FT-
Forward LOX Bulkhead	0	25	0	0	S-OT-
Forward LOX Y-Ring	1	5	5	5	S-OT-
LOX cylinder	1	133	133	133	S-OT-
Aft LOX Bulkhead	1	25	25	25	S-OT-
Aft LOX Y-Ring	1	5	5	5	S-OT-
Forward Skirt Interface	1	10	10	10	S-SS-SKI
Forward Skirt	1	104	104	104	S-SS-SKI
Equipment Bay structure			***0***		
Thermal cover	0	0	0		
Engine Thrust Frame			***25***	**25**	S-SS-TRC
Thrust cone	1	19	19	19	S-SS-TRC
Engine attachment plate	1	6	6	6	S-SS-TRC
SECONDARY STRUCTURE			**25**	**25**	I-IS-
PROPULSION SYSTEM			**339**		
– Reference Engine –	1	250	250	250	S-EN-
Feed system	1	15	15	15	S-PV-PIP
Collector	1	5	5	5	S-PV-PIP
Pressure regulation	1	10	10	10	S-PV-VAL
Check valves	2	3	5	5	S-PV-VAL
He gas for LOX Press.	1	9	9		
He Tanks	4	11	45	45	S-PT-
CH4 gas for CH4 Press.	1	22	22		
AOCS			**51**		C-AC-
THRUST VECTOR CONTROL			**49**	**49**	S-TV-
STAGE SEPARATION SYSTEM			**0**		
THERMAL CONTROL			**8**	**8**	S-SS-THM
AVIONICS			**85**		
COMMUNICATIONS				26.2	A-AV-COM
GNSS antenna	2.0	0.2	0.4		
ATN	4.0	0.4	1.5		
GNSS receiver + IMU	2.0	8.0	17.6		
RTC	4.0	1.5	6.6		
DATA HANDLING					
ECU	4.0	3.0	13.2	13.2	A-AV-DHL
POWER					
Pyro battery	2.0	0.8	1.8	27.7	A-AV-PWR
Functional battery	2.0	3.5	7.7		
BDP	2.0	8.3	18.3		
PYROTECHNICS	1.0	10.0	11.0	11.0	S-IS-
HARNESS	1.0	5.0	6.6	6.6	S-SH-
Stage dry Mass			**1878**		
PROPELLANT			**14180**		
Stage Lift-off Mass			**16058**	**kg**	

References

[13] Nigel Drenthe. Identifying Factors influencing Cost per Flight of Small Commercial Launchers. *Literature Research*, TU Delft, 2016.

[45] Dietrich E. Koelle. *Handbook of Cost Engineering and Design of Space Transportation Systems.* Number TCS-TR-200. TransCostSystems (TCS), Ottobrunn Germany, 8.2 edition, October 2013.

[83] Georg Reinbold. Expert Judgment Consultation - Personal Communication, August 2016.

C

Inflation Tables

Inflation tables for both the European Union and the United States will be detailed here. The EU values are derived from Organisation for Economic Co-operation and Development (OECD) data [76], and the US values are adopted from NASA's New Start Inflation Indices of 2014 [35]. Cumulative inflation Table C.1 is included; dividing a later year by a previous year will yield the cost factor increase between those years.

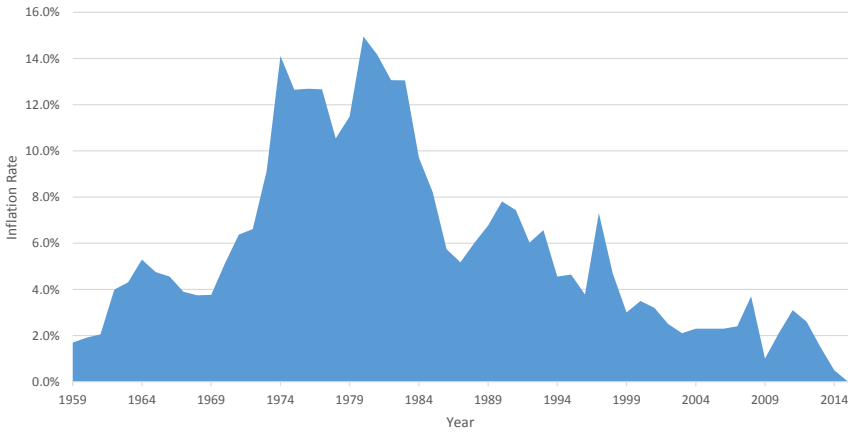


Figure C.1: European Union Inflation [76]

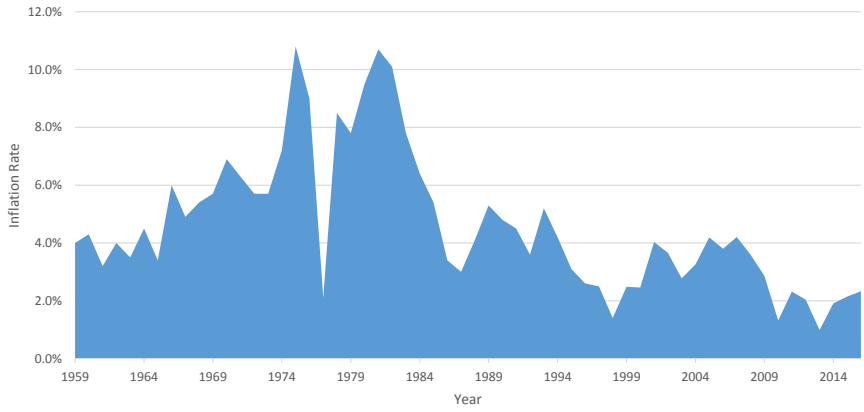


Figure C.2: United States Inflation [36]

Table C.1: EU and US Cumulative Inflation

Year	EU Inflation	US Inflation
1959	1	1
1960	1.019	1.043
1961	1.040	1.076
1962	1.081	1.119
1963	1.128	1.159
1964	1.188	1.211
1965	1.244	1.252
1966	1.301	1.327
1967	1.351	1.392
1968	1.402	1.467
1969	1.455	1.551
1970	1.529	1.658
1971	1.627	1.762
1972	1.734	1.863
1973	1.892	1.969
1974	2.160	2.111
1975	2.433	2.339
1976	2.741	2.549
1977	3.089	2.824
1978	3.414	3.044
1979	3.806	3.333
1980	4.376	3.690
1981	4.995	4.063
1982	5.648	4.380
1983	6.385	4.660
1984	7.005	4.912
1985	7.580	5.079
1986	8.015	5.231
1987	8.430	5.445
1988	8.937	5.734
1989	9.542	6.009
1990	10.287	6.280
1991	11.052	6.506
1992	11.718	6.844
1993	12.488	7.131
1994	13.057	7.352
1995	13.664	7.544
1996	14.180	7.732
1997	15.215	7.840
1998	15.931	8.035
1999	16.408	8.233
2000	16.983	8.565
2001	17.526	8.878
2002	17.964	9.124
2003	18.342	9.422
2004	18.763	9.817
2005	19.195	10.190
2006	19.637	10.619
2007	20.108	11.000
2008	20.852	11.316
2009	21.060	11.465
2010	21.503	11.730
2011	22.169	11.970
2012	22.746	12.088
2013	23.087	12.319
2014	23.202	12.583
2015	23.202	12.876

References

[35] Charles D. Hunt. FY14 NASA New Start Inflation Indices (NNSI). Cost Analysis Division, Online NASA Publication, February 2014.

[36] Charles D. Hunt and Michel O. van Pelt. *Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars.* BiblioGov, Noordwijk, The Netherlands, 2004.

[76] OECD. OECD Consumer Price Index Inflation Figures. www.oecd.com, February 2016.

D

Historical EUR/USD Exchange Rates

This appendix contains exchange rates between the Euro and Dollar which are used in all cost estimates in the model SOLSTICE developed for this research. Before the creation of the Euro in 1997, theoretical exchange rates are fixed at the 1997 rate of 1.2160 EUR/USD [75].

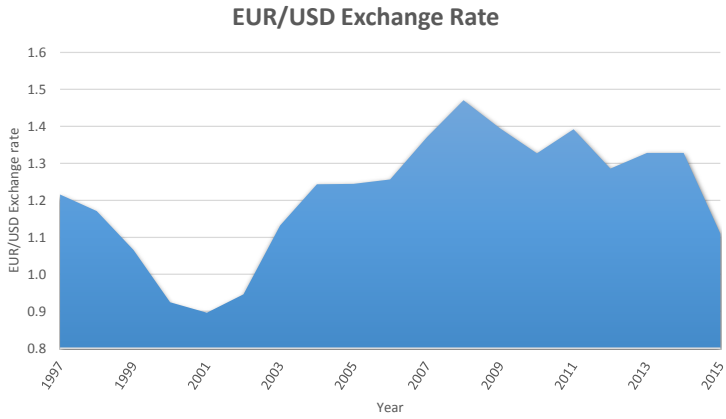


Figure D.1: Euro/United States Dollar exchange rates

Table D.1: Historical EUR/USD Exchange Rates

Odd Years		Even Years	
Year	**Exchange Rate**	**Year**	**Exchange Rate**
2015	1.1101	2014	1.3285
2013	1.3281	2012	1.2858
2011	1.3923	2010	1.3272
2009	1.3943	2008	1.4707
2007	1.3708	2006	1.2562
2005	1.2445	2004	1.2437
2003	1.1322	2002	0.9459
2001	0.8960	2000	0.9242
1999	1.0658	1998	1.1709
1997	1.2160	1996	1.2160
...	...	...	...

References

[75] OANDA. Historical eur/usd exchange rates. www.oanda.com, March 2016.

E

SOLSTICE Flight Unit Cost Estimating Relationships

Here, Cost Estimating Relationships which are used in SOLSTICE are listed. Mass is related to cost through Equation (E.1), where C is the subsystem element's cost, M its mass, and a and b are constants.

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

The NASA Air Force Cost Model (NAFCOM) provides standard b-values which are listed in Smart [88]. Using sample data, the a-values corresponding to the NAFCOM mass-cost curves were derived. This same sample data is also incorporated in a regression curve with separate a and b coefficients. If the sample data passes two significance tests listed in Chapter 2, the regression curve is used as an approximation of the equipment's cost. When this is not the case, the NAFCOM-derived curve is chosen. NAFCOM and regression a and b values are listed in Table E.1 along with the choice between them made based on these tests. The range in which these CERs derived is applicable is also shown in Table E.2. Mass and cost in these CER's are in kilogram and k€ respectively.

The Log. SE is the logarithmic standard error σ of the linear regression in log space. The Relative Standard Error and Cost Modeling Accuracy is the ratio of standard error to standard deviation, as in Equation eqrefeq:sdex

$$\frac{SD[X]}{E[X]} = \sqrt{e^{\sigma^2} - 1} = \sqrt{e^{0.128^2} - 1} = 12.9\% \tag{E.2}$$

Table E.1: Subsystem elements' Cost Estimating Relationships in the form of $C = aM^b$ derived from sample data, with logarithmic standard error and Cost Modeling Accuracy. Also listed are standard NAFCOM b-values [88] with a-values based on sample data. Mass and cost are in kilogram and k€ respectively.

				Regression				NAFCOM		
				a value	b value	Log. SE	RSE/CMA	a value	b value	Used
Stage										
	Solid Casing		S-SC-	90.72782	0.44422	0.128	12.9%	321.12767	0.30	Regression
	Pressurizant Tank		S-PT-	19.99465	0.71253	0.271	27.6%	22.21748	0.70	Regression
	Fuel Tank		S-FT-	19.99465	0.71253	0.271	27.6%	22.21748	0.70	Regression
	Oxidizer Tank		S-OT-	19.99465	0.71253	0.271	27.6%	22.21748	0.70	Regression
	Stage Structure									
		Thrust Cone	S-SS-TRC	2.79930	0.91199	0.125	12.6%	9.39259	0.70	Regression
		Skirt	S-SS-SKI	2.79930	0.91199	0.125	12.6%	9.39259	0.70	Regression
		Thermal Control	S-SS-THM	2.79930	0.91199	0.125	12.6%	9.39259	0.70	Regression
	Engine(s)		S-EN-	31.48271	0.78811	0.347	35.8%	322.07959	0.50	Regression
	Thrust Vector Control		S-TV-	33.90978	0.60977	0.136	13.7%	35.44885	0.60	Regression
	Pressurization System		S-PS-	11.50618	1.06948	0.471	49.8%	72.19775	0.60	Regression
	Pipes & Valves									
		Pipes	S-PV-PIP	8.95877	0.68815	0.333	34.3%	8.96336	0.70	Regression
		Valves	S-PV-VAL	8.95877	0.68815	0.333	34.3%	8.96336	0.70	Regression
	Stage Harness		S-SH-	27.45211	0.44623	0.339	34.9%	14.20721	0.75	Regression
Payload										
	Payload Adapter		P-PA-	124.86209	0.31031	0.129	13.0%	26.01794	0.70	Regression
	Payload Fairing		P-PF-	4.09558	0.96587	0.091	9.2%	23.59239	0.70	Regression
Avionics										
	Avionics									
		Comms	A-AV-COM		*One data point only*			51.11253	0.80	NAFCOM
		Power	A-AV-PWR	56.13918	0.66916	*Two data points only*		42.01174	0.80	NAFCOM
		Data Handling	A-AV-DHL	141.82428	0.79249	0.162	16.3%	141.68203	0.80	Regression
		GNC	A-AV-GNC	69.05491	0.82458	0.235	23.8%	72.86034	0.80	Regression
		Avionics Harness	A-AV-HNS	27.45211	0.44623	0.339	34.9%	14.20721	0.75	Regression
Attitude Control										
	Attitude Control Module		C-AC-	44.04074	1.06207	0.761	88.6%	257.84198	0.75	Regression
Interstage										
	Interstage Structure		I-IS-	6.70369	0.68041	0.191	19.3%	6.16655	0.70	Regression

Table E.2: Mass range where the regression CERs in Table E.2 are applicable. *Engine range has been verified outside of data-point scope to 200

				Range [kg] Min	Max
Stage					
	Solid Casing		S-SC-	543	53,077
	Pressurizant Tank		S-PT-	62	4,742
	Fuel Tank		S-FT-	62	4,742
	Oxidizer Tank		S-OT-	62	4,742
	Stage Structure				
		Thrust Cone	S-SS-TRC	22	1,036
		Skirt	S-SS-SKI	22	1,036
		Thermal Control	S-SS-THM	22	1,036
	Engine(s)*		S-EN-	200	6,740
	Thrust Vector Control		S-TV-	23	110
	Pressurization System		S-PS-	5	134
	Pipes & Valves				
		Pipes	S-PV-PIP	6	400
		Valves	S-PV-VAL	6	400
	Stage Harness		S-SH-	4	35
Payload					
	Payload Adapter		P-PA-	30	123
	Payload Fairing		P-PF-	26	3,000
Avionics					
	Avionics				
		Comms	A-AV-COM	-	-
		Power	A-AV-PWR	4	25
		Data Handling	A-AV-DHL	1	5
		GNC	A-AV-GNC	1	13
		Avionics Harness	A-AV-HNS	4	35
Attitude Control					
	Attitude Control Module		C-AC-	10	1,100
Interstage					
	Interstage Structure		I-IS-	22	350

Table E.3: Indication of what parts of a launch vehicle belong to the CERs in Table E.1

S-SC-	Included in the solid casing is the propellant mass and thrust vector control
S-PT- *S-FT-* *S-OT-*	The pressurizant tank, fuel and oxidizer tank and insulation are assumed to have the same CER. Tanks with insulation are heavier, but also more costly so the mass/cost complexity factor is assumed constant
S-SS-TRC *S-SS-SKI* *S-SS-THM*	Structural elements are assumed to have the same complexities and the same CERs. Includes MLI, front and aft skirts
S-EN-	Liquid rocket engines include kerosene and hydrogen engine data-points to account for lack of knowledge of whether methane engines' costs lie between them
S-TV-	Including PDU
S-PS-	Roll control, pilot pressure, main tank pressure (and where applicable anti-pogo)
S-PV-PIP *S-PV-VAL*	Pipes and valves are assumed of equal complexity. It is recognized that valves have actuators that are higher-cost, however these elements aren't cost drivers
S-SH-	Cable harnesses throughout the stages, excluding avionics cables
P-PA-	Payload adapter with latches
P-PF-	Payload fairing
A-AV-COM	Antennas
A-AV-PWR	Batteries and power systems excluding cables which belong to the stage harness
A-AV-DHL	Entire data handling system
A-AV-GNC	Guidance, navigation and control hardware including IMU's
A-AV-HNS	Differing from stage harness, used only once in upper stage
C-AC-	Separate attitude control module that is featured only once in the upper stage
I-IS-	Including separation system and pyros

References

[88] Christian Smart. Bayesian Parametrics: How to Develop a CER with Limited Data and Even Without Data. *Missile Defense Agency*, April 2014.

F

Learning Curve

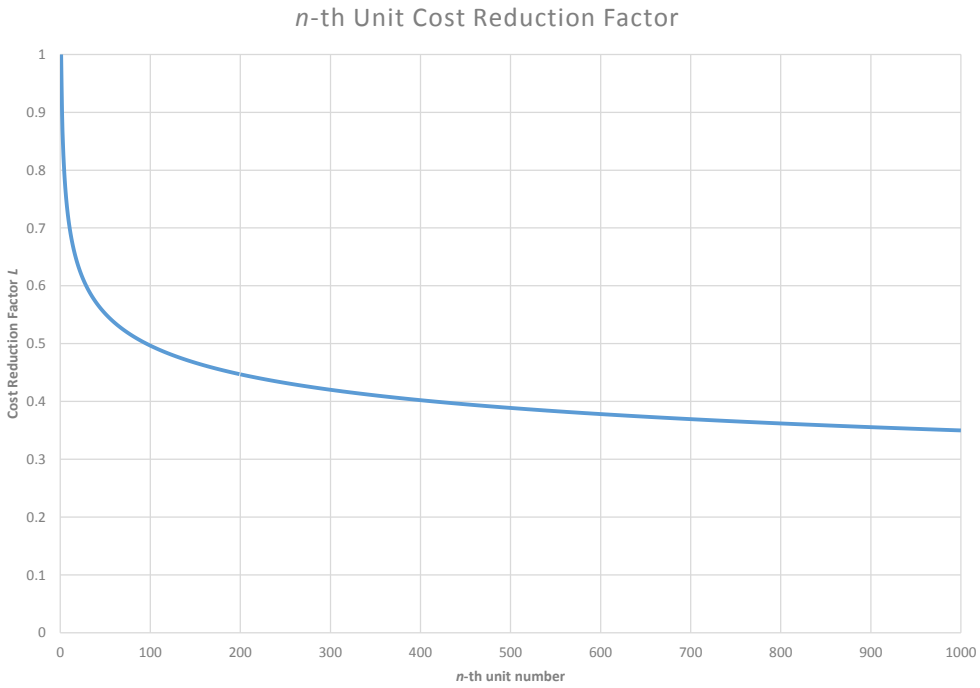


Figure F.1: Cost improvement factor L_m for n-th unit manufacturing costs, relative to T1

Featured here is the cost improvement slope assumed during manufacturing. A standard 90% cost improvement factor in a Crawford Learning Curve or Unit Learning Theory is applied [4]. This means each doubling of production results in a cost decrease of 10%. The cost reduction factor L_m is constructed by means of:

$$L_m = n^{\frac{\ln p}{\ln 2}} \tag{F.1}$$

with a standardized learning factor p of 90% or 0.9 applied throughout. The following table gives the normalized n-th unit cost for unit 1 up and until 50, with corresponding *Cumulative Cost* and *Average Cost per Unit*, which is the cumulative cost divided by the number of units. To determine the cost for one production batch, cumulative costs for the relevant unit numbers must be subtracted from each other. For example, the batch production cost for unit 20-26 is the cumulative cost of 26 units, reduced with the cumulative cost of the preceding 19 units. $C_{20-26} = Cu_{26} - Cu_{19} = 18.32 - 13.97 = 4.35$

Table F.1: Normalized costs w.r.t. the first unit, by applying the Crawford cost improvement curve [4] during the manufacturing phase. A learning factor of 90% is applied, which means each doubling of production sees costs that are 90% that of previously produced units

Unit Number (n)	***n*-th Unit Cost L_m**	**Cumulative Cost L_c**	**Average Cost per Unit**
1	1.00	1.00	1.00
2	0.90	1.90	0.95
3	0.85	2.75	0.92
4	0.81	3.56	0.89
5	0.78	4.34	0.87
6	0.76	5.10	0.85
7	0.74	5.84	0.83
8	0.73	6.57	0.82
9	0.72	7.29	0.81
10	0.70	7.99	0.80
11	0.69	8.69	0.79
12	0.69	9.37	0.78
13	0.68	10.05	0.77
14	0.67	10.72	0.77
15	0.66	11.38	0.76
16	0.66	12.04	0.75
17	0.65	12.69	0.75
18	0.64	13.33	0.74
19	0.64	13.97	0.74
20	0.63	14.61	0.73
21	0.63	15.24	0.73
22	0.63	15.86	0.72
23	0.62	16.48	0.72
24	0.62	17.10	0.71
25	0.61	17.71	0.71
26	0.61	18.32	0.70
27	0.61	18.93	0.70
28	0.60	19.53	0.70
29	0.60	20.13	0.69
30	0.60	20.73	0.69
31	0.59	21.32	0.69
32	0.59	21.91	0.68
33	0.59	22.50	0.68
34	0.59	23.08	0.68
35	0.58	23.67	0.68
36	0.58	24.25	0.67
37	0.58	24.82	0.67
38	0.58	25.40	0.67
39	0.57	25.97	0.67
40	0.57	26.54	0.66
41	0.57	27.11	0.66
42	0.57	27.68	0.66
43	0.56	28.24	0.66
44	0.56	28.81	0.65
45	0.56	29.37	0.65
46	0.56	29.92	0.65
47	0.56	30.48	0.65
48	0.56	31.04	0.65
49	0.55	31.59	0.64
50	0.55	32.14	0.64

References

[4] Timothy P. Anderson. Learning Curve Primer, Part 1 - Unit Theory. *The National Estimator*, pages 12–16, Fall 2011. Society of Cost Estimating and Analysis.

G

Liquid Rocket Fuel Prices

The liquid rocket fuel prices listed here are adhered to in the research. Their stated cost are in varying economic years and are standardized to 2015 prices per kilogram costs.

Table G.1: Liquid rocket fuel price basis, ESA internal reference

Fuel Type	**Price [€/kg]**	**Year**	**2015**
N2O4	1.37	2002	1.77
UDMH	12.97	2002	16.75
LOX	0.11	2004	0.14
LH2	4.85	2004	6.00
GHe	34.60	2002	44.69
LHe	27.70	2002	35.78
H202	11.11	2011	11.63
N2	84.89	2011	88.85
O2	66.36	2011	69.45
CH4	1.35	2015	1.35
Kerosene	0.062	2015	0.06

H

NAFCOM b-values

This appendix lists NASA Air-Force Cost Model (NAFCOM) b-values that determine the slope of a mass-cost regression curve in the NAFCOM model which is of the form:

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

b-values for Design, Development, Test and Evaluation (DDT&E, the development phase definition of NASA) are given by Smart [88] but not used to construct the development cost estimate: the Flight Unit (FU) costs are used to estimate development costs with T1 equivalents.

Table H.1: b-values for NAFCOM regression curves [88]

	b-values		**Variance of b-values**	
Subsystem/Group	**DDT&E**	**Flight Unit**	**DDT&E**	**Flight Unit**
Antenna Subsystem	0.85	0.80	0.0338	0.0161
Aerospace Support Equipment	0.55	0.70	0.0698	0.0982
Attitude Control/ Guidance and Navigation Subsystem	0.75	0.85	0.0120	0.0059
Avionics Group	0.90	0.80	0.0055	0.0044
Communications and Command and Data Handling Group	0.85	0.80	0.0053	0.0003
Communications Subsystem	0.85	0.80	0.0208	0.0141
Crew Accommodations Subsystem	0.55	0.70	0.0826	0.0565
Data Management Subsystem	0.85	0.80	0.0048	0.0025
Environmental Control and Life Support Subsystem	0.50	0.80	0.0048	0.2662
Electrical Power and Distribution Group	0.65	0.75	0.0064	0.0043
Electrical Power Subsystem	0.65	0.75	0.0878	0.0161
Instrumentation Display and Control Subsystem	0.85	0.80	0.1009	0.0665
Launch and Landing Safety	0.55	0.70	0.0960	0.0371
Liquid Rocket Engines Subsystem	0.30	0.50	0.1234	0.0483
Mechanisms Subsystem	0.55	0.70	0.0050	0.0167
Miscellaneous	0.50	0.70	0.0686	0.0784
Power Distribution and Control Subsystem	0.65	0.75	0.0106	0.0053
Propulsion Subsystem	0.55	0.60	0.2656	0.1730
Range Safety Subsystem	0.65	0.75	-	-
Reaction Control Subsystem	0.55	0.60	0.0144	0.0092
Separation Subsystem	0.50	0.85	-	-
Solid/ Kick Motor Subsystem	0.50	0.30	0.0302	0.0105
Structures Subsystem	0.55	0.70	0.0064	0.0038
Structures/Mechanical Group	0.55	0.70	0.0029	0.0023
Thermal Control Subsystem	0.50	0.80	0.0055	0.0045
Thrust Vector Control Subsystem	0.50	0.60	0.7981	0.0234

References

[88] Christian Smart. Bayesian Parametrics: How to Develop a CER with Limited Data and Even Without Data. *Missile Defense Agency*, April 2014.

ESA Methane Launcher Flight Unit Standard Errors

The Tables I.2 and I.1 in this appendix include the logarithmic standard errors of the regression and NAFCOM estimates, for each of the equipment elements in the liquid methane rocket concept. The upper (C_{upp}) and lower (C_{low}) cost bounds are obtained by filling in this standard error σ in the relationships illustrated in Equation (I.1) and Equation (I.2).

$$\ln C_{upp} = \ln C + \sigma \rightarrow C_{upp} = C \cdot e^{\sigma} \rightarrow \left(\frac{C_{upp}}{C} - 1\right) \cdot 100\% = \left(e^{\sigma} - 1\right) \cdot 100\% \tag{I.1}$$

$$\ln C_{low} = \ln C - \sigma \rightarrow C_{low} = \frac{C}{e^{\sigma}} \rightarrow \left(\frac{C_{low}}{C} - 1\right) \cdot 100\% = \left(\frac{1}{e^{\sigma}} - 1\right) \cdot 100\% \tag{I.2}$$

Table I.1: Logarithmic Standard Error of the cost of elements in Stage 2 of the Liquid Methane Rocket Concept

Unit	Equipment	Part	Part ID	Stand. Err.(LOG)
Stage 2	*Liquid Stage*			
	Solid Casing		S-SC-	-
	Pressurizant Tank		S-PT-	0.2711
	Fuel Tank		S-FT-	0.2711
	Oxidizer Tank		S-OT-	0.2711
	Stage Structure			
		Thrust Cone	S-SS-TRC	0.1253
		Skirt	S-SS-SKI	0.1253
		Thermal Control	S-SS-THM	0.1253
	Engine(s)		S-EN-	0.3469
	Thrust Vector Control		S-TV-	0.1359
	Pressurization System		S-PS-	0.4708
	Pipes & Valves			
		Pipes	S-PV-PIP	0.3333
		Valves	S-PV-VAL	0.3333
	Stage Harness		S-SH-	0.3393
Interstage				
	Interstage Structure		I-IS-	0.1909

The inter-group correlation matrix used to derive total stage estimate errors is shown in Table I.3 [8]. Zero values are inserted where correlation is assumed not to exist.

Table I.2: Logarithmic Standard Error of the cost of elements in Stage 1 of the Liquid Methane Rocket Concept

Unit	Equipment	Part	Part ID	Stand. Err.(LOG)
Stage 1	*Liquid Stage*			
	Solid Casing		S-SC-	-
	Pressurizant Tank		S-PT-	0.2711
	Fuel Tank		S-FT-	0.2711
	Oxidizer Tank		S-OT-	0.2711
	Stage Structure			
		Thrust Cone	S-SS-TRC	0.1253
		Skirt	S-SS-SKI	0.1253
		Thermal Control	S-SS-THM	0.1253
	Engine(s)		S-EN-	0.3469
	Thrust Vector Control		S-TV-	0.1359
	Pressurization System		S-PS-	0.4708
	Pipes & Valves			
		Pipes	S-PV-PIP	0.3333
		Valves	S-PV-VAL	0.3333
	Stage Harness		S-SH-	0.3393
Payload				
	Payload Adapter		P-PA-	0.1290
	Payload Fairing		P-PF-	0.0914
Avionics				
	Avionics			
		Comms	A-AV-COM	0.0507
		Power	A-AV-PWR	0.0582
		Data Handling	A-AV-DHL	0.1619
		GNC	A-AV-GNC	0.2346
		Avionics Harness	A-AV-HNS	0.3393
Attitude Control				
	Attitude Control Module		C-AC-	0.7613
I&T				
	Stage Integration & Test		I&T	-
	PAA I&T		I&T-P-	-

Also featured here is an illustration of the range of project cost risk contributors other than the Cost Modeling Accuracy (CMA) determined in this report, which is the spread of the estimate which is due to the data. Other contributors include Project Owned Events (POE), which stem from potential future negative (or positive) events that may occur or not and includes Development Risk. They also include External Project Events (EPE), which are risks induced by an unfavorable project environment such as procurement policy, industrial set-up and geo-return constraints. Finally there is a Design Maturity Margin (DMM) risk, in which the Technology Readiness Level (TRL) imposes an uncertainty on the eventual effort needed for the design, and therefore also the cost. [16]

Commercial companies have to mitigate POE just as agencies do, while certain EPE risks such as those arising from geo-return constraints and industrial set-up (if producing most of their subsystems in-house) are inherently avoided. It was also assessed that commercial companies utilize heritage proven technologies more; linking this to the DMM it is clear that this is also a cost risk mitigating procedure. [13]

Table I.3: Correlation matrix used to develop stage Flight Unit CMA estimate from subsystem group uncertainties

	Solid Stage	Tanks	Structures	Engine and TVC	Pressurization System	Pipes & Valves	Stage Harness	Payload Structure	Avionics	Attitude Control	Interstage
Solid Stage	**1**	0	0	0	0	0	**0.2**	**0.2**	0	**0.2**	**0.2**
Tanks	0	**1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	0	**0.2**	0
Structures	0	**0.2**	**1**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	0	**0.2**	**0.2**
Engine and TVC	0	**0.2**	**0.2**	**1**	**0.2**	**0.2**	**0.2**	0	0	**0.2**	0
Pressurization System	0	**0.2**	**0.2**	**0.2**	**1**	**0.2**	**0.2**	0	0	**0.2**	0
Pipes & Valves	0	**0.2**	**0.2**	**0.2**	**0.2**	**1**	**0.2**	0	0	**0.2**	0
Stage Harness	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**1**	0	0	**0.2**	0
Payload Structure	**0.2**	**0.2**	**0.2**	0	0	0	0	**1**	0	**0.2**	0
Avionics	0	0	0	0	0	0	0	0	**1**	0	0
Attitude Control	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	**0.2**	0	**1**	0
Interstage	**0.2**	0	**0.2**	0	0	0	0	0	0	0	**1**



Figure I.1: Range of project cost risk contributors [16]

References

[8] Raymond P. Covert. Correlations in Cost Risk Analysis. Annual SCEA Conference, June 2006.

[13] Nigel Drenthe. Identifying Factors influencing Cost per Flight of Small Commercial Launchers. *Literature Research*, TU Delft, 2016.

[16] ESA Cost Engineering Team. *TEC-SYC Cost Risk Procedure*. European Space Agency, Keplerlaan 1, Noordwijk, February 2010.

J

Validation Data

The approximated mass breakdowns of the Falcon 1 (Table J.1 and Table J.2), Falcon 9 (Table J.3 and Table J.4) and Pegasus XL (Table J.5 and Table J.6) launch vehicles are featured here. The development and manufacturing costs are estimated using the T1 equivalents method in SOLSTICE.

The Flight Unit (FU) costs form the basis of the development and manufacturing costs of a total batch of 50 units (50u). The Falcon 9 launch vehicle cost estimates also have a *Rank* parameter attached, which dictates how many units have been produced previously. It shifts the learning cost improvement forward forward for the number of units previously produced.

Commercial companies produce more parts in-house, and therefore retain more profits themselves. This leads to reduced costs, and is accounted for by the profit retention cost reduction factor of $c_p = 0.970$. It takes into account the amount of profit a subcontractor is making p, as well as the scope of subcontracted work under Business As Usual (BAU) and commercial development, s_{BAU} and s_{COM} respectively.

$$c_p = \frac{s_{COM} \cdot p + 1}{s_{BAU} \cdot p + 1} \tag{J.1}$$

Table J.1: Falcon 1, Stage 1 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 1	*Liquid Stage*			**1,494**		**8,729**	**60,085**	**272,009**
	Solid Casing		S-SC-	-	-	-	-	-
	Pressurizant Tank		S-PT-	38	1	268	1,845	8,354
	Fuel Tank		S-FT-	305	1	1,177	8,103	36,681
	Oxidizer Tank		S-OT-	0	1	-	-	-
	Stage Structure							-
		Thrust Cone	S-SS-TRC	90	1	169	1,163	5,264
		Skirt	S-SS-SKI	271	1	463	3,185	14,419
		Thermal Control	S-SS-THM	0	1	-	-	-
	Engine(s)		S-EN-	630	1	5,061	34,838	157,713
	Thrust Vector Control		S-TV-	44	1	342	2,357	10,670
	Pressurization System		S-PS-	67	1	1,032	7,106	32,171
	Pipes & Valves							
		Pipes	S-PV-PIP	24	1	79	543	2,458
		Valves	S-PV-VAL	14	1	55	382	1,729
	Stage Harness		S-SH-	12	1	82	563	2,550
Payload				**125**		**755**	**5,197**	**23,525**
	Payload Adapter		P-PA-	5	1	80	548	2,481
	Payload Fairing		P-PF-	121	1	675	4,649	21,044
Avionics				**4**		**211**	**1,451**	**6,568**
	Avionics							
		Comms	A-AV-COM	0	1	0	0	0
		Power	A-AV-PWR	3	1	100	687	3,109
		Data Handling	A-AV-DHL	1	1	111	764	3,459
		GNC	A-AV-GNC	0	1	-	-	-
		Avionics Harness	A-AV-HNS	0	1	-	-	-
Attitude Control				**-**	**-**	**-**	**-**	**-**
	ACM		C-AC-	-	1	-	-	-
I&T				**3.2%**	**-**	**306**	**2,107**	**9,540**
	Stage I&T		I&T	-	1	276	1,897	8,590
	PAA I&T		I&T-P-	-	1	30	210	950

Table J.2: Falcon 1, Stage 2 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 2	*Liquid Stage*			**538**		**2,994**	**20,607**	**93,287**
	Solid Casing		S-SC-	-	-	-	-	-
	Pressurizant Tank		S-PT-	21	1	178	1,224	5,543
	Fuel Tank		S-FT-	171	1	781	5,376	24,337
	Oxidizer Tank		S-OT-	0	1	-	-	-
	Stage Structure							
		Thrust Cone	S-SS-TRC	50	1	100	688	3,114
		Skirt	S-SS-SKI	152	1	274	1,884	8,529
		Thermal Control	S-SS-THM	0	1	-	-	-
	Engine(s)		S-EN-	52	1	709	4,878	22,084
	Thrust Vector Control		S-TV-	25	1	241	1,659	7,511
	Pressurization System		S-PS-	38	1	558	3,839	17,380
	Pipes & Valves							
		Pipes	S-PV-PIP	13	1	53	365	1,654
		Valves	S-PV-VAL	8	1	37	257	1,164
	Stage Harness		S-SH-	6	1	63	436	1,972
Interstage				**30**		**68**	**467**	**2,113**
	Interstage Structure		I-IS-	30	1	68	467	2,113
Stage I&T				**3.2%**	**-**	**97**	**665**	**3,013**
	Stage I&T		I&T	-	1	97	665	3,013

Table J.3: Falcon 9, Stage 1 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Rank	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 1	*Liquid Stage*			**12,669**			**55,501**	**168,323**	**1,366,699**
	Solid Casing		S-SC-	-	-	-	-	-	-
	Pressurizant Tank		S-PT-	243	1	3	1,002	6,895	30,144
	Fuel Tank		S-FT-	4742	1	3	8,321	57,272	250,393
	Oxidizer Tank		S-OT-	0	1	3	-	-	-
	Stage Structure								
		Thrust Cone	S-SS-TRC	2060	1	3	2,946	20,279	88,659
		Skirt	S-SS-SKI	0	1	3	-	-	-
		Thermal Control	S-SS-THM	0	1	3	-	-	-
	Engine(s)		S-EN-	522	9	3	39,277	56,651	878,466
	Thrust Vector Control		S-TV-	196	1	3	847	5,833	25,500
	Pressurization System		S-PS-	134	1	3	2,167	14,915	65,209
	Pipes & Valves								
		Pipes	S-PV-PIP	487	1	3	633	4,357	19,050
		Valves	S-PV-VAL	70	1	3	167	1,147	5,017
	Stage Harness		S-SH-	40	1	3	142	975	4,261
Payload				**1,923**			**5,237**	**36,050**	**157,610**
	Payload Adapter		P-PA-	123	1	3	755	5,200	22,734
	Payload Fairing		P-PF-	1800	1	3	4,482	30,850	134,876
Avionics				**249**			**8,274**	**56,949**	**248,982**
	Avionics								
		Comms	A-AV-COM	8	1	3	281	1,931	8,442
		Power	A-AV-PWR	58	1	3	1,088	7,487	32,732
		Data Handling	A-AV-DHL	96	1	3	5,468	37,640	164,561
		GNC	A-AV-GNC	32	1	3	1,154	7,944	34,731
		Avionics Harness	A-AV-HNS	54	1	3	283	1,948	8,517
Attitude Control				**68**			**6,079**	**41,841**	**182,930**
	Attitude Control Module		C-AC-	68	1	3	6,079	41,841	182,930
I&T							**2,371**	**16,322**	**73,891**
	Stage I&T		I&T		1	-	1,753	12,064	54,614
	PAA I&T		I&T-P-		1	-	619	4,258	19,277

Table J.4: Falcon 9, Stage 2 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Rank	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 2	*Liquid Stage*			**2,211**			**8,967**	**61,720**	**209,541**
	Solid Casing		S-SC-	-	-	-	-	-	-
	Pressurizant Tank		S-PT-	81	1	32	458	3,152	12,060
	Fuel Tank		S-FT-	646	1	32	2,010	13,838	52,951
	Oxidizer Tank		S-OT-	-	1	32	-	-	-
	Stage Structure								
		Thrust Cone	S-SS-TRC	190	1	32	335	2,307	8,827
		Skirt	S-SS-SKI	574	1	32	918	6,319	24,180
		Thermal Control	S-SS-THM	-	1	32	-	-	-
	Engine(s)		S-EN-	522	1	288	4,364	30,039	88,317
	Thrust Vector Control		S-TV-	94	1	32	541	3,726	14,258
	Pressurization System		S-PS-	-	1	32	-	-	-
	Pipes & Valves								
		Pipes	S-PV-PIP	50	1	32	132	910	3,483
		Valves	S-PV-VAL	30	1	32	93	641	2,451
	Stage Harness		S-SH-	25	1	32	114	788	3,013
Interstage				**814**			**641**	**4,410**	**16,874**
	Interstage Structure		I-IS-	814	1	32	641	4,410	16,874
Stage I&T				**3.2%**			**303**	**2,088**	**9,454**
	Stage I&T		I&T	-	1	-	303	2,088	9,454

Table J.5: Pegasus XL, Stage 1 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Rank	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 1	*Solid Stage*			**17,844**			**7,095**	**48,838**	**221,090**
	Solid Casing		S-SC-	17,834	1	-	7,018	48,310	218,700
	Pressurizant Tank		S-PT-						
	Fuel Tank		S-FT-						
	Oxidizer Tank		S-OT-						
	Stage Structure								
		Thrust Cone	S-SS-TRC						
		Skirt	S-SS-SKI						
		Thermal Control	S-SS-THM						
	Engine(s)		S-EN-						
	Thrust Vector Control		S-TV-	0	1	-	0	0	0
	Pressurization System		S-PS-						
	Pipes & Valves								
		Pipes	S-PV-PIP						
		Valves	S-PV-VAL						
	Stage Harness		S-SH-	10	1	-	77	528	2,390
Payload				**100**			**593**	**4,079**	**18,466**
	Payload Adapter		P-PA-	0	1	-	0	0	0
	Payload Fairing		P-PF-	100	1	-	593	4,079	18,466
Avionics				**73**			**1,815**	**12,496**	**56,568**
	Avionics								
		Comms	A-AV-COM	1	1	-	51	352	1,593
		Power	A-AV-PWR	57	1	-	1,067	7,343	33,241
		Data Handling	A-AV-DHL	1	1	-	142	975	4,415
		GNC	A-AV-GNC	12	1	-	532	3,661	16,575
		Avionics Harness	A-AV-HNS	2	1	-	24	164	745
Attitude Control				**0**			**0**	**0**	**0**
	Attitude Control Module		C-AC-	0	1	-	0	0	0
I&T				**3.2%**			**300**	**2,066**	**9,351**
	Stage Integration & Test		I&T	-	1	-	224	1,542	6,982
	PAA I&T		I&T-P-	-	1	-	76	523	2,369

Table J.6: Pegasus XL, Stage 2 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Rank	Total FU [k€]	Development Phase [k€]	Manufacturing [50u, k€]
Stage 2	*Solid Stage*			**4,336**			**3,799**	**26,150**	**118,382**
	Solid Casing		S-SC-	4,331	1	-	3,743	25,763	116,628
	Pressurizant Tank		S-PT-						
	Fuel Tank		S-FT-						
	Oxidizer Tank		S-OT-						
	Stage Structure								
		Thrust Cone	S-SS-TRC						
		Skirt	S-SS-SKI						
		Thermal Control	S-SS-THM						
	Engine(s)		S-EN-						
	Thrust Vector Control		S-TV-	0	1	-	0	0	0
	Pressurization System		S-PS-						
	Pipes & Valves								
		Pipes	S-PV-PIP						
		Valves	S-PV-VAL						
	Stage Harness		S-SH-	5	1	-	56	387	1,754
Interstage				**0**			**0**	**0**	**0**
	Interstage Structure		I-IS-	0	1	-	0	0	0
Stage I&T				**3.2%**			**120**	**826**	**3,738**
	Stage Integration & Test		I&T	-	1	-	120	826	3,738

Table J.7: Pegasus XL, Stage 3 mass breakdown, Flight Unit, Development and Manufacturing Costs (50 units)

Unit	Equipment	Part	Part ID	Mass [kg]	Number	Rank	Total FU [k€]	Development Phase [k€]	Manufacturing [50u,k€]
Stage 3	*Solid Stage*			**994**			**1,998**	**13,756**	**62,272**
	Solid Casing		S-SC-	989	1	-	1,942	13,368	60,517
	Pressurizant Tank		S-PT-						
	Fuel Tank		S-FT-						
	Oxidizer Tank		S-OT-						
	Stage Structure								
		Thrust Cone	S-SS-TRC						
		Skirt	S-SS-SKI						
		Thermal Control	S-SS-THM						
	Engine(s)		S-EN-						
	Thrust Vector Control		S-TV-	-	1	-	0	0	0
	Pressurization System		S-PS-						
	Pipes & Valves								
		Pipes	S-PV-PIP						
		Valves	S-PV-VAL						
	Stage Harness		S-SH-	5	1	-	56	387	1,754
Interstage				**0**			**0**	**0**	**0**
	Interstage Structure		I-IS-	0	1	-	0	0	0
Stage I&T				**3.2%**			**63**	**434**	**1,966**
	Stage Integration & Test		I&T	-	1	-	63	434	1,966

K

Original Research Project Plan

Cost Estimating for 100-700 kg Payload Class Commercial Launchers

Nigel Drenthe - 4049977
Space Systems Engineering
Research Proposal for Barry Zandbergen and Ricky Curran

September 30, 2016

K.1. Introduction

This proposal will be about estimating cost per flight (CpF), and the corresponding price per flight (PpF) of commercial launch vehicles with a payload mass between 100-700 kilograms. The market for frequent low-cost scheduled launches to space for this class of satellites is growing [6], but a dedicated tool for estimating their launch costs is not yet available at the TU Delft or ESA [13]. This will be the result of this research.

Creating such a tool is important for launch service providers, because determining a Price per Flight establishes a competitive place in the nascent commercial launch market for small satellites. Also, decisions on project feasibility and funding are made on the basis of these estimates [94]. Such a tool is also crucial for an organisation like the European Space Agency, either to evaluate proposals for shared technology development/funding requests on their feasibility, or to estimate rocket development costs outside of agency business as usual (BAU).

Ultimately, the tool will be used to estimate costs for the development, manufacturing and operations phases in an early project stage. By combining these, the cost per flight and price per flight will be determined. It will be used to cost a liquid methane conceptual launch vehicle design currently under study at ESA.

The problem at hand is twofold. First, the models currently available are not geared towards estimating costs for this size of rocket [13]. They were developed for larger vehicles. Extrapolating these relationships to smaller rockets leads to cost values that previous analyses [97] indicate are too high. A translation needs to be made from modeling large, to modeling small launchers. Secondly, dedicated launch vehicle models like *TRANSCOST* take the lower cost of commercially made and operated vehicles into account at an abstract level only, with a single multiplication factor of between 0.45 and 0.55 to compensate for actual commercial costs. [45]. Therefore a translation also needs to be made from government-sponsored to commercially developed rockets.

The approach that will be taken in this research will deal with both these issues. Costs for the development and manufacturing phases of a commercial rocket will be composed from Cost Estimating Relationships (CERs) at equipment level in a reduced engineering build-up that does not include work-package level task descriptions. By doing this, a careful selection can be made of CERs that are cost-minimized by a competitive market. The tactics commercial companies employ to lower costs were identified [13], and will also be used as criteria for this trimming. In this manner, adding up these equipment level costs into total costs, the estimate will be representative for commercial rockets.

By selecting a source for equipment-level cost quotes carefully, not only the commercial nature of the developing company will be reflected, but the problem of launcher size will also be addressed simultaneously. For example, one of the cost sources will be the highly competitive satellite market. Not only are these costs minimized by the market, but large satellites also feature equipment of the size equivalent of a small launcher, like fuel tanks. By applying this approach, costs for small commercial commercially operated rockets will be modeled.

K.2. Research question and objective

The cost per flight is in general terms the vehicle recurring (manufacturing) cost, and the direct/indirect operations costs lumped together. Add to that the amortized development costs and a profit margin when the launch service provider is a company, and one arrives at the Price per Flight [45].

The research will aim to estimate for the aforementioned range of liquid methane rocket concepts the development, manufacturing and operations costs, and subsequent price and cost per flight (CpF/PpF). This will be done from mass or volume inputs for equipment-level parts of the launch vehicle.

The various sub-objectives of the research are:

- Construct a price per flight model for cost estimating commercial rockets
- Model uncertainties of the PpF model
- Validate the PpF model
- Determine the CpF/PpF range of the conceptual launch vehicles under study at ESTEC
- Amalgamate cost estimates into a cost range per kilogram launched corridor
- *Optionally* add a learning curve to the operations phase estimate & revalidate, or add a sensitivity analysis of the model to a change in technical input parameters

Because the cost per flight will be determined anyhow on the way to price per flight, the main research question will be:

Is it possible to estimate price per flight of a small commercial launch vehicle through costing of individual rocket design elements?

As there are no dedicated models to do so, the novelty of answering this question and issuing the accompanying model is that the research will determine for the first time at such a level a cost estimate for a small commercial launch vehicle. Models such as NAFCOM overestimate actual costs for commercial development outside agency Business as Usual (BAU) [72], while dedicated launch vehicle cost models such as TRANSCOST are not suited to determine costs for small launchers [97], therefore the proposed model will fill a gap left by previous research.

The research will have been considered successful if the actual Price per Flight of the validation cases (discussed in the methodology section) lie within the uncertainty range determined by the model. This uncertainty range is beforehand not known, but typically development phase estimates range between -20% and +20%, while flight unit CERs from which production costs are derived lie within -10% and 10%. Because the estimate consists of both, the preliminary target uncertainty range will be set at ±20%.

K.3. Methodology and test cases

K.3.1. Data Used

By having a number of differing tools available to complement the others' estimates where lacking, all aspects of development, manufacturing and operations phases' costs will be determined. The tools available are *TRANSCOST* and also, in a partnership agreement, and validity checks can be performed with ESA CERs to make the tool useful internally. Due to their up to date underlying pricing database, they are useful for costing development and manufacturing phases, even more so as *TRANSCOST* CERs were developed primarily for a larger class of launcher. However the operations cost relationships in *TRANSCOST* are useful if ESA internal data is lacking on that part.

K.3.2. General methodology

The proposed research will be built up by layering the model, much like an onion. First, a useful core will be built that functions correctly and will verified. Then additions in the form of outer layers will be added that plug into the basic model, each layer with their own step of verification. This way, throughout the various stages of development, the deliverable model will stay verified. It also ensures that a functioning and usable product is set-up at the end of the thesis period, irrespective of planning setbacks. A baseline thesis goal will be set that, if achieved, will satisfy the requirements set out by the TU Delft and supervisor Barry Zandbergen, and the customer in the form of ESA. Finally, validity checks will be performed with a reference Falcon 1 launch vehicle validation case, and other cases in the form of the Pegasus XL launch vehicle and a previous study on small launchers by Van Kesteren for which equipment on the vehicle is known [97].

Finally, as a bonus, an attempt to simplify the equipment level launch vehicle breakdown to a payload mass will be made, in order to compare the PpF results to costs quoted by commercial launch companies identified in the literature research [13] for which the launch vehicle components are not known in sufficient detail.

The build-up of the cost model is shown in Figure K.1.

K.3.3. Detailed methodology

The detailed steps performed in the proposed research are listed below, and are also described in Figure K.5.

Basic Model

First, the launch vehicle will be broken down into equipment level parts. Although not completely fixed, a preliminary breakdown for a liquid launcher single stage is given in Table K.1. The reason for selecting this level of depth is that CERs are available at this level, and a deeper level breakdown would be more suitable to a time-consuming bottom-up cost estimate [94]. A more shallow breakdown would be more akin to an entire systems parametric estimate like Koelle's [45], and would not allow for CER selection to reflect the *commercial* and *small* launch vehicle adaptations needing reflection in the estimate. A reduced version for solid rocket motors is shown in Table K.2. It is reduced because cost data is available for the entire solid rocket motor casing including propellant storage.

These masses or where more applicable the volumes of these parts will be used to determine their costs for a first flight unit (FU). Using this flight unit cost, CERs using that FU cost will be set up to estimate costs for the development phase including proto-flight model, which are non-recurring costs (NRC). After this is done, the FU cost will be used as a basis for deriving the manufacturing phase portion of the recurring costs (RC). For the latter one of the most important things to include is a decrease in costs for every unit manufactured due to learning [13]. To this end, the learning curve identified in the literature research will be implemented. This will decrease the manufacturing costs of equipment elements from the breakdown, for each subsequent element manufactured. The factor decrease can be determined for the production of a batch of n units, or for the n-th unit.

Next the CERs will be selected for the operations phase (which in principle do not rely on the aforementioned breakdown). This includes estimates for indirect operating costs (IOC) and direct operating costs (DOC). This is the second and final part of the recurring costs (RC). CER selection will also be motivated by

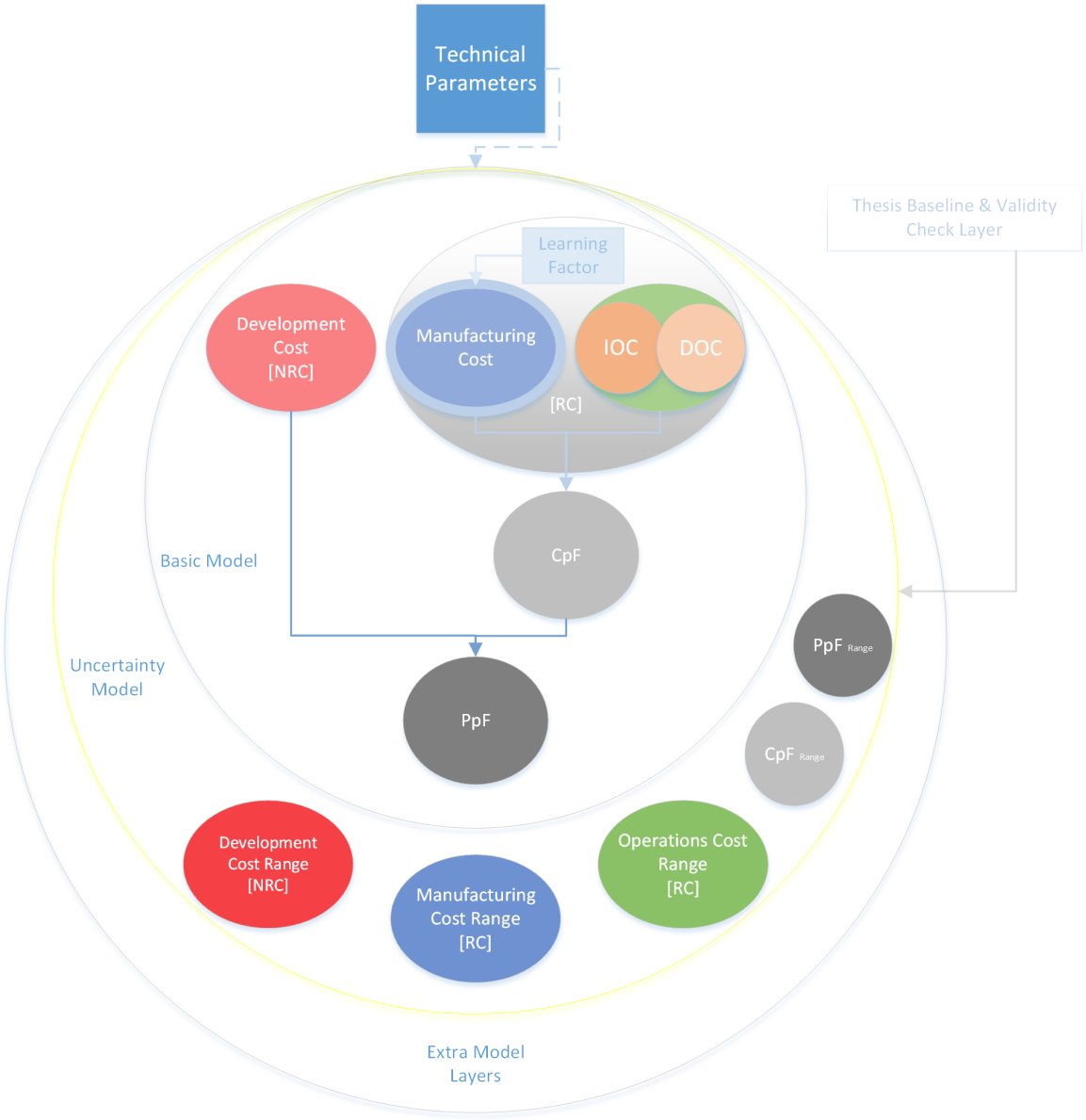


Figure K.1: Methodology for building and extending the cost model iteratively

Table K.1: Liquid Launch Vehicle Breakdown

Unit	**Equipment**	**Part**
Stage	Pressurizant Tank 1	Pressurizant Tank
	Pressurizant Tank 2	Pressurizant Tank
	Fuel Tank	Fuel Tank
	Oxidizer Tank	Oxidizer Tank
	Stage Structure	Thrust Cone
		Main Structure
		Thermal Control
		Harness
	Engine(s)	
	Thrust Vector Control	
	Propellant	Fuel
		Oxidizer
		Pressurizant
		Pressurizant
	Pipes & Valves	Pipes
		Valves
Interstage	Interstage Structure	
Payload	Payload Adapter	
	Payload Fairing	
Avionics	Avionics	Comms
		Power
		Data Handling
		GNC
		Harness
	Avionics Bay Structure	
Attitude Control	Attitude Control Module	

Table K.2: Solid Launch Vehicle Breakdown

Unit	**Equipment**	**Part**
Stage	Solid Casing	
	Thrust Vector Control	
Interstage	Interstage Structure	
Payload	Payload Adapter	
	Payload Fairing	
Avionics	Avionics	Comms
		Power
		Data Handling
		GNC
		Harness
	Avionics Bay Structure	
Attitude Control	Attitude Control Module	

these launchers' size considerations. They will also be selected by using the key commercial tactics found in the literature study, to ensure these are representative for a commercial estimate.

The general form of the CERs selected will consist of data with a regression curve, for which a generic one is illustrated in Figure K.2 [2]. Of course there is an amount of uncertainty about the estimated curve, because no sample data-point will lie exactly on it. In the initial build that will be verified, such an uncertainty will not be included, but will be the subject of analysis in a later addition to the model.

The CERs of course rely on technical parameters as inputs. The type of inputs are specific to each re-

lationship. It is expected that some of the inputs will be set to a fixed value as a reference. Those that are allowed to be varied, and where the final model will depend on, will need to be selected. This will be done in conjunction with an opportunity for the student to participate as an Assistant Systems Engineer on an ESA concurrent design facility (CDF) initial study on air-launched rockets, which will be held for a month starting the 15th of March 2016.

Once the CERs and their technical parameter inputs have been selected based on the CDF study, the CERs for each element in the rocket breakdown in the development and manufacturing phases will be combined into one model for both phases. At this point each of the three phases is modeled. When an example technical input setting is chosen, such as for instance a sample liquid methane launch vehicle concept, a data-point will be generated which corresponds to the cost of that vehicle. These cost figures are also obtained for each of the three phases. Once completed these models will be useful for estimating development, manufacturing and operations phase costs separately.

The next step is to model this uncertainty. To this end the relative standard error will be determined for all three phase estimates previously calculated, as well as for the eventual CpF and PpF. This will be done by building up the RSE from all equipment-level CER uncertainties. The cost estimates for the concepts at this point be accompanied by an uncertainty range. Changing the model inputs to reflect a different launcher concept will result in similar data points with uncertainty ranges. A possible payload or equipment mass with associated cost uncertainties will look something like the example curve in Figure K.2.

Baseline thesis model At this point the cost model is able to estimate development, manufacturing and operations costs, as well as the CpF and PpF along with all their uncertainties borne from the distribution of initial cost estimating relationship data. The model at this point will be the baseline goal of the thesis.

Validity checks will be performed with a reference Falcon 1 launch vehicle validation case for which equipment on the vehicle is known, and other cases in the form of the Pegasus XL launch vehicle and a previous study on small launchers by Van Kesteren [97]. If the actual costs lie within the uncertainty range around the cost calculated by the model, a priori estimated to be ±20%, the criterion for success will have been met. If necessary, the selected CERs may be re-evaluated to attain a more realistic estimate.

Possible extra model layers

Time permitting, subsequent extra layers will be added to the model. Analogous to that of the manufacturing phase, a similar learning curve could be applied to the operations costs, where increasingly frequent launches make the cost per launch, and therefore also the Cost per Flight and Price per Flight less. This will again yield slightly different uncertainty ranges for the mass/cost curves, but now with the new learning factor included.

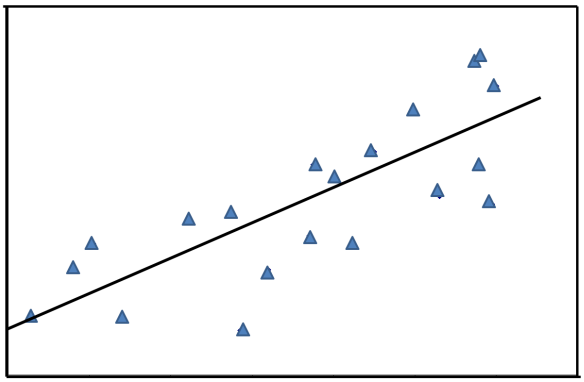


Figure K.2: A generic example of a regression curve

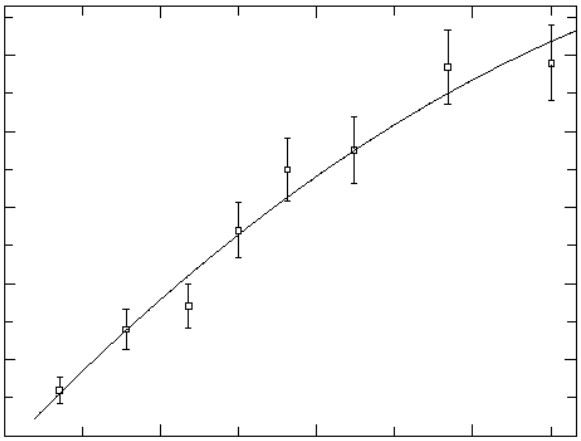


Figure K.3: Generic uncertainty mass or volume versus cost curve

As an all-out extra, and when the above has been completed entirely, the technical input parameters may be varied to study their effects on the final Cost/Price per Flight figures.

K.4. Expected Results

When discussing costs, there is of course always an element of uncertainty in this estimate. Rather than outright resulting in one single price per flight, cost per flight, development/manufacturing/operations cost etc., the outcomes will be ranges of cost with a certain confidence interval based on historical data.

It is expected the results of the validation cases fall within the range estimates determined by the proposed study. If not, it can be investigated whether selecting alternative CERs that belong to a different past program can provide a better final cost figure.

A cost figure range for the commercial launch vehicle concepts under study at ESTEC will result from the proposed study. Now the costs of commercially developing and operating such rockets will be known.

When combining this result with the cost ranges obtained from the validation cases, the whole dataset will be overlaid onto a payload vs. Price per Flight graph. These points and uncertainties form a corridor between which prices for small commercial launches should lie. As a second extra validity check, this corridor will be overlaid on the payload cost per flight curve for small launchers in Figure K.4. This way, it will finally be possible to qualitatively compare the model results to launch prices of rockets for which no equipment breakdown is available.

Ultimately, the resulting tool shall be used to estimate small launcher costs for each of the three phases, as well as the projected CpF and PpF, in early project stages. While CpF is relevant to agencies seeking to develop such launch capability, the PpF may be used to evaluate quoted commercial prices per launch such as in Figure K.4. In the future, shared technology development initiatives or requests for funding from ESA by commercial launch companies based on launch price can be accurately assessed.

K.4.1. Limitations & Recommendations

The proposed research and model will be able to estimate for a rocket or launch vehicle concept the cost and price per flight and its associated uncertainty. It works on the assumption that the specific launch vehicle is manufacturable and operable in that configuration.

It will not be possible to generate a payload/cost curve with this model. This is because payload mass can not be directly related to system mass without incurring inherent uncertainties on that part. To do so requires an extensive study on launch vehicle sizing, which does not lie within the cost estimating scope that is the

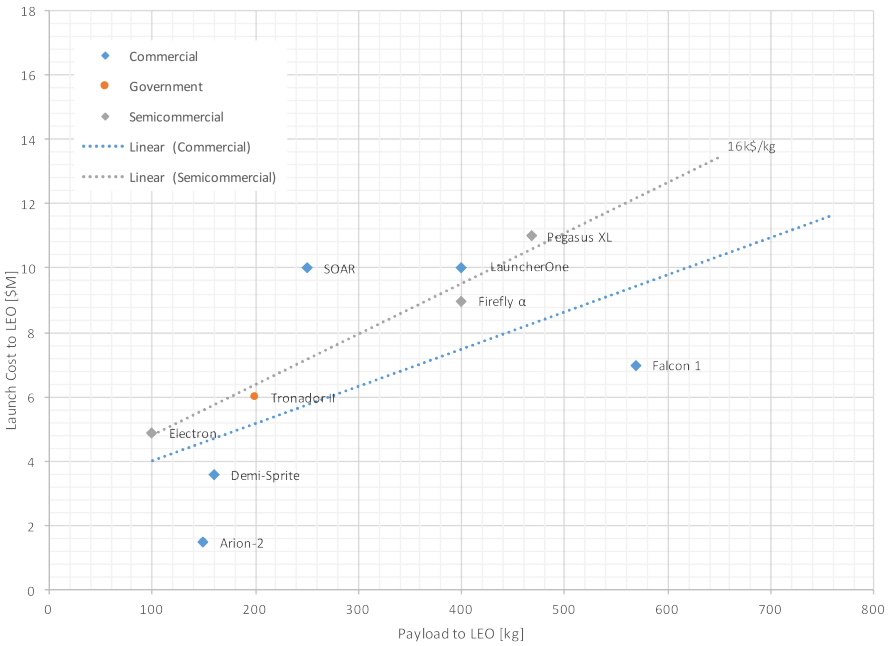
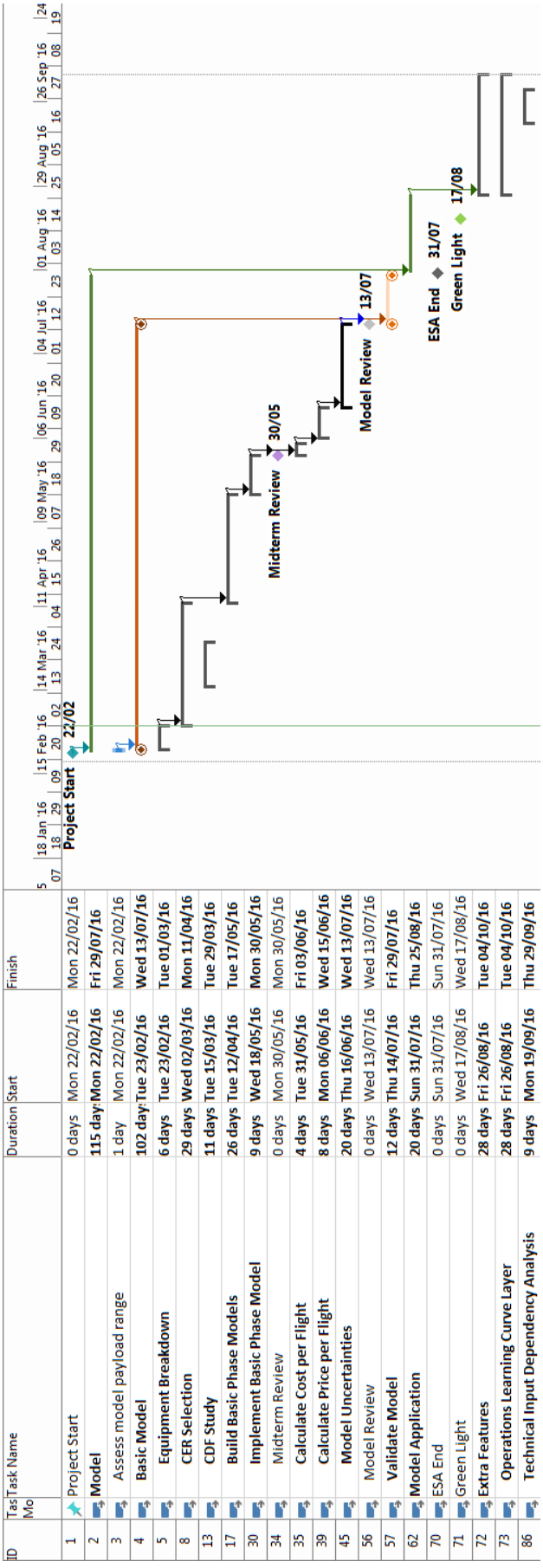


Figure K.4: Launch prices of small commercial rockets

focus of this research. However this is a potentially interesting feature to add in the future, so as to make the evaluation of quoted commercial prices more straightforward. This is because often the only available data on a certain rocket is launch price to LEO and its payload capacity. This can be done by linking a launch vehicle mass model to the cost tool.

K.5. Project Planning

The work described above is divided into tasks, and planned for the duration of the project. The proposed plan is shown in Figure K.5.



ID	Task Mo	Task Name	Duration	Start	Finish
1		Project Start	0 days	Mon 22/02/16	Mon 22/02/16
2		**Model**	**115 day**	**Mon 22/02/16**	**Fri 29/07/16**
3		Assess model payload range	1 day	Mon 22/02/16	Mon 22/02/16
4		**Basic Model**	**102 day**	**Tue 23/02/16**	**Wed 13/07/16**
5		**Equipment Breakdown**	**6 days**	**Tue 23/02/16**	**Tue 01/03/16**
8		**CER Selection**	**29 days**	**Wed 02/03/16**	**Mon 11/04/16**
13		**CDF Study**	**11 days**	**Tue 15/03/16**	**Tue 29/03/16**
17		**Build Basic Phase Models**	**26 days**	**Tue 12/04/16**	**Tue 17/05/16**
30		**Implement Basic Phase Model**	**9 days**	**Wed 18/05/16**	**Mon 30/05/16**
34		Midterm Review	0 days	Mon 30/05/16	Mon 30/05/16
35		**Calculate Cost per Flight**	**4 days**	**Tue 31/05/16**	**Fri 03/06/16**
39		**Calculate Price per Flight**	**8 days**	**Mon 06/06/16**	**Wed 15/06/16**
45		**Model Uncertainties**	**20 days**	**Thu 16/06/16**	**Wed 13/07/16**
56		Model Review	0 days	Wed 13/07/16	Wed 13/07/16
57		**Validate Model**	**12 days**	**Thu 14/07/16**	**Fri 29/07/16**
62		**Model Application**	**20 days**	**Sun 31/07/16**	**Thu 25/08/16**
70		ESA End	0 days	Sun 31/07/16	Sun 31/07/16
71		Green Light	0 days	Wed 17/08/16	Wed 17/08/16
72		**Extra Features**	**28 days**	**Fri 26/08/16**	**Tue 04/10/16**
73		**Operations Learning Curve Layer**	**28 days**	**Fri 26/08/16**	**Tue 04/10/16**
86		**Technical Input Dependency Analysis**	**9 days**	**Mon 19/09/16**	**Thu 29/09/16**

Figure K.5: Research Gantt Chart

References

[6] Daniel N. Baker and S. Pete Worden. The Large Benefits of Small-Satellite Missions. *EOS, Transactions, Americal Geophisical Union*, 89(33):301–302, August 2008.

[2] Boston University School of Public Health. Correlation and linear regression. Online, January 2016.

[13] Nigel Drenthe. Identifying Factors influencing Cost per Flight of Small Commercial Launchers. *Literature Research*, TU Delft, 2016.

[45] Dietrich E. Koelle. *Handbook of Cost Engineering and Design of Space Transportation Systems*. Number TCS-TR-200. TransCostSystems (TCS), Ottobrunn Germany, 8.2 edition, October 2013.

[72] NASA Associate Deputy Administrator for Policy. Falcon 9 Launch Vehicle NAFCOM Cost Estimates. Presentation, NASA, August 2011.

[94] O. Trivailo, M. Sippel, and Y.A. Şekercioğlu. Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning. *Progress in Aerospace Sciences*, 53:1 – 17, 2012. ISSN 0376-0421. doi: http://dx.doi.org/10.1016/j.paerosci.2012.02.001.

[97] MW Van Kesteren. Air Launch versus Ground Launch: A Multidisciplinary Design Optimization Study of Expendable Launch Vehicles on Cost and Performance. Master's thesis, TU Delft, Delft University of Technology, 2013.