POLITECNICO DI TORINO

Master Thesis

Aerospace Engineering

# PRELIMINARY DISCUSSION COST FOR A RLV


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A.A. 2020/2021

*To my Brother,*

*my Parents*

*and my Friends*

# Abstract


Rockets are every year more important in the context of Space exploration and Space transportation. One of the goal of these last decades a part the incrementation of the safety is the reduction of the price thanks to reusability.

Reusability of the first stage of a launch vehicle using vertical landing techniques also presents the potential for further price per kilogram reductions.

The combination of reusing the first stage of a small launch vehicle presented the most promising solution to reducing these prices.

Due to the secrecy of the economic sphere in the aerospace sector the scope of this research is to estimate the cost for a reusable launch system thanks to the method explained in the *Handbook of Cost Engineering.*

The data from estimation were compared to the data found on the internet thanks to a lot of tweets and interview released by Space X in order to understand if all the rumors circulating are true.

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# Nomenclature

AA= Amalgamation Approach;

AACE= The Association for the Advancement of Cost Engineering through Total Cost Management International;

ACE=Advocacy Cost Estimate;

ACEIT= Automated Cost Estimating Integrated Tools;

Aces= Advanced Cost Estimating System;

ACostE= Association of Cost Engineers;

ADCS= Attitude Determination and Control Subsystem;

AGE= Aerospace Ground Equipment;

AHP= Analytic Hierarchy Process;

AMCM= Advanced Missions Cost Model;

ASPE= American Society of Professional Estimators;

ATLO= Assembly, Test, and Launch Operations;

CBS= Cost Breakdown Structure;

CE= Cost Estimation;

C&DH= Command and Data Handling;

CECM= Cost Estimating Cost Model;

CEH= Cost Estimating Handbook;

CEM= Cost Estimation Method;

CER= Cost Estimation Relationship;

COCOMO= Constructive Cost Model;

COSYSMO= Constructive Systems Engineering Cost Model;

COTS= Commercial Off The Shelf

DDT&E= Design, Development, Test & Evaluation;

EADS= European Aeronautic Defence and Space Company;

ESA= European Space Agency;

FA= Federal Aviation Administration;

FAR= Federal Acquisition Regulation;

GAO= General Accounting Office;

GOTS= Government Off The Shelf;

HLLV= Heavy Lift Launch Vehicle;

HQ= Headquarters; IA&T, Integration, Assembly and Test;

ICE= Independent Cost Estimate;

ICEC= The International Cost Engineering Council;

IOC= Initial Operating Capability;

ISPA= International Society of Parametric Analyst;

JPL= Jet Propulsion Laboratory;

LCC= Life Cycle Cost;

LH2= Liquid Hydrogen;

LOOS= Launch and Orbital Operations Support;

LOX= Liquid Oxygen;

LPA= Launches per annum;

LVCM= Launch Vehicle Cost Model;

MESSOC= Model for Estimating Space Station Operations Costs;

MICM= Multi-Variable Instrument Cost Model;

MSFC= Marshall Space Flight Centre;

MUPE= Minimum Unbiased Percentage Error;

NAFCOM= NASA/Air Force Cost Model;

NASA= National Aeronautics and Space Administration;

NASCOM= NASA Cost Model;

NICM= NASA Instrument Cost Model;

OHB= Orbitale Hochtechnologie Bremen;

PAF= Project AIR FORCE;

PBS= Product Breakdown Structure;

PCEH= Parametric Cost Estimating Handbook;

PEI= Parametric Estimating Initiative;

PLC= Product Life Cycle;

PM= Program Management;

PRICE= Parametric Review of Information for Costing and Evaluation;

RAND= Research and Development;

REDSTAR= Resource Data Storage and Retrieval Library;

ROM= Rough Order of Magnitude;

SAIC= Science Applications International Corporation;

SART= Space Launcher Systems Analysis;

SCEA= Society of Cost Estimating and Analysis;

SE= Systems Engineering;

SEER= Systems Evaluation and Estimation of Resources;

SOC= Space Operations Centre;

SOCM= Space Operations Cost Model;

SSCAG= Space Systems Cost Analysis Group;

SVLCM= Spacecraft/Vehicle Level Cost Model;

TLC= Technological Life Cycle;

TransCost Model= Model for Space Transportation Systems Cost Estimation and Economic Optimization;

TT&C= Telemetry, Tracking and Command;

USCM= Unmanned Space Vehicle Cost Model;

VQ= Vendor Quote;

WBS= Work Breakdown Structure

# Introduction

The objective of this thesis is the study of the costs related to reusable launchers, specifically Falcon 9. The scientific interest on which this analysis is based originates as a consequence of the scarce knowledge on the subject and the scarce existence of material. The main unknowns are in general the costs of production and development. The estimates calculated in the analyzes are affected by large uncertainties and there are fundamental problems that make it difficult to have a clear and precise picture. The estimates are based on previous knowledge, which is very few given the topicality of the topic and the scarcity of sources from which to draw information. The data collections mainly derive from interviews found online and deriving from tweets. The estimates obtained in this way therefore give general indications that differ from those obtained numerically from the cost manuals. The second problem was the use of an obsolete manual in which there are hypothetical formulations on possible calculations regarding the costs of reusable aircraft. The results obtained were then revised and modified by factors of different entities. In the future, with a greater possibility of interactions with space agencies and access to confidential data, it will be possible to conduct a deeper and more detailed analysis.

# Chapter 1

## 1 Introduction

‘’Space: the dimensions of height, depth, and width within which all things exist and move’’

Since the beginning of time, space has always been a fascinating, attractive and curious place and our main goal has always been to be able to explore it and return home to be able to tell about it. With the passing of the decades and the frenetic growth of society, we began to look for alternative methods that would allow exploration to keep up with the times.

What, therefore, allows you to reach space efficiently? The launchers.

Launch vehicles are the core of space exploration and progress and a critical component in achieving access to space.

While government and commercial space activity continue to develop and enable new uses of space for the good of mankind, the accessibility to space is jeopardized by the high cost of launch vehicles. The high cost of today’s space launch vehicles can be attributed to the technical challenges of space flight, low launch frequency, and the demand for increasingly greater vehicle reliability. Therefore, the goal to bring space launch cost down from several hundred million dollars to single-digit millions still remains today but thanks to Space-x and others similar reality something is changing.

The demand to decrease the cost of a space mission applies all mission like whether scientific, commercial, military and all the others aspect.

There are two types of launch vehicles: reusable launch vehicles (RLVs), which are capable of returning from space, and can be refuelled and later sent on another mission; and expendable launch vehicles (ELVs), which are deployed and then discarded after one use. For this thesis discussion will focus, primarily, on RLVs and how improved RLV quality and lower costs.

A reusable launch system is a launch system planned to allow for recovery of some or all of the component stages.

An expendable launch system is designed to be used only once, and its components are not recovered.

The development of reusable launch space systems began between 1935 and 1945 (by the Silbervogel project. After the post-war epoch cosmonautics were experiencing a rapid development that resulted in a piloted space flight and a landing on the Moon in 1969. Reusable launch systems became a major subject of development in the early 1970s and gave rise to the largest project in the field of reusable space vehicles. Space Shuttle program, which was the first reusable space vehicle to be operational was the first. At present these Space Shuttles have already been retired from 2011 for technical and economic reasons. Some economic and operational objectives of the project have not been fulfilled. The fact that he failed to achieve the intended goal made him the protagonist of criticism even though his initial aim was to lower costs.

*Figure 1 Saturn V*

At today there are no manned RLVs.

At present it is possible to talk about the epoch after shuttles program, which is characterized by the transition from state agencies to private projects. Especially in the case of the development of space transport systems and transport to Earth's orbit.

Private projects often offer lower costs for the research and the space transportation than state-run organizations but State organizations however still play an unique role, notably in shifting the current astronautics limitations.

The most important thing about developing RLVs is about the possibility to change from on-schedule launch to on-demand launch.

But, while it remains evident that RLVs potentially offer desired benefits, there exist problems about technical problems and cost.

RLVs are the key to a low-cost access to space and real progresses have been made in the last 5 years.

SpaceX since its foundation in 2002 intended to develop a reusable rocket system that would allow a reduction launch prices and kick-start the space economy. At present it is the most important and influential company in the field of reuse of space transport systems. SpaceX has developed a reusable rocket launching system to successfully re-use the first stage of Falcon 9 and Falcon Heavy. First successful rescue was in December 2015 and first successful relaunch in March 2017.

In the future the significant competition for SpaceX in the field of reusable systems could represent Blue Origin company, which is also involved in the development of RLV. In 2015 Blue Origin successfully landed with a sub-orbital New Shephard carrier rocket.

The extremely low direct operating costs quickly exceed the high development costs for launch rates above about 20 per year. A reusable system is the most flexible system due to their extremely low direct operating costs.

Reusable launch systems are the systems of choice if it is believed that future launch rates will increase significantly and will require responsive and flexible launch skills.

It appeared to make sound economic sense to reuse a launch vehicle that cost as much as a small airliner, rather than throw the launch vehicle away after using it only once.

RLVs can be categorized into two main types defined according to the mode of take-off and landing. They can be horizontal or vertical take-off vehicles with either horizontal or vertical landing capabilities. An RLV may be categorized further as being single-stage-to-orbit (SSTO) or two-stage-to-orbit (TSTO). In the future, RLVs will incorporate advanced control systems that will make them much safer and more reliable than ELVs.

## 1.1 History of RLV

Almost all operational space launchers are now expendable launchers which serve only once. In an era marked by global congestion of launch, launch cost and reliability play a key role in the competition between launchers. The idea of making multi-stage launchers was born at the beginning of the twentieth century, thanks to Konstantin Tsiolkovsky. The developers of astronautics realized early the great technological difficulty to achieve with a single-stage the Earth orbit (SSTO for Single Stage To Orbit) and that the two stages (TSTO for Two Stages To Orbit) was more accessible.

A short definition of reusable launch systems can be: a launcher, which is responsible for placing a payload into Earth orbit, civil or military, where one of the major building blocks can be retrieved and reused.

This element may be a first stage or part therefor the upper stage. The most famous example of a partially reusable launcher is the American Space Shuttle. The Space Shuttle was a partially reusable low Earth orbital spacecraft system operated by the NASA as part of the Space Shuttle program that includes different kinds of vehicles. The Space Shuttle was capable of returning from orbit by its own, to land and fly later (Columbia, Challenger, Discovery, Atlantis, and Endeavour). The demonstration of recovery/reuse was successful but at a cost such that this technology was abandoned in 2011, in favor of a return to expendable launchers.

Today, in a very competitive environment, it is important to significantly reduce the launch cost, to increase the availability of launchers and to develop new applications or new abilities. Recent innovations by *SpaceX* and *Blue Origin* have boosted momentum. Some launchers targeting space tourism are inherently recoverable and reusable, they constitute a sector of activity which is really interesting.

Looking at the history of reusable launch systems, past concepts, of which very few have given rise to demonstrations, much less to operational systems, can be schematically categorized as those for the recovery and reuse of the upper stage and those for the recovery and reuse of the lower stages. The military projects have not been realized and it may be thought that the infrastructure to be developed on the ground had certain limitations for the planned missions.

Most of the reusable upper stages are winged vehicles capable of landing from an orbit for example. Vehicles must therefore possess true aerodynamic qualities in the hypersonic, supersonic, transonic and subsonic domains. They can be used as means of orbiting a payload or for other types of military or civilian operations.

The Crew Return Vehicle (CRV), was a proposed dedicated escape module for the International Space Station (ISS).

*Figure 3 Spyuz MS-15 NASA Gov.*


*Figure 2 Boeing X-20 Dyna-Soar - Wikipedia*

Over two decades, many projects that never saw the light have been considered. The only one that met the criteria is the Soyuz which rotates every six months. In addition, USAF has developed a program called Boeing X-20 Dyna-Soar which involves the creation of a space plane. The spacecraft could be used for multiple military missions, including aerial ones, bombing, space rescue, satellite maintenance, and as a space interceptor to disrupt enemy satellites. The program started from October 24 1957 to December 10 1963, and was cancelled just after spacecraft construction begun. [38]

Mercury and Vostok were other spacecrafts under development at those time. They were based on space capsules with ballistic re-entry programme. Dyna-Soar was more like Space Shuttle and it could travel to distant targets at the speed of an intercontinental ballistic missile and it was also designed to glide to Earth like an aircraft controlled by a pilot. It could land at an airfield and landing with a parachute. Dyna-Soar could also reach Earth orbit, like Mercury or Gemini. These characteristics made Dyna-Soar the most advanced concept than other human spaceflight missions of those period.

In the history of reusable launch systems, there was also *Hermes*, a proposed spaceplane designed by the French *Centre national d'études spatiales* (CNES) in 1975, and later by the European Space Agency (ESA). It was superficially similar to the American Boeing X-20 Dyna-Soar and the larger Space Shuttle.

In the 1980s, the German government became increasingly interested in the concept of reusable. The high costs unfortunately stopped development in 1995.

During the 2010s, it was proposed to relaunch the Hermes vehicle to serve as a partially reusable air-launched spaceplane launch system, known as SOAR.

*Figure 4 Hermes space Shuttle - Pinterest*

Now, let's mention Sänger, a West German concept design for a two-stage-to-orbit spaceplane. It is named after Eugen Sänger, who had been a key figure in the growth of the concept for aerospace company *Junkers*. Its first personification, designated as Saenger I, started developed during the 1960s. During the 1980s, the German government took increasing interest in the project for use as a reusable launch system. Work on the project was terminated during 1995 as consequence of the high projected costs of proceeding and perceived limited performance gains in comparison to existing expendable launch systems such as the Ariane 5 rocket.

The reuse of the lower stage has given rise to a wide variety of formulas: to deliver a large take-off thrust, solid propellant engines are used in several states. The reuse of this type of engine was considered on Ariane 5 but abandoned and was performed on the American Space Shuttle; in fact, the parachute recovery is done at sea, which imposes a rather heavy logistics system and finally the economic interest is not reached. The launch can be airborne, that is to say that the first stage is a piloted aircraft or automatic; this flexible enough formula certainly has a future for launching small satellites; there have also been many launchers projects using an aerobic powered first stage.

Cause the cost of these engines is high the recovery of a first stage equipped with liquid propellant can be economically attractive and their original design can provide for reuse; several technologies have been imagined: by rotor, by parachute, return of boosters using wings and aerobic engines, vertical powered return, by recovering only a few critical parts including the engines. The concepts on which research and development are based today are achievements and demonstrations in progress with SpaceX, which has managed several recoveries of the first stage of the Falcon 9, either on barge at sea or on land near the launch site and the reuse of a first stage for several times.

*Figure 5 Falcon 9 - Space X*

Blue Origin from its New Sheppard for space tourism has also achieved several vertical returns.

Safety is until now one of the main difficulties encountered by the reusable launchers.

Reuse inevitably induces a loss of performance compared to expendable launchers, and if we examine the problem from the sole economic point of view, by using the cost of the kilogram placed into orbit, the result for reuse is not at the rendezvous.

Let’s try to specify these different problems. In the first place, it should be remembered that the solutions to be implemented depends on the mission profiles concerned. There is consequently no general optimal solution.

## 1.2 Main differences

The potential benefits and technical feasibility of launcher reusability as a key paradigm for sustainable access to space have been recently demonstrated by private companies (i.e., SpaceX and Blue Origin with the successful vertical takeoff and vertical landing [VTVL] of reusable boosters).

A reusable launch system (RLS, or reusable launch vehicle, RLV) is a launch system whose purpose is to partially or totally recover the launched aircraft.

At present, several fully reusable sub-orbital systems have been flown and partially reusable orbital systems too.

A huge variety of system concepts have been proposed, and several are represented in those which have actually flown. The first aircraft to achieve suborbital flight was the *North American X-15*.

*Figure 6 X-15 - Pinterest*

The first reusable vehicle to reach orbit was NASA's Space Shuttle. It was projected to reduce launch costs below those of expendable launch systems, but instead ended up being more expensive. The last Shuttle was retired in 2011.

During the 21st century began a big interest in reusable launch systems due to the commercial opportunities that this world permits.

The most challenging aspect of reusable vehicle design is about tank and insulation material. A second important aspect is about all the parts necessary for the return.

Reusability is an important aspect in fact cryogenic tanks will also be studied.

RLV launchers have more propellant to permit the re-entry so payload will be less than the expendable and this is one of the most important things.

Evaluating for example the new gen of Falcon 9 there are a lot of differences between the rocket that land on the ground or on the boat and consequently the costs change.

The first stage of SpaceX Falcon 9 rocket is reusable instead the second stage is expendable. This rocket is currently in use for the NASA *Commercial Orbital Transportation Services* program and commercial satellite launches. SpaceX is also developing the fully reusable *BFR* for manned missions to other plant far away. Two prototype sub-orbital spaceplanes for Virgin Galactic and the Blue Origin New Shepard rocket has recoverable first stages and capsules but are only capable of suborbital flights.

### 1.2.1 Costs differences

The main problems about costs are all the process required in order to reuse the launcher.

Reusing a launcher means that you have to make many launches in a short time to reduce costs.

A lot of improvements are required to make space launch safer, more reliable, simpler and high reusable. These advanced technologies have a very high cost.

Thermal protection is necessary on both current and future vehicles because flight speeds will increase over the years and therefore also the heating of the protective structures. [37]

Another emergent technology intelligent vehicle health management systems could allow the launch vehicle to determine its own health without human inspection.

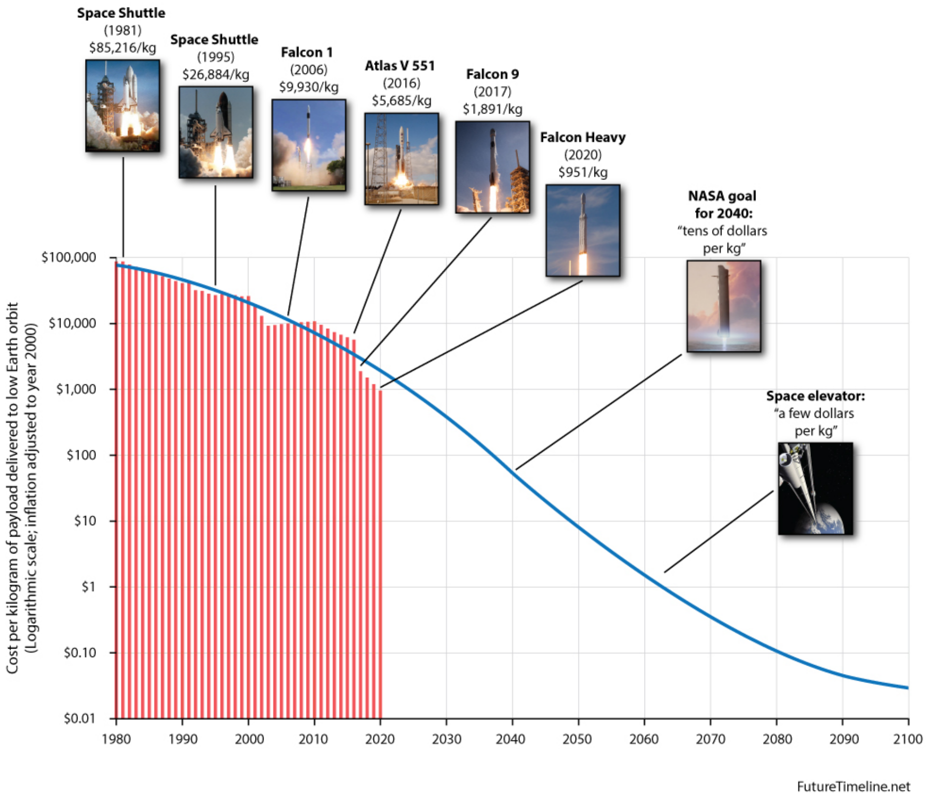


*Figure 7 Cost-Year diagram – Future timeline.net*

The sensors on the vehicle send signals to determine if damage occurs during the flight and once landed, thanks to the on-board computer, the maintenance to be carried out and the overall state of greeting of the vehicle are known. [39]

The RLV systems included development and therefore a larger number of launches needs take place before the total cost-per-pound of payload falls below current expendables.

Between 1970 and 2000, the cost to launch a kilogram to space remained fairly steady, with an average of US $ 18,500 per kilogram. When the space shuttle was in operation, it could launch a payload of 27,500 kilograms for $1.5 billion, or $54,500 per kilogram. It costs just $ 2,720 per kilogram for SpaceX's Falcon 9 rocket. It is the rocket used to access the ISS. NASA will seek to reduce the cost of reaching space to hundreds of dollars per pound within 25 years and a few tens of dollars per pound within 40 years.

## 1.2.2 Performances' differences

Considering Atlas V and Falcon 9 they are two totally different rockets from two competing companies (ULA and SpaceX)

The only similarity between rockets is that kerosene is the same fuel for their first stage of both.

RD-180 it's the main engine of Atlas V. RD-180 is very efficient high-tech rocket engine, using advanced oxygen-rich staged combustion cycle. This engine it's also expensive and does not have very high thrust to weight ratio. The engine has two chambers but only one is needed cause its powerful, though with only one RD-180 the capacity is not very good and often also Solid Rocket Boosters(SRBs) are used to give more thrust at liftoff, when more performance is needed.

Falcon 9 uses much cheaper and lighter Merlin 1d, and nine of them. Merlin 1d uses less advanced and less efficient gas-generator cycle, but it has been tweaked very far. This is a simple engine, it can reach high thrust-to-weight ratio.

The economic price of the engines is given by the fact that each rocket uses nine of them so the production is very high and in series. the Space x also uses innovative technologies such as additive (3D printing). Another important fact is that 9 engines give more thrust at a lower price and lower cost.

As the first stage of Atlas V is more efficient, it burns for longer so smaller and less powerful second stage is needed.

The second stage of the Atlas V is the Centaur, small, light and based on hydrogen. The Centaur's RL-10 engine is very small and weak but efficient while the Falcon 9 uses a second stage about 5 times heavier. This engine is also about 9 times more powerful than the Centaur's RL-10 engine from the Atlas V. The reusable first stage of the Falcon 9 features landing grids and legs that allow it to perform a powered landing, either on a barge at sea or on a platform near the departure area.

The single engine of the Atlas V cannot be operated at such a low thrust level as to allow landing. Since the rocket is much lighter when it lands with the propellant tanks almost empty, it is possible to use 1-3 engines of the Falcon 9 to obtain quite low thrust.

This is the reason that allows the falcon 9 to be reusable.

# Chapter 2

## 2 Cost analysis introduction

In the past, achieving maximum performance has dominated design criteria for space programs and missions with take full advantage performance erroneously once seen as being synonymous with minimising weight. This philosophy, however, has now been made obsolete and cost become the new dominant design criterion. In today's competitive environment, limited resources and rigid mission budgets constitute a real monetary barrier for access to space, meaning that cost must be a major consideration within the scope of mission planning and certainly for all management decisions and processes. Therefore, cost engineering, the new paradigm for spacecraft design is an essential component during the preliminary stages of any space program, as well as consistently and progressively throughout the entire project realization.

Cost estimation and cost modelling are the two elements of significant interest within industry as seen by the rapid advancements and evolution of the processes

The two components have been classified as being key functions within the whole cost engineering and cost control frameworks. In fact conclusions from a cost estimate performed during the early Phase-0/A are often a determining factor for program achievement. Inside a research context, a preliminary cost estimate performed at a pre-Phase 0 stage can determine if a developing program is achievable or not within a stipulated, available budget. An initial cost over estimate can result in a project not being funded, or non-selection within a competitive context. On the other hand, significant cost under-estimation increases the risk of financial loss and program failure by influencing the decision making process associated with budget allocation. [13]

So the need for representative and proper cost estimation during the very early program research, establishment and development phase is evident. Here it is important to note that a cost estimate is a dynamic value rather than a fixed, static one, and as such, should be reviewed regularly so as to absorb and reflect some new information which becomes accessible. Early in program planning, available specifications and program details may be limited and the resulting cost estimate would therefore have a higher uncertainty than one made later on during the program life cycle. However at this early stage, a representative cost estimate reflective of all available information and data at the given time can optimally support the project funding and establish an adequate initial budget.

Most recently, global, social, economic and political context and events have seen the aerospace industry as a whole evolve significantly, and in part, space access has deviated from its fundamentally scientifically oriented and largely government financed origins. Governments have been partially exclude and replaced by markets as the principal engines of technological change. At present, space tourism in the form of sub-orbital civilian access is becoming a practicable reality while furthermore the promise of civilian orbital flights is also progressing firmly from its embryonic phases.

An example  of a new kind of flight is the SpaceLiner. This hypersonic, suborbital vehicle is very long term project, and aims to revolutionize the space market by marrying an ultra-fast means of point-to-point transportation with the allure of thrill seeking and a strong space tourism component. SpaceLiner has the abilities to travel from West Europe to Australia in 90 minutes, an extraordinary speed by today's transportation measures.

Here, it is interesting and relevant to consider the aspect of cost estimation from another point of view concerning the price range that a typical 'space access consumer' is prepared to sustain. This could include orbital or sub-orbital flights with a tourism or high speed transportation oriented focus. Obviously the price to the consumer of each access to space will be closely associated with the total costs of development, production and operation for each respective space program itself, with incorporation of a certain profit margin within a commercial context. Therefore actual program costs will be directly reflected in the ticket or flight costs incurred by the consumer.

For example, recent suggestions have implicated that the fleet of vehicles SpaceX Falcon 9 "break the cost model NAFCOM NASA / Air Force". So with the recently emerged foreseen advancements to space access through the advent of commercial space travel it is essential for cost estimators and experts to stay abreast of the technological changes and have the capability to obtain indicative, relevant and justifiable estimates even as implementation of novel, unusual technologies furthermore integrated within new company structures.

Returning back from the costs of applications to the costs of the space vehicles and launchers themselves, to enhance such progressive trends within the space sector, stringent and consistently applied cost engineering principles and practices are key to ensure that estimated costs for new,  are representative or at the least indicative of expected costs while being reflective of all available inputs and information at the time. As mentioned previously, a cost estimate is a dynamic, continuously varying quantity. Knowing that it is impossible to predict the exact costs of the program, the timely and specific application of certain principles, practices and methods, such as the revision of cost estimates at regular intervals during the life cycle of the program to incorporate any changes and reflect new information, supports budgeting decisions and avoid unexpected budget blow-outs. Furthermore, at various program phases the amount of defined information increases as program specifications and requirements crystallize. So it is important to identify the most appropriate cost estimation approach at each phase from a diverse selection of cost estimation methods, models and techniques. [13]

There are many excellent resources that list and describe general and specific cost estimating methods, models and tools applicable to the space sector. In fact, many of the larger documents have been lengthy government-funded projects and studies. In 1977 the RAND Corporation published a comprehensive study as part of the AIR FORCE project aimed at listing and evaluating the validity of parametric spacecraft costing methods for current and future applications with less attention to system mass, emphasizing the importance of the simultaneous utility of human logic and reasoning when using and applying the cost model. As a consequence another two detailed RAND studies into deficit of cost estimation methods were released in 2008. In the RAND document which addresses cost estimation of space systems within the Air Force Space and Missile Systems Centre (SMC), provide future suggestions for improving the processes, methods, tools and resources based on the study's findings. Documents contain descriptions of some key cost estimation models, such as the Unmanned Space Vehicle Cost Model (USCM), the NASA/ Airforce Cost Model (NAFCOM) and Small Satellite Cost Model. Other documents, such as NASA's Cost Estimating Handbook and the online DoD Parametric Cost Estimating Handbook also offer their own lists of various industry-relevant cost estimation tools and processes.[13]

Lists vary a lot based on sources. There are many specific estimation methods for mission hardware and software, development, operations, management and risk analysis, among others, but usually with limited, brief descriptions per entry. Alternatively, the literature will focus on a very limited range of select models and methods, while omitting key others.

This thesis seeks to provide a niche and robust summary for the major cost estimation methods, approaches and resources applied in the space industry for space hardware, with existing (COTS) and government (GOTS) standard commercial tools and software. . Many of the commercially available products have classified databases and have associated annual license fees.

They are therefore not deemed focal to very early program phases where research into program development is still ongoing, specifications are not yet clearly defined, but a cost estimate for the anticipated program is nonetheless required to proceed further. For wholeness, these models are, however, included and shortly discussed within the review due to their consistent application in the space industry. Manuals, handbooks and reports directly applicable to space sector cost estimation at a specific complete system level are also delineated, since they are seen as valuable resources for advanced methodology development for reusable launch vehicles (RLV). [13]

Firstly the significant cost estimation methodologies applicable to the space sector are outlined and discussed. For this reason, their implementations in key existing models, tools and resources are provided, with each the associated features, factors, benefits, defects and applications detailed and discussed.

## 2.1 Cost estimation methods for the space sector and Cost engineering

### 2.1.1 Role of effective initial cost estimation within a cost engineering framework.

The cost estimate is an integral element of the program planning, management, overall system design and cost engineering framework. While cost estimation and cost engineering are different disciplines, the two are closely related. Cost engineering is a multifaceted discipline and science which addresses cost estimation and control, business planning and management, profitability analyses and scheduling of major and complex engineering projects through the application of engineering principles. By applying this definition, cost estimation is therefore a constituent component or subset of the larger cost engineering framework , and is defined as the process of prediction of product or output costs, resulting in an estimate. As noted above, a cost estimate by itself, however, is not a static or deterministic value. In contrast, it is a variable so it must be progressively updated, revised and readjusted throughout the program life cycle. It is true that an estimate will almost always vary from the final program cost due some hidden factors and events which cannot be factored in during formulation of the estimate. So a realistic budgeting is a crucial first step to underpin future program success, the basis for which is derived from a preliminary program cost estimate.

Hence it is logical to state that a justifiable, competent, informed cost estimate reflective of all the data which is available during the early program planning forms a solid foundation for an adequate and tolerable program budget. In turn this increases chances for a program's timely and efficient execution and ultimately realisation. A too high estimate may result in a lost contract award, while an underestimated figure would lead to cost overruns during project implementation. An old heuristic approach is optimal for application during early program phases where many program parameters, such as configuration, mission and environment, were undefined and unclear. This approach is very important because draws upon past experience and knowledge while adjusting for differences between the new and historical data. Even today in the space sector, such a heuristic approach still forms the fundamental of most cost estimation methods and models.

Here, during early mission phases, effective planning management also directly integrates into the cost estimation framework, since the two are directly co-dependent. It is clear that time delays result in an increased costs not factored for in an initial cost estimate, and therefore in cost overruns. The final goal is to meet project deadlines and achieve cost targets while successfully attaining the required technical performance.

This thesis focuses on the cost models, methods and tools aspects. Identification, selection, application and sometimes development of cost estimating models, methods and tools within the space sector is a difficult task given the highly variable nature, scope as good as scientific and technical requirements applicable to every mission. This decision ultimately depends on the program phase, the accuracy required, available resources and information and risk analyses, and is the responsibility of the program manager, and subsequently the estimator themselves.

### 2.1.2 Cost risk and uncertainty assessment

In addition to careful scheduling, to minimise the cost excess and scheduling delays, the effects of unexpected events must be considered during initialisation of a program. This process is particularly important during formulation of a program's initial cost estimate, when a detailed understanding and assessment of potential cost risks is essential.[26] Various aspects and definitions can be applied to the terms 'risk' and 'uncertainty' within the context of a program and the required or existing cost estimate for that program.

#### 2.1.2.1 Risk and uncertainty of unexpected events

The meaning of the term 'risk' varies finely but distinctly from the meaning of 'uncertainty', and this definition is important to establish and understand. Risk is about the probability of a certain event occurring and its consequent impact on a project, and therefore risk can be in part anticipated for and factored in within an estimate. So while potential risks for a project can be identified, analyzed, planned for and managed, the uncertainty element for unexpected costs during project lifetime is impossible to fully address during the early program phase. In particular any given project can never be entirely risk-free, cause various cost risk quantification analysis methodologies, strategies and approaches exist to address this aspect and are very usefull. While cost risk estimation is an acutely important element within the cost estimation process and cost engineering framework, it is not examinate into in great detail within the scope of this thesis.[26]

#### 2.1.2.2 Uncertainty of cost estimate

The development and implementation and therefore the usefulness of all cost models includes factors, data inconsistencies and model simplifications which therefore lead to uncertainty.

The uncertainty mentioned above also includes the fact that there is a correlation with the phases of the program.

usually, at the beginning of a program, a few specific details of the mission are known and therefore the uncertainty is very high.

as the program progresses there will be more details and therefore the initial uncertainty will decrease and therefore the initial cost estimate will be reviewed and will evolve over time. the actual costs normally exceed the initial estimates, therefore the initial estimates are based on the basic and probable costs without considering any problems, delays that can therefore cause these data to change.

### 2.1.3 Diversity of cost estimation within the space sector

An important aspect in the discipline of cost estimation within the space sector is the ability to account for a wide range of missions. The missions considered include those from smaller satellites to reusable launchers.

In the different phases of the program, the cost estimates for the hardware and software are separate. The most important aspect in these cases is the correct choice of the method to be used and the appropriate tools since this has a positive or negative impact. The stage of the program and the related details of the technical definition determine the choices. In addition, the available data from past missions is also important.

There are several specialized models for estimating different aspects of mission costs. Here is a list: SICM, NICM, MICM, COSYSMO, SOCM, MESSOC, ACEIT. in this thesis we refer to COTS and GOTS approaches applicable to a global system.

The importance of cost analysis in engineering is undisputed, but the real and complete understanding of this matter remains undefined. The analysis works well if the cost engineer follows the guidelines and refers to previous missions while trying to adapt the data to the period in which the analysis is taking place.

A hasty and not well structured estimate leads to an overrun of the budget and therefore there is the risk of not reaching the end of a mission due to lack of funds.

Thanks to the presence of many methods and professional organizations, we are continuing towards a standardization of principles and we try to encourage the union of data so as to have solid foundations from which to start. Among others, these include the International Society of Parametric Analysts (ISPA), the Society of Cost Estimating and Analysis (SCEA), the Space Systems Cost Analysis Group (SSCAG), the Association for the Advancement of Cost Engineering through Total Cost Management (AACE) International, American Society of Professional Estimators (ASPE), Association of Cost Engineers (ACostE) and International Cost Engineering Council (ICEC). The main objective therefore must be to collaborate, giving life to particular and standard cost estimates.

### 2.1.4 Cost estimation methods

There are three main basic cost estimation (CEM) methods that form the backbone of the tools applied for cost estimation in the space sector: bottom-up engineering, analogy and parametric approaches.[13] The bottom-up approach includes both basic and detailed cost estimates. As for the top-down methods, on the other hand, they concern parametric estimates and analogies. Statistical approaches can also be added, which are classified as gross estimation methods.

Another unofficial but widespread approach is the one called 'expert judgment' (EJ). The techniques mentioned can also be combined to have a hybrid estimation. Looking to the future, it is increasingly important to have more and more precise estimates especially with the advent of space tourism and seeing the promising prospects for commercial launches. Ultrafast space transport is also growing rapidly. The problem regarding these two aspects is the lack of precedents that limit the application of the above methods. In the next paragraphs the most widely used methods will be exposed but what one wants to achieve in the short future and the official recognition of an estimation method.[26]

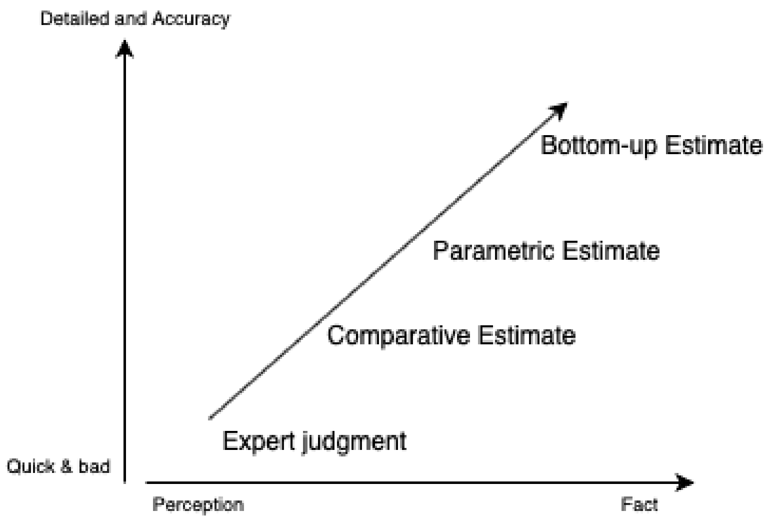


*Figure 8 [26] Different method*

#### 2.1.4.1 Parametric cost estimation

Parametric estimation is a widely used method not only in the space sector but also in industrial and government applications. Parametric estimation is therefore a method to economically approach proposals and program cost assessments.

It is used in planning and used with the CEM which is officially accepted (FAR) for the preparation of proposals. It is also the basis for several key models and software used for early stage cost estimation of space programs, such as the TransCost model, USCM, and NAFCOM.

Normally the parametric estimation is used with a top-down approach as often only the basic requirements are possessed. System and subsystem criteria are usually established later.

Historical data are very important and it is thanks to them that a series of CER relationships (cost estimation relationships) are determined.

CERs try to relate cost to physical, technical and performance parameters which are known to be strongly correlated with program costs. To address deviations from CER parameters, specific complexity factors or manually defined user inputs can be applied for a particular mission of interest. Normally the determination of the costs of the mission is considered correct only if carried out with these methods as the formulation of the same CERs is very difficult. The larger the databases, the higher and more reliable the CER credibility is. It also takes a lot of resources and time to carry out these analyzes which aim to obtain enough data and figures that are sufficiently detailed. The DoD Parametric Cost Estimating Handbook identifies nine major data sources they include

basic accounting records, contracts,

cost reports and proposals, historical and technical databases, other information systems and organizations,

and functional specialists. However, most of the missions are classified as secret and if you add competitiveness, everything becomes very difficult. Furthermore, all developed CER credibility must be verified through comparison and sufficient correlation with existing projects.[7]

### 2.1.4.2 Engineering build-up estimation

Known as bottom-up, grassroots or detailed cost estimation, this very specific analytical approach is generally applied to a mission when all parameters at system and subsystem levels are known and distinctly defined. Cost estimates are made at the lowest level and need to break down the project into small parts. These subsets take the form of a Cost Breakdown Structure (CBS) or Work Breakdown Structure (WBS)).

It's the engineers' job the low level cost estimates, the sum of which then constitutes the overall cost estimate for the program.[30]

It is common for labour requirements and others factors, such as material quantities, to be identified and estimated separately, with any additional overhead costs, such as administrative expenses, being concurrently factored in to obtain the total estimate.

Therefore engineering build-up is inherently an extremely resource-intensive approach with significant associated costs, as time and effort. Very careful attention must be paid to the organization of the WBS and CBS to avoid duplications and omissions of tasks, which would then reflect directly and misleadingly on costs.

An important weakness of this CEM is the inability to quickly adapt to scenario changes or specifications, requirement and design alterations, which frequently arise during early planning phases. Se si sono effettuate delle modifiche bisogna ricostruire delle stime. Le stime richieste sono molto dettagliate anche se basso livello e servono per applicare il metodo. Nelle fasi iniziali è difficile che siano disponibili e quindi questo approccio non viene preso in considerazione.

The resulting cost estimate can be extremely accurate since it is unique to the specific industry and application if applied during later project phases when sufficient details are available (i.e. Phases A–D).

If a clear view of the principles contributing to the cost has been provided, the factors can also be reused in individual projects giving excellent estimates. Through this method it is also possible to have information on the main factors that contribute to the total cost. This allows for future missions to adjust accordingly.

#### 2.1.4.3 Analogy estimation

Analogy cost estimation relies on an extrapolation based comparison between different precedent or existing efforts which are deemed to be similar or 'analogous' with the item being evaluated. Given the great similarity between the two projects, it is necessary the intervention of analysts who give their in-depth judgment and who, in case of need, make adjustments to the differences. The differences can be both in project sizing and team experience.

The method cannot always be used but instead its use is limited as it is very complicated but if it happens successfully the confidence for comparison is based only on a single data point.

The necessary data must therefore be detailed enough. The method then depends on the past experience, knowledge and judgment of the expert regarding consequent adjustments or extrapolations.

Strengths of the analogy CEM include its quick and effective application at any time throughout the various program phases at a minimum cost, since analogy can be applied even before specific program specifications are known. And if a close suitable analogue is found, the resulting estimate is then based on sound factual historical data and is justified.

Analogy can be eventually broken down into Loose Analogy (LA) and Close Analogy (CA). Loose Analogy requires only few 'loosely similar' data points not closely related to new project, and adjusts relevant past broad experience for reasonable changes in complexity. Close Analogy requires very similar data points from another program or through technical development studies, and refers direct past experience with adjustments made for only minor changes in complexity, and is therefore more resource intensive.[26]

#### 2.1.4.4 Expert judgment estimation

This method is a commonly used method although the estimate is made subjectively and thanks to the skills and knowledge of the expert in charge. This method is a fundamental point for the CEM analogy. According to ESA's Engineering Costing Techniques specifications, EJ is considered the fourth cost estimation method. There are many misconceptions regarding this method as it is an intuitive method. Most of the people who criticize this method are not part of the cost estimating community and are also often subject to political pressure.[26]

The method is applied when historical data is insufficient or does not exist at all. EJ is a time consuming method as the expert group takes a long time to collect data even though the costs are very low. Normally EJ is used as a backup control for the CER method.

#### 2.1.4.5 Analytical Hierarchy process

In the AHP the expert judgment is used to assign rankings, the priority scales finally deduct an overall relative score. Priority scales are generally determined by pairwise comparisons. The goal of this method is to reduce complicated decisions to simple comparisons. Furthermore, this method is also applicable to decision-making processes as during the pairwise comparisons experts know how to determine which criteria dominate over others. The problem of the method is only given by the fact that the judgments of the experts are subjective and given by experience. [26]

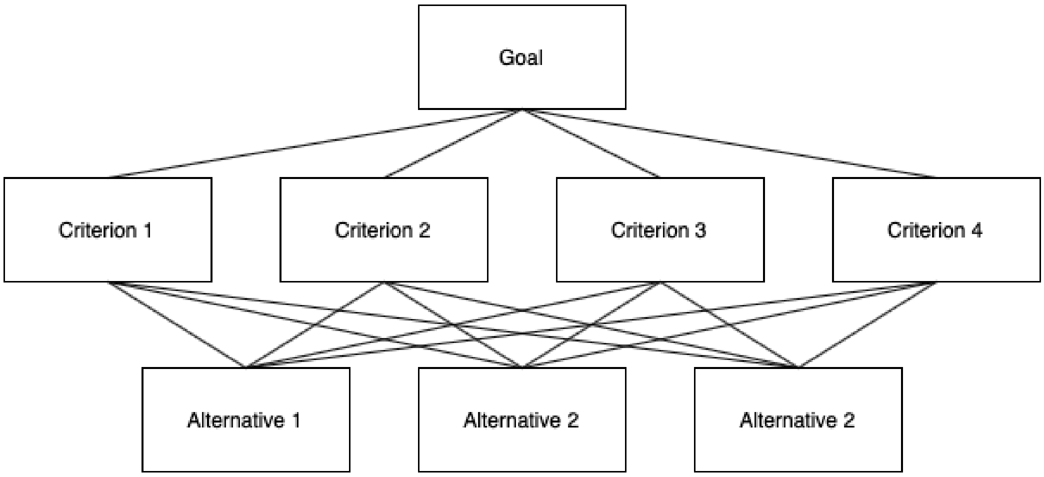


*Figure 9 AHP architecture*

### 2.1.5 Cost estimation methodology selection

Identifying the most correct CEM that most accurately identifies program costs is a very important action as it allows for a relevant cost estimate. The one who decides the method to use is the project manager while its feasibility and suitability is up to the estimator. Throughout the life cycle of the program, information, levels of detail, and sometimes key

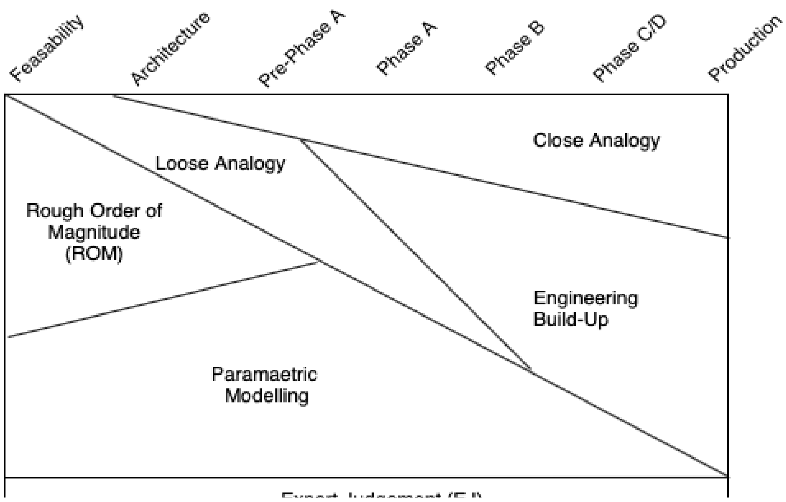


*Figure 10 Qualitative application of CEMs according to project phase [36]*

project requirements and specifications change. Whenever the project phase changes, the cost estimate must be re-made and updated taking into account the new information. The different phases of the program take different EMF into consideration.

## 2.2 Cost estimating tools and models

After choosing the methodology to use, it is very important to search and find the model or tool to use.

As not all models or tools are applicable for a single purpose, numerous options have been developed around the previously discussed EMC principles.

The many options developed serve to address the complex issue of cost estimation within a diverse space sector.

Furthermore, a mission can be divided into three clear phases for its life cycle costs covering all aspects, elements and components. These stages are:

• Development,

• Production

• Operations

They include both software, hardware and various processes such as archiving, maintenance, disposal and support.

In the figure you can have a visual representation of the respective cost components for each phase of the mission and of the associated software and hardware elements. There are various sets of tools, methods and templates for addressing the different links, represented by arrows. The solid arrows pointing to the space hardware element represent the cost estimation methods and tools specifically considered in this thesis.[26][30]

Several key COTS and GOTS software packages are available in the market in addition to detailed manuals, manuals and other various templates, and cost estimators must select the most suitable costing means for a given project.

The person who is concerned with calculating the cost must be able to justify the choice of the cost model, as dictated by the purpose of the project, the phase and the level of design details available. [13]

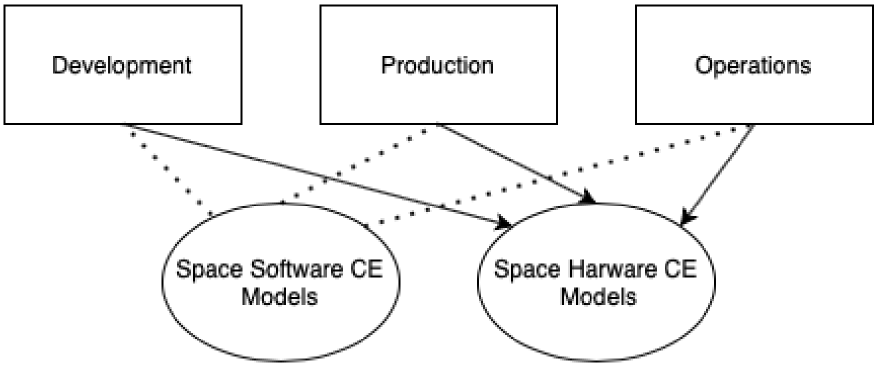


*Figure 11 Interrelation of mission Phases with CE model [26]*

### 2.2.1 COTS cost estimation models

While many other excellent tools exist, this section describes six key COTS models commonly used to formulate space sector appropriate cost estimates, as shown in the figure on the right.

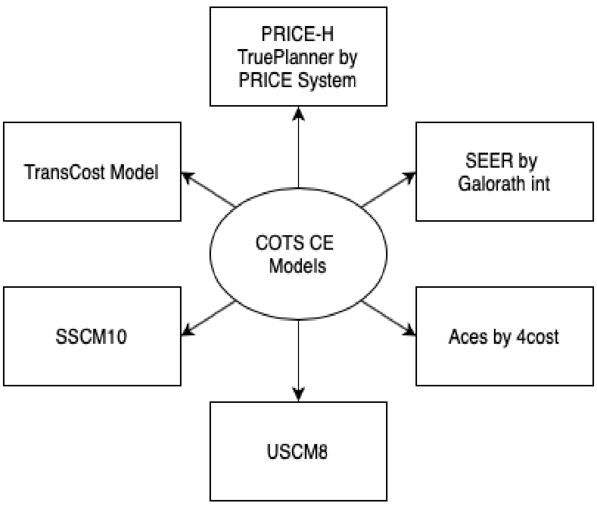


*Figure 12 Scope of COTS [26]*

Within this context, the NASA COTS definitions will be applied, which refers to those commercial models requiring no modifications or maintenance over the product life cycle to meet the needs of the procuring agency. [26]

The TransCost Model, the Unmanned Space Vehicle Cost Model (USCM) and the Aerospace Corporation Small Satellite Cost Model(SSCM) are are all available freely. The remaining models COTS models and tools, including PRICE Systems Solutions, SEER by Galorath Incorporated and aces by 4cost, all require annual license fees.

#### 2.2.1.1 TransCost Model

The TransCost model is a model that serves primarily for cost estimation and economic optimization of space transport systems. It also takes care of the development, operations and production phases of the launch vehicles. It is therefore of interest in the context of this review. The model itself is integrated into the Cost Engineering Manual for Space Transport Systems.

Starting from a 1971 work by Dietrich E. Koelle, it was designed to be used in the conceptual phases of the mission. Now being a model with a very low cost and very easy to use, it is used in the initial transport.

Initially conceived as a cost engineering tool, TransCost uses parametric CEM with rudimentary CERs derived from a vehicle and engine database of cost data for European and US spacecraft and engine projects within the period 1960-2009. It is a dynamic model, so both the database and the CERs are updated continuously and the latest model available since October 2010 is TransCost version 8.1.

The model itself addresses three areas of the launch vehicle life cycle costs :

- Development
- Production
- Operations

Each category is further broken down into subcategories, each with its own unique respective CERs, which address distinctly identified categories of expendable and reusable vehicles, and include solid propellant boosters, liquid propellant, pressure-fed as well as turbo and ramjet engines, and crewed capsules and space systems.[26]

Different factors underpin each CER, and include vehicle mass, number of units produced, number of launcher stages, and expected launch rate. A range of ten complexity factors are then further assigned, which address the impacts of varying:

- Technological advancements
- Quality level
- Team experience
- Regional productivity series
- Production effects from increased number of participating contractor organisations
- Subcontractor-ship or government involvement
- Optimum schedule deviations
- Past technical experience

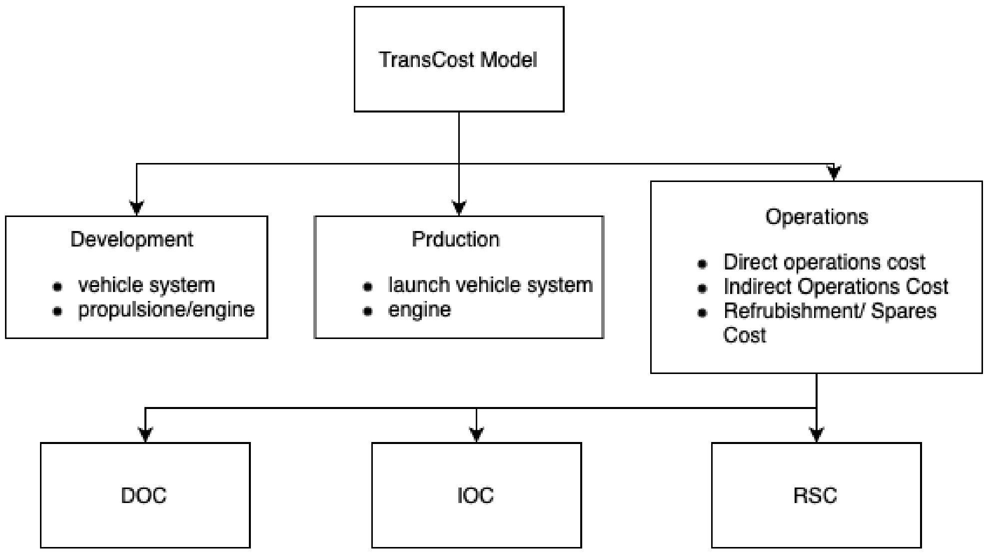


*Figure 13 How TRANSCOST category structure [36]*

A visual representation of the TransCost Model structure breakdown is presented in the figure.

A particular feature of the model is the use of the 'Work-Year' costing unit, which provides cost of inconsistencies due to international currency conversion rates and annual inflation fluctuations.

TransCost and all constituent CERs are entirely transparent with each CER specified, explained, and all underlying reference projects shown, with accuracy for historic cost data regression.[26]

The open nature of TransCost also means that it can be easily implemented within various programming environments, such as Excel.

#### 2.2.1.2 Unmanned Space Vehicle Cost Model (USCM)

The USCM is a parametric handbook and cost model from the Air Force, with the latest Version 8 released in 2002 providing CERs to facilitate estimation of unmanned, earth-orbiting space vehicles as well as flight hardware, aerospace ground segment, design, development, testing and evaluation and launch and orbital operations support.

The freely available USCM8 document features transparent, visible CER equations. Furthermore the rigorous CER development process, which identifies cost driver parameters, relates them to costs and is followed up by validation through comparison with engineering expectations, is described. Based on a NASA, military and commercial satellite database, a particular feature of the model is that CERs at subsystem and component levels are based on the Minimum Unbiased Percentage Error (MUPE) regression technique. Finally a hypothetical case is presented to demonstrate applicability of the USCM using specific relevant CERs provided within the USCM. Table 1 shows a record of the data point count for each version of the USCM through its development and modification iterations.

### 2.2.2 GOTS cost estimation models and sources

This section explains three of GOTS cost estimation models and tools frequently used for space sector cost estimation, as shown in the figure.

Here, the NASA GOTS definitions is applied. GOTS products are those specifically developed for a government agency by the agency itself, or sometimes by an external entity, although from funding, specification and strict controls enforced by the agency. Two sources reviewed here, NAFCOM and NASA’s Cost Estimation Website are available to industry, while the DoD LVCM is also outlined, although classified and restricted to governmental use only.

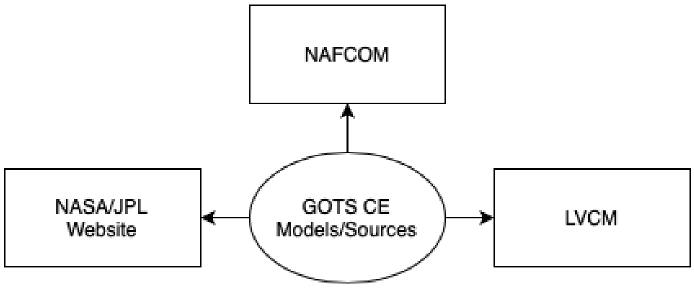


*Figure 14 Scope of reviewed GOTS cost estimation models and sources [36]*

### 2.2.2.1 NASA/Air Force Cost Model (NAFCOM)

The NASA-operated automated cost estimation model was established in 1989 and developed by Science Applications International Corporation (SAIC) for the Marshall space Flight Center and the Air Force Cost Analysis Agency. To date, there are eight versions and the most recent of which is NAFCOM11.

The model is based on comprehensive historical data from the completed space programs of the Air Force and NASA.

This model uses weight relationships to predict the development and production costs of new space programs, and the best time to use it is in the early stages of the project at the system and subsystem level. There are two versions of the software, a limited government version and a contractor-releasable version. The NAFCOM database consists of technical and programmatic data at the component, subsystem and space systems level. It is made up of about 122 reference projects from the REDSTAR library (Resource Data Storage and Retrieval Library). Notably, these include 76 unmanned land orbits and 24 unmanned planetary spacecraft and 8 manned spacecraft, including 366 scientific instruments, as well as 11 launch vehicles and 3 rocket engines.[26]

The database also has many curricula of the projects that are used to derive the CERs in which the missions are described. the work structures and the difficulties and anomalies of the process. NAFCOM is predominantly a parametric model and uses underlying multivariable CERs to obtain cost estimates on a wide range of space hardware, including Earth-orbiting spacecraft, manned and unmanned spacecraft, launch vehicles and higher stages, rocket engines liquid and tools. Obviously within the scope of this review, NAFCOM applications for RLVs are niche.

To estimate costs, NAFCOM uses a WBS basis or, alternatively, a functional basis consisting of estimated hours and dollars for skills, materials and subcontracts. The inputs allow the user to select historical data points from the database to implement a multivariable regression CER or a specific analogy approach to obtain the estimate. A customized and specific user-defined approach is also possible. Multiple inputs of subsystem-level cost drivers as well as complexity generators that take into account technical and programmatic complexities minimize the subjectivity of inputs and ensure that a data-driven and statistic-based estimate is achieved.

NAFCOM applications for RLV vehicles are few. For cost estimation NAFCOM uses the WBS and entering the Inputs allow the user to select historical data points from the database to implement a multivariable regression CER or a specific analogy approach to obtain the estimate.

Inputs for the NFACOM project include discrete technical parameters like:

- Weight
- Materials
- Power
- Requirements
- Design life

All these parameters can be extracted from program technical documentation.

Inputs for other subjective cost drivers include:

- Contractor experience
- Management levels
- Technology level
- Any changes in requirements which are usually well documented in management reports and program reviews

Process based schedule estimation also allows for three levels of schedules to be generated, while cost time phases show the cost spread at a subsystem level.

In addition, cost trades facilitate for fast sensitivity analysis addressing weight, new design engineering or manufacturing management, and enhanced engine estimating functionality incorporating algorithms from the U.S. Airforce jet engine cost model. Productivity gains are also incorporated through embedded time variables in most NAFCOM CERs, and through modelling of other engineering and manufacture technology improvements which reduce cost. The output is then provided in two categories being

- Design
- Development, Test and Evaluation (DDT&E) production costs

Other calculated costs include Integration, Assembly & Test (IA&T), ground support equipment, system test operations, Systems Engineering (SE), launch and support operations, Project management.[13]

### 2.2.2.2 NASA Cost Estimation Website

This publicly available NASA/JPL website features numerous educational examples through simple, online cost estimation models and tools encompassing a wide scope of purposes and frequently used for 'sanity checks'. All tools are written in Java- Script, and consequently require a browser with this capability.

Tools include inflation, learning curve and cost spreading calculators, with some launch vehicle data also provided. Specific cost estimation models then address aircraft and engines, soft- ware and mission operations, which include, amongst others, the DSN Cost Estimating Cost Model (CECM), the Mission and Space Operations Cost Models (MOCM and SOCM) and the Constructive Cost Model (COCOMO) Software Model. These are the Spacecraft/Vehicle Level Cost Model (SVLCM) and the Advanced Missions Cost Model (AMCM).

The SVLCM is a top level model which provides ROM cost estimates for spacecraft development and production, accurately including launch vehicle stages, engines and scientific instruments. SVLCM uses a common database with NAFCOM and is a simplified derivation thereof. User inputs include the type of spacecraft, dry weight, quantity and a learning curve factor if more than a single unit will be produced.

The AMCM offers another means to achieve fast ROM estimates for development and production costs of a wide scope of space, military and navy applications, including spacecraft and space transportation systems, aircraft, missiles, land vehicles, and ships. The AMCM is most suitable for use during early conceptual stages of a mission where few details are known at subsystem and system level and where multiple elements per scenario are foreseen. Input data includes unit production quantity (including spares, test and prototype units), mission type and dry weight, Initial Operating Capability (IOC) year (for spacecraft, this is the year of first launch), block number representative of the level of system design inheritance, and a complexity factor which encompasses the level of programmatic and technical difficulty analogously anticipated for the new system. [26]

In addition to the cost estimation models and tools, the NASA Cost Estimation Website also offers a comprehensive scope of links to associations, organizations and agencies, as well as books, government and technical reports, periodicals, software and other references pertaining to cost estimation within the aerospace industry, making it in itself a valuable resource.

#### 2.2.2.3 Aerospace Launch Vehicle Cost Model (LVCM) for DoD

The Department of Defense Aerospace Launch Vehicle Cost Model is a parametric model only available to the Aerospace Corporation project managers and cost analysts on an internal use basis. With the incorporation of proprietary data from previous DoD launch vehicle programs and being governed by strict ITAR regulations, LVCM is classified tool for the commercial industry.

The fundamental purpose of the LVCM is to produce cost estimates of existing, modified and new launch vehicles by determining subsystem components of overall research, development, operations, testing and evaluation costs. Total vehicle LCC (life cycle cost) are also determined, and annual fiscal year funding for the overall vehicle program, established. In accordance with the parametric CEM, underlying CER equations relate cost as explicit functions of input variables.

Input variables must be entered by an experienced user who possesses a detailed knowledge of the input parameters, which include data about:

- foreseen launch site
- propellant type

- weight
- precedent production quantities of subsystems, amongst others including structure, thermal control, electrical power and wiring, reentry protection, landing system, C&DH, instrumentation, propulsion, payload fairing and more.

### 2.2.3 Cost estimation handbooks, reports and guides

This section tells about five important cost estimation handbooks, reports and guides specifically relevant and frequently applied within the space sector.

These are:

- NASA Cost Estimating Handbook
- ISPA Parametric Estimating Handbook
- DoD Parametric Cost Estimation Handbook
- RAND Project AIR FORCE Reports
- GAO Cost Estimating Assessment Guides

These handbooks are numerous and generally tend to focus one particular elements of cost, such as cost risk or life cycle.

#### 2.2.3.1 NASA Cost Estimating Handbook

The NASA Cost Estimating Handbook (CEH) offers a very informative, concise overview on internal cost estimation within the National Aeronautics and Space Administration. NASA cost requirements as well as roles and responsibilities within the NASA framework are outlined. It also explained and listed the cost estimation processes.

Four CEMs are specified:

- Parametric
- engineering build-up
- analogy
- ROM

All of these CERs are explained with respective strengths and weaknesses stipulated. COTS and GOTS tools implemented within the NASA framework are also listed and functionally outlined, appropriately but not comprehensively.

Dedicated chapters then address various aspects including financial analysis techniques, benefits assessment and analysis, cost risk, and career development.

The handbook itself is a living document with several iterations and modifications. The latest versions available include the NASA CEH 2002, 2004 and the most recent NASA CEH 2008. The handbook in itself is not an actual cost model, but a very informative and thorough piece of literature detailing cost estimation practice and processes employed and applied within NASA.

#### 2.2.3.2 ISPA Parametric Estimating Handbook

The ISPA Handbook is a joint compilation and publication of the International Society of Parametric Analysts, ISPA and the Society of Cost Estimating and Analysis, SCEA.

In the last edition (4th) the complete guide for parametric practices and their implementation of all the relevant sections is explained.

The manual also allows us to understand when the estimates are acceptable and the basis for the development of CERs.[26]

It is an important manual given that it also explains the importance of data collection, then entering into the specifics of how the proposals are discussed. In the book there are also many practical examples that allow you to understand everything well.

#### 2.2.3.3 RAND's Corporation Reports for Project AIR FORCE

Several documents addressing cost estimation practices have been produced by the non-profit Research and Development Corporation RAND within the scope of Project AIR FORCE (PAF), a specially formed division of the RAND Corporation created by and for the United States Air Force. This federally funded research and development centre executes studies and analyses to address

specific identified challenges and issues within industry.

In 1977 a RAND report critically assessed the validity of the parametric CEM for spacecraft current at the time, with a focus of improving estimates of future programs. More recently in 2009, RAND released a stringently peer-reviewed technical report and handbook entitled ‘‘Guidelines and Metrics for Assessing Space System Cost Estimates’’, based on a preliminary 2007 draft document. The purpose of this final handbook was to assist analysts with evaluating cost estimates for space systems acquisitions, in particular for use by the DoD in response to an increased priority of space systems for US defence and security. In the end the handbook provides an exhaustive background on the challenges of cost assessment for space systems and offers information to facilitate for the evaluation of completeness, reasonableness, and uniformity of space system cost estimates. Chapters cover the basics of space systems within a DoD context, provide examples of average costs for past components, subsystems and systems from various space programs, and list some applicable cost models and their features, namely USCM, NAFCOM, and SSCM. [30][26]

Another report from RAND Project AIR FORCE entitled ‘‘Improving the Cost Estimation of Space Systems. Past Lessons and Future Recommendations’’, offers an instructive compilation of data, methods and information applicable to cost estimation, and through drawing upon past experience, makes suggestions for improving the processes, methods, tools and resources based on the study’s findings.

2.2.3.4 DoD Parametric Cost Estimating Handbook

This Department of Defense parametric CEH was established in 1994 as an initiative to explore ways to expand the use of parameters. Key objectives were identified as providing basic training and information in the areas of parametric use, evaluation and tools. The goal was to produce better cost estimates and ultimately reduce cycle times and reduce costs. The DoD Parametric Cost Estimating Handbook (PCEH) defines parametric CEM and addresses CER development topics, associated data collection approaches, and data processing techniques. Examples of some existing parametric cost models for both hardware and software applied in industry are also provided and discussed. The DoD PCEH is freely accessible on the Internet, but has been assigned an "inactive model status" by NASA, which means that although based on actual historical information, the data has not been updated recently. Therefore, this manual cannot be considered as a cost estimate.

2.2.3.5 GAO Cost Estimating and Assessment Guide

In 2009, GAO released a paper addressing best practices and cost estimation methods. While it is a general document, not sector specific, it provides a rigorous set of guidelines applicable within the space sector. The "GAO Costing and Evaluation Guide" describes best practices and methodologies used by federal costing organizations and industry to develop and manage capital program costs. Reliability of cost estimates is emphasized in order to prevent the occurrence of cost overruns, missed deadlines and performance shortages, while ensuring that reliable cost estimates are applied throughout the life of government acquisition programs.

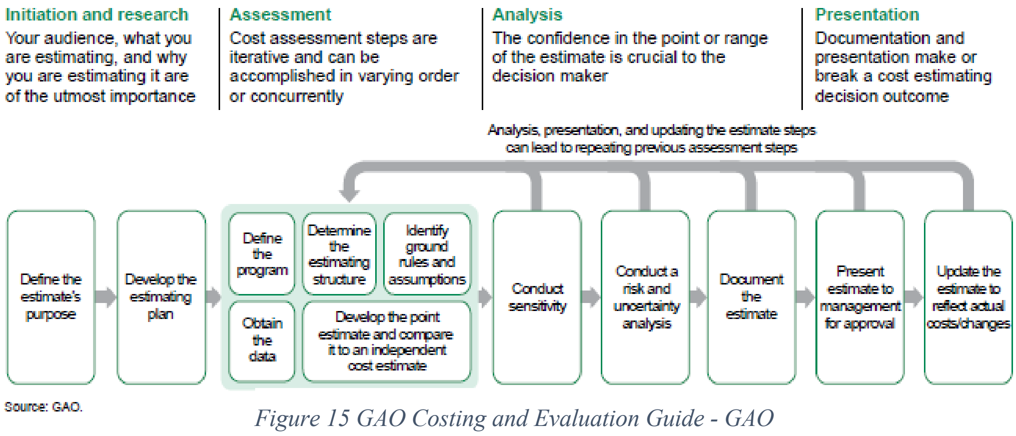

*Figure 15 GAO Costing and Evaluation Guide - GAO*

Consisting of 20 chapters and supporting appendices, the guide discusses other issues of the LCC program including the scope of cost estimation, planning, methods, validation, documentation, presentation and team, acquisition of data and actual risk, uncertainty management and sensitivity analysis. [26]

### 2.2.4 A mixture approach to cost estimation

In order to obtain an general system level cost estimate for a program, the mission elements must be costed with respect to their development, production and operations phases including launch and ground operations and support. The CEMs and the available models, tools and resources reviewed within this thesis are more appropriate, in varying degrees, for use in particular circumstances and for specific applications during different project phases. It is therefore common for estimators to combine multiple different CEMs and also tools to obtain a hybrid cost estimate for an overall system.

This type of approach manages to support the engineering activities present in large projects in the best possible way and makes it possible to compare the different models.

For example, Hunt and van Pelt list the various CEMs in their thesis which compares ESA and NASA cost estimation approaches and end results for a human mission to Mars.

Here, two important points must be underlined. The first being a distinction between a cost estimation methodology (CEM) and a cost estimation tool or model. CEMs refer to a fundamental approach or principle of performing a cost estimate, like the parametric or analogy approaches. In turn models like NAFCOM and TransCost, refer to commercial, government or other products which are based around a specific underlying CEM. It is important to again stress that while a suitable method, model or tool is key for an estimation, the science of cost estimation also incorporates the essential elements of reliable data, as well as an experienced, knowledgeable estimator. Together, the three elements combine to produce a robust, justifiable estimate to support a realistic project budget.

Many of the significant cost estimations, in particular for large scale, complex, international projects like those within the space sector, rely on strategic combinations and amalgamations of numerous methods, and sometimes also numerous models and tools. Such a CEM and model amalgamation approach (AA) is utilised for two different yet complementary intent. The first is to formulate an completely new cost estimate which deals with the unique requirements and specification for a particular project, and where different CEMs better address the various project elements, components or processes to be costed. An example of this is where a system model, such as the SSCM, is applied, but where the resulting cost estimate is expressed as a sum of constituent subsystem cost estimates. The SSCM is a parametric-based tool. Here, the estimator may decide to take out particular sub-system estimate components and replace them with, for example an analogy or bottom-up estimate if more in-depth details are available for that sub-system, or if past experience can offer a more representative cost for that segment.

Alternatively Amalgamation Approach (AA) can be implemented as a sanity check to an already existing evaluation. This is often the case when a previously applied method has specific limitations known by the estimator, which compromise credibility of the resulting cost estimate. In such a case, AA may act as a staunch sanity check for the order of magnitude of the original estimate, to either support it, or put it into question. An alternative CEM or tool should be applied if the difference is significant and this may potentially indicate that the original estimate should be reconsidered if the two are drastically divergent. True, it is important to be aware that the difference could lie in the sanity check method itself, in which case the responsibility to make this critical distinction remains to be made by the estimator based on their expertise and experience.[26]

From the time when numerous CEMs exist, many combinations of different methodologies are possible. Decision of which particular methods to combine and apply, is delegated by the project manager in close coordination with the cost estimator themselves. Open and stable communication between the two parties at this stage is crucial, as is, of course, the experience and knowledge of the estimator. Such a decision integrates a number of determining factors which include the available information with respect to program definition and scope, specifications and requirements, estimated level of cost estimate detail, and availability of resources such as costing tools or models, available data, finances, employees and time. In any case, it is essential that any decision must be fully justifiable and defensible in scope of the latter constraints and overall project margins. In addition, it's important that each method or tool is implemented by a professional and experienced estimator who intricately understands the capabilities of their method or tool. After all, using a multitude of models does not automatically means a more accurate estimate if the methods are wielded by an inexperienced operator.

# Chapter 3

## 3 Preliminary Cost analysis of a Reusable Launcher

In recent years there is a rapid rise production of small satellites that need a dedicated launch system. At the present there are three different solution for bringing small satellites into orbit. The first solution is about a cluster launch in which a group of satellites are launched to the same orbit as part of a rideshare agreement. For this kind of launch the cost was about \$110k per kg in 2014. A second solution involves having them share a ride alongside larger satellites in a dedicated launch vehicle. Obviously with this method orbital parameters of the small satellites are dependent on the needs of the primary satellite. The cost is between \$200k and \$325 for a 3U CubeSat. The third solution concerns the small satellites launch (SLVs). Both public space agencies and private companies have been developing small launch vehicles with payload capacities below 1000 kg in order to provide a lower cost alternative to the first two presented options.

For example Falcon 9 (the expendable version) in 2018 offered a maximum payload of 22800 kg (LEO) and a cost of \$2.675k per kg. As explained before a dedicated small launch vehicle offers lower advertised prices compared to rideshare and cluster solution. At the present just a few companies can offer (after a demonstration) a reduction of launch prices and this is an important detail. Among currently active small launch vehicles, the Kuaizhou-1A from the China Aerospace Science and Technology Corporation leads the way at an advertised launch price of \$20.54k (2018) per kilogram to orbit, followed by Rocket Lab's Electron at \$33.55k (2018) per kilogram and Northrop Grumman's Minotaur I at \$38.00k (2018) per kilogram.

| Rocket | Cost per kg |
|---|---|
| **Falcon 9 the expendable version** | $2.675k (2018) |
| **Kuaizhou-1A** | $20.54k (2018) |
| **Rocket Lab's Electron** | $33.55k (2018) |
| **Northrop Grumman's Minotaur I** | $38.00k (2018) |
| **HAAS 2CA** | $10.27k (2018) |
| **Vector's Vector-H** | $12.39k (2018) |

*Table 1 Cost per Kg of different worldwide launcher*

However, several companies currently developing small launch vehicles are advertising even better rates, from the Indian Space Research Organization with its Small Satellite Launch Vehicle offering a launch price of $8.83k (2018) per kilogram, to ARCA Space Corporation with its HAAS 2CA at $10.27k (2018) per kilogram, and Vector's Vector-H offering a launch price of $12.39k (2018) per kilogram.

At the same time, reusability of a launch vehicles has become a topic of interest because reduce overall launch prices, especially when focusing on the first stage. Doesn't exist any fully reusable launch system but is demonstrated the advantage of a partial reusable one. The advantage of reduction production costs over the life cycle of the system due to reuse of a software and hardware is provided and depend on factors. Launch rate, number of reuses and number of units produced are the main factors. In the past Space Shuttle had an horizontal landing and the cost per launch was much more expensive than anticipated ($1.55B). In the last five years Falcon 9 and Falcon Heavy successes with vertical take-off and vertical landing and the cost decreased because of reusable rockets. In combination with a reusable system, launch prices could further decrease by up to 30% for small launch vehicles as well. However, this is all assuming that the advertised launch prices and statements made from SpaceX officials are indeed valid. If we analyze the data from the Space Shuttle it's possible to note that winged orbital vehicle are much more costly than initially planned.

Initially SpaceX's program was to recover the first stage of Falcon 9 by a parachute system but this method failed so they decide for a vertical landing system.

Visiting the historical precedents has led to the conclusion that vertical take-offs and landings are the best solutions for reusable vehicles.

The real advantage about reusability is the potential reduction in launch price over the system's life. Falcon 9 has a lower production cost and this mitigate the higher cost of the development and operations. From this information is clear that the tool used to determine development of a small reusable launch vehicle should focus in cost minimization. An improvement on the reported average of $29.90k (2018) per kilogram to orbit of small launch vehicle manufacturers would present a cost-effective solution to orbit. As established in the literature study, two different launch vehicles are to be optimized for a payload of 100 kg and 500 kg to a Sun-synchronous orbit at an altitude of 650 km. As such, through a 30% reduction in launch prices, these systems are deemed cost-effective if they can achieve a price per launch below $2.00M (2018) and $10.0M (2018), respectively. At the early design phases, public companies and private agencies could benefit from a tool that both predicts the cost of developing such a system given a specific mission and optimizes this system for minimum cost or maximum payload performance. Such a tool would also allow critical valuation of claims made by reusable and small launch vehicle designers. [40]

## 3.1 Reusability for Falcon 9

In this section are explained the main differences between expendable and reusable rocket, in particular Flacon 9 that at the present is the only able to save the first stage coming back with a spectacular vertical landing.


*Figure 16 Falcon 9 - Space X*

### 3.1.1 Structural differences

Elements that must be added to a first stage in order to make it reusable include landing legs and associated hydraulics, cold gas thrusters for high-altitude controllability under zero main-engine thrust conditions and grid fins for added controllability. While these components affect the geometry and mass of a launch vehicle, conclusions from literature are that changes to the geometry are insignificant. For retro-propulsion reusability, these assumptions are valid because the landing legs and grid fins are stowed against the body of the launch vehicle pre-deployment and do not affect the aerodynamics of the vehicle, while the cold gas thrusters are stored inside the first stage.

An estimated landing gear mass of  2100 kg for the Falcon 9 v1.1, which equals a 10.0% increase in inert mass, validates this statement.

As an initial estimate, the reusable hardware mass is assumed to equal 10.0% of the first stage inert mass, where the cold gas thruster and grid fin masses can be considered negligible, being lumped within this 10.0%. [40]

### 3.1.2 Trajectory differences

There are two different trajectory options for retro-propulsion recovery. The first landing option considers that the reusable first stage arrive and land in a different pat compared to the starting point pat. The goal of both the menoeuvre is to slow down to rocket to zero velocity at the desire landing point in order to reuse the first stage. With this kind of re-entry, the rocket need two burns: one called 're-entry burns' that permit to re-enter the atmosphere and a second

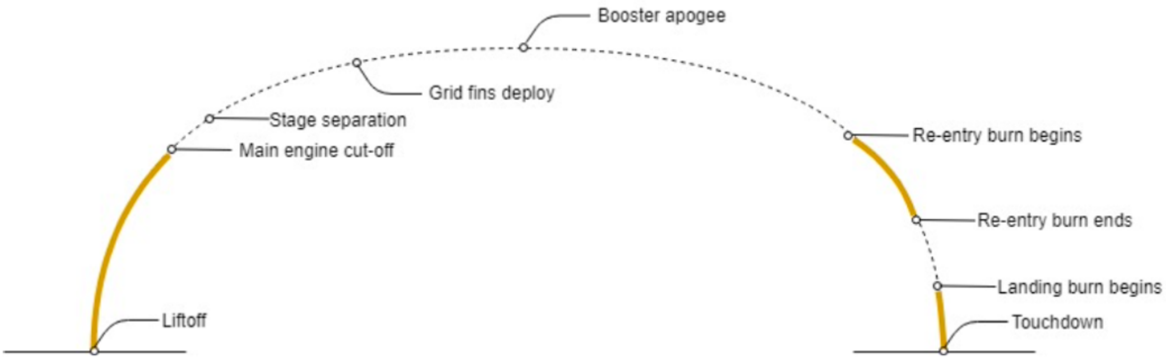


*Figure 17 Downgrade landing flight profile [31]*

'landing burn' necessary for the touchdown. The second option consider that rocket return at the starting point for landing. This return-way needs one more burn that permit the rocket to alter the trajectory after the separation and redirect it towards the launch site.

If we consider the 'reusable trajectory' we also have to consider requirements of reorienting and all the attitude data necessary for the return. For example rocket must be at zero velocity at the desire landing altitude. On the previous study for example it's explained that landing burn will begin below an altitude of 15 km and the re-entry burn will begin between an altitude of 55 km and 30 kn. The boostback manoeuvre time vary between 20 s and 60 s and the pitch angle in this moment will be set to 190°. [40]

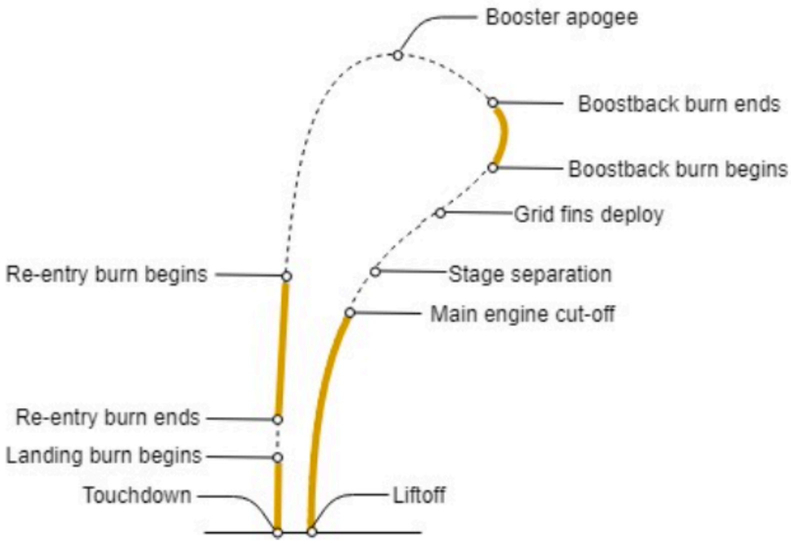


*Figure 18 Return-to-launch-site flight profile – [31]*

## 3.2 Cost analysis

The main goal is to reduce the launch costs of launch vehicles. Accounting for reusability, it is important to exactly estimate the price per launch of a reusable launch vehicle to determine its price-reduction capabilities. This chapter presents a cost model. The following sections detail the changes made to the model and its applicability to the multidisciplinary design analysis environment. Subsequently, the reusability cost model and its verification and validation are presented.

In general, the cost per flight of a launch vehicle is the sum of its development, manufacturing and operations costs, as depicted in the equation. This is elaborated on in more detail in the following sections.

$$CpF = C_{dev} + C_{man} + C_{ops}$$

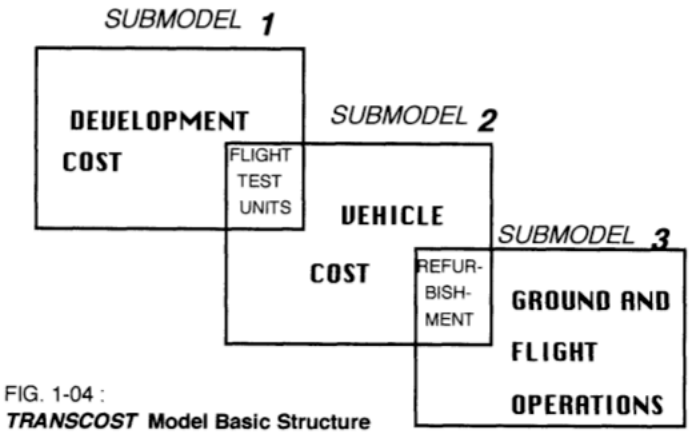


*Figure 19 TRANSCOST Model Basic Structure - KOELLE*

Three components explain launch vehicle design costs:

- Development costs

Development cost are the cost required to design and test the launch vehicle. It makes up the largest portion of costs in terms of raw dollars.

- Production costs

Production costs are all of the costs related to the manufacturing and production of a launch vehicle, including all testing, quality, and engineering support costs. The vehicle's engines take up a plurality of the production cost.

- Operations costs

Operations costs are defined by what is required to take a launch vehicle and send it into orbit. This includes transporting and assembling the launch vehicle stages; the cost of propellants and other consumables for the flight; all costs associated with the launch site and the crew who handles launch operation activities; and any additional fees such as insurance for potential loss of payload or damage to property in the event of a catastrophic failure.

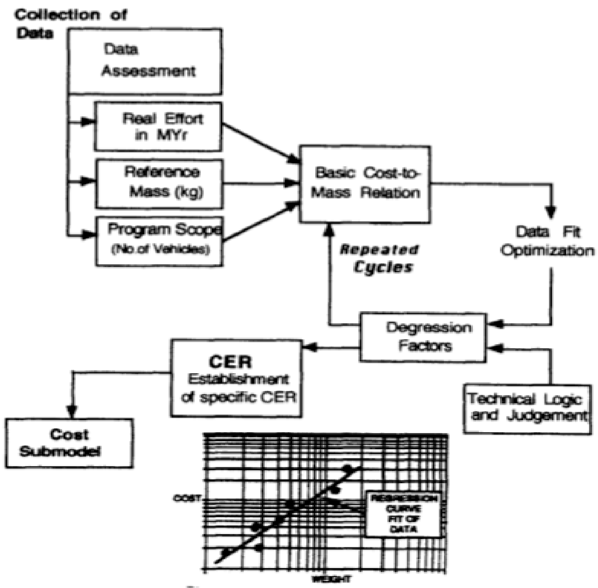


*Figure 20 Cost derivation process - KOELLE*

The cost Module was developed using information on the internet after a long research. Every interview, tweet or conference was took into consideration and with the use of an old version of the Handbook of Cost Engineering with TransCost 7.2, by D. E. Koelle some costs were determined.

The Handbook estimates costs through the use of Cost Estimating Relationships (CERs). CERs are similar in nature to MERs: actual cost data for launch vehicles is plotted against relevant vehicle data and normalized using certain cost factors, and the equation for the resulting trend line becomes the CER.

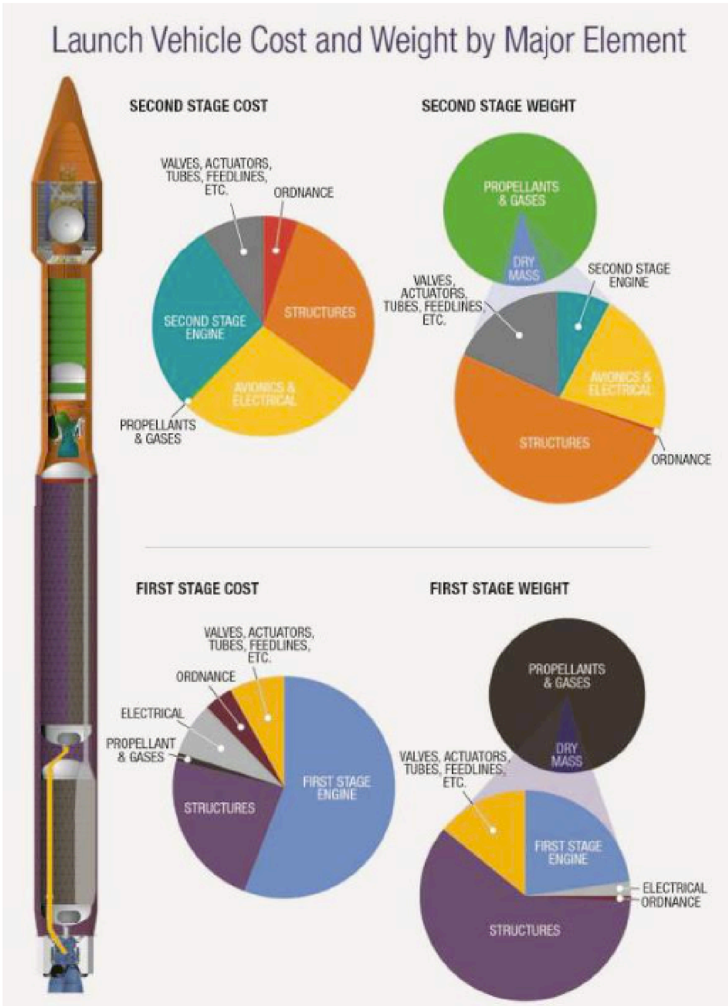


*Figure 21 www.zhuanlan.zhihu.com*

The basic development CER formula is:

$$C = a \bullet m^b$$

Where:

- C is the cost in WYr;
- a is a constant;
- M is a primary characteristic of the item being costed;
- x is an exponential value.

Third, certain cost factors are applied to the generic costing equation to develop a normalized cost equation for the item being sized. There are a total of fourteen different cost factors, although not all fourteen are applied to every equation. What cost factors to use as well as the value to use for it depends on the specific CER and factors surrounding the item that is being costed.

The factors are:

- $f_0$ is the system engineering/integrator factor

  This factor is applied to CER used to find the total development or production cost. The value to use for this factor depends on whether it is being applied to development or production costs and depends on the number of stages (N).

- $f_1$ is the technical development status factor.

  This factor is applied to development costs and indicates how new the project's concept and technology are. Values for this factor vary from 0.3 to 1.4. For reusable system is used a range form 1.1 to 1.3

- $f_2$ is the technical quality factor.

  Unlike other cost factors, the value for f2 depends on what specifically is being sized. For example, for the development cost of an expendable ballistic or transfer stage the value of f2 is found by dividing a ratio of actual masses and a ratio of reference masses in plots provided by the Handbook while the value for the development of a liquid-propellant engine with turbopumps is calculated based on the number of engine development and qualification firings.

- $f_3$ the team experience factor.

  The team experience factor is used to modify the development cost based on the level of experience the team has with designing that type of item. It ranges from a low of 0.5 for teams with "superior experience" to a high of 1.4 for a team that has little to no prior experience with what is being designed. In this study is used 1.1

- $f_4$ the learning cost reduction factor.

  This factor is used on production and operation CERs to apply the effects of cost reduction for increased familiarization with the processes involved and making those processes more efficient. This factor varies between 0.70 and 0.85, but only if there is a launch rate of at least five of the same type of vehicle per year. Otherwise this factor is set to 1.00.

- $f_5$, the refurbishment cost factor.

  The refurbishment cost factor applies to components only. The refurbishment cost factor is based on a fraction of the theoretical cost of producing a new unit.

- $f_6$ the optimum development schedule factor.

  f6 applies the cost effect of putting in extra work to finish a project early or of keeping staff on longer than expected to complete work due to delays and/or rework. The value for f6 is determined from a figure provided in the handbook based on the percentage ahead or behind schedule the project is where 100% is on time and results in a factor equal to 1.00.

- $f_7$, the program organization factor.

  Costs begin to increase if a program is split up amongst several major contractors. This factor adjusts the development cost in these instances, and is calculated by taking the number of parallel major contractors and raising it to the 0.2 power.

- $f_8$, the country productivity factor.

  The amount of time, and thus money, spent on a project can vary significantly from country to country for a variety of reasons. The cost factor f8 adjusts the cost based on the location the work is being done in, and the value for the factor depends on the specific country the work is begin done in.

- $f_9$, the subcontractor cost factor.

  Similar to f7, costs begin to increase as subcontractors are used to handle different parts of a project. This factor is determined through interpolation of two different figures provided by the Handbook based on the number of subcontractors, their estimated profit margin, and their percentage share of the total work being performed.

- $f_{10}$, the cost engineering factor.

  In the Handbook all CERS are developed as "business-as-usual" method. These tend to be slow and expensive because this method focus on maximization of performance rather than minimization of cost. The value of this factor varies depending on how extensively cost engineering principles are pursued and whether the CER is a for development or production costs. If they are not considered, the factor is set to 1.00 but in this case the factor is set to 0.8.

- $f_{11}$, the commercial venture factor.

As the system being planned is a commercial launch vehicle; for example private companies such SpaceX and Blue Origin are not under the same governmental and customer restrictions. Thus, this reduces the development cost by a factor of 0.5.

- $f_V$, the launch vehicle type factor.

  This factor applies only to certain operations CERs and is used to factor in the change in handling for different vehicle types. The value to use is specific to the type of vehicle system. For example, liquid-propellant vehicles with cryogenic propellants require specialized equipment and procedures for handling propellants and thus has an fv of 1.0, while liquid-propellant vehicles with storable propellants do not require these and have a factor of 0.80.

- $f_c$, the assembly and integration factor.

  The preparation of a launch system involves several ways. Three methods are indicated by the Manual: vertical assembly and checkout on a launch pad; vertical assembly and verification in an assembly building, then transport to a launch pad. Values of 1.00, 0.85, and 0.70 are respectively assigned to these three methods.

In order to compare values generated from TransCost CERs to estimates from other tools either the TransCost CER results must be revised down or the other set of values revised up. Third, cost values are given in units of "Work-Year" (WYr), which is a custom unit developed D. E. Koelle to more accurately compare cost data between countries and different years. The handbook provides a table to convert from WYr to USD, Euros, or Yen. A copy of this table may be found in Appendix A.

### 3.2.1 Premise

Cost data estimate for Falcon 9 is very difficult to source because data are not public.

The values from studies performed by NASA in 2011 for the Falcon 9 v.1.0 are not applicable to the total development cost of the new reusable Falcon 9.

The following study is therefore based on data obtained from non-certified sources joined to TRANSCOST [2][3].

Some information that are known are:

- According to Elon Musk, the marginal cost for a reused Falcon 9 launch is only about $15 million. He explained that the majority of this amount was represented by the $10 million it costs to manufacture a new upper stage. It is not reusable so it is necessary to make a new one for each launch. [3]

- Elon Musk has stated in the past that the first stage represents about 60% of the total cost of the rocket, while the second stage represents about 20%. So if the cost of producing a second stage is $10 million, as mentioned above, the first stage should cost around $30 million to manufacture.

- The remaining $5 million include costs of reusing the payload fairings (Musk probably only counts fairing refurbishment costs in this scenario because it costs $5–6 million to manufacture a new set of fairings), helium, fuel and oxygen, and also the cost of recovering the booster and fairings.

- Most importantly, the cost of refurbishing the recovered booster is only $250,000, according to Musk. That's a very low amount, which could indicate that the booster refurbishment process does not require much manpower, expensive hardware replacements or complex inspections. [3] [2]

- Falcons only started to be reused after the introduction of the v1.2 design variant at the end of 2015. Since then, SpaceX has done 100 launches (October 26) and is expected to conduct around 20–40 more launches every year.

- Elon Musk says that while reusability of the Falcon 9 reduces maximum payload capacity by less then 40%, recovering and refurbishing the booster represents less than 10% of the overall costs

- SpaceX charges $62M for a standard launch [1].

- Musk noted in March 2017 that the company had spent over $1 billion in reusable launch technologies, which meant the firm also needs to recoup the development costs from the reuse program rather than directly passing on those savings to the consumer. [5]

- Based on this information, it can be expected that the total development cost of the Falcon 9 should be less than $3B, the production cost of the engines should be well under $1M, and the total production cost of the first stage should be approximately 60% of the total production costs.

### 3.2.2 Development Cost Estimate

Development Cost estimation is one of the most difficult costing areas since a lot of subjective influence can be found in the definition of a development program.

The major criteria which impact the development cost of a launch vehicle are:

- Vehicle mass
- Vehicle number of stages

- Type and number of engines
- Company experience
- Program budget planning an schedule
- Etc.

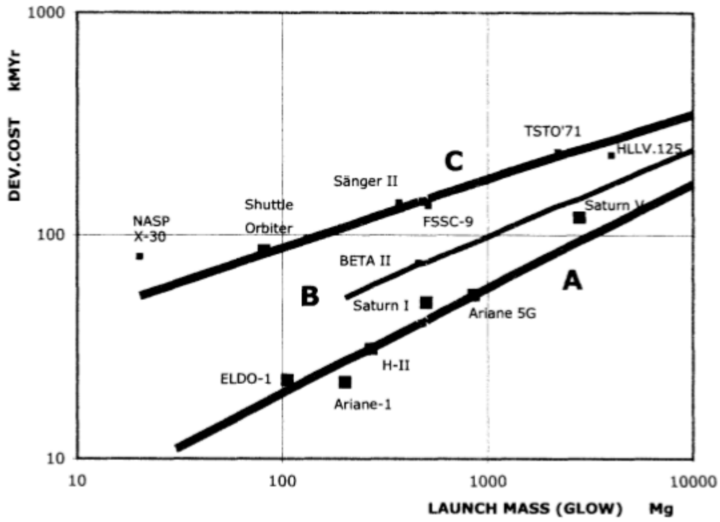


*Figure 22 KOELLE*

The backbone or basis of each cost model are the CERs, the cost estimation relationship.

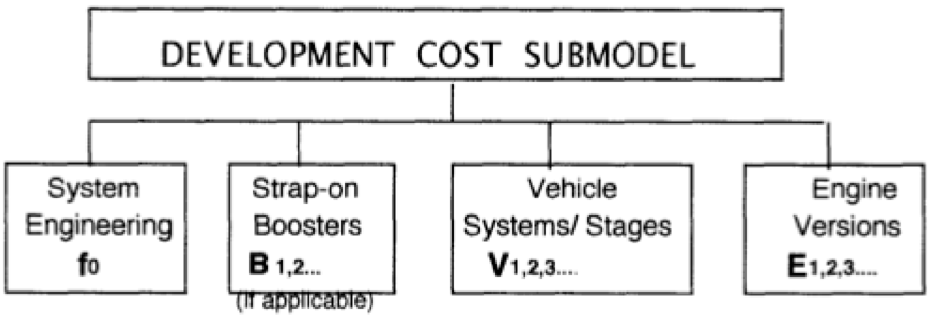


*Figure 23 Development cost - KOELLE*

The total development cost

$$C_D = f_0(\Xi\mathrm{H_B} + \Xi\mathrm{H_V} + \Xi\mathrm{H_E})f_6f_7f_8$$

The procedure from CER element cost data to realistic element cost. To vehicle cost and finally to the development program cost are:

- BASIC Dev. CER $C = aM^x$
- Elements Dev cost (vehicles, booster, engines) $H = Cf_1f_2f_3f_8$
- Launch vehicle dev cost $C_D$ $C_D = f_0\Xi H$
- TOTAL SYSTEM DEV COSTO $C_{tot} = f_0\Xi H\ f_6f_7f_8$

*Table 2 Development cost estimation*

| DEVELOPMENT | Formula | CER MYR | Calcuate value |
|---|---|---|---|
| **Engine stage 1** | $H_{EL} = 277\ M^{0.48}f_1f_2f_3$ | 6212,588 | 2,0942 B$ |
| **Engine stage 2** | $H_{EL} = 277\ M^{0.48}f_1f_2f_3$ | 6212,588 | 2,0942 B$ |
| **Vehicle Stage 1** | $H_{VE} = 98.5M^{0.555}f_1f_2f_3f_8f_{10}f_{11}$ | 8016,2764 | 2,702 B$ |
| **Vehicle Stage 2** | $H_{VE} = 98.5M^{0.555}f_1f_2f_3f_8f_{10}f_{11}$ | 3096,63 | 1,043 B$ |
| **Total** | | | ~ 8 B$ |

The total development costs are abnormally higher than expected.

It’s consulted the Handbook of Cost Engineering in an attempt to find methods which would be used to bring the calculated development cost down, but the Cost Module is already at the lower bounds of what the Handbook recommends. Maybe the future version will provide specific module for the reusable rocket with vertical return.

### 3.2.3 Production Cost Estimate

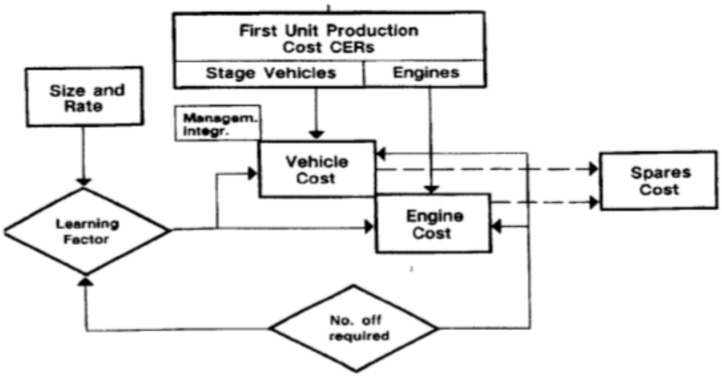


*Figure 24 Production cost - KOELLE*

In case of reusable launch vehicles also cost spares have to be considered. TRANSCOST model do not provide subsystem and components cost excepts engines.

$$F = n\ a\ M^{x} f_4$$

- F= total effort
- N= number of units to be built
- X =specific cost/mass sensivity value for each hardware group
- M= reference mass
- F4= cost reduction factor for series production

*Table 3 Production cost estimation*

| Production | Formula | Mass kg | CER MYR | USD $ |
|---|---|---|---|---|
| **Engine stage 1** | $F_{EL} = 1{,}30nM^{0{,}35}f_4$ | 470 | 70,5534 | 23,78 M$ |
| **Engine stage 2** | $F_{EL} = 1{,}30nM^{0{,}35}f_4$ | 470 | 7,839 | 2,642 M$ |
| **Vehicle Stage 1** | $F_{VP} = 1{,}30M^{0.65}f_4$ | 22200 | 220 | 27 M $ |
| **Vehicle Stage 2** | $F_{VP} = 1{,}30M^{0.65}f_4$ | 4000 | 16,58 | 5,59 M $ |
| **TOT** | | | 320 | 68 M$ |

The engine production cost is abnormally high also in this case. The cost for a single engine is about 2,64 Million. The stage alone production cost for the first stage is also high compared to what is expected when compared to the production cost of all of its engines.

Maybe in the future version of Handbook there will be a specific formulation for vertical landing launcher.

### 3.2.4 Operations cost

The cost of refurbishing the recovered booster is only $250,000, according to Musk. That’s a very low amount, which could indicate that the booster refurbishment process does not require much manpower, expensive hardware replacements or complex inspections. TRANSCOST is the only publicly available model for estimating space transportation operations cost.

Source of historical operations and support cost are not available because the private space industry guards this data closely.[32]

The parametric method proposed by Koelle has been applied but it overstimates costs and there are no clear information and indication of where this overestimate stems from.

The cost of refurbishing that recovered booster is only $250,000, according to Musk. That's a very low amount, which could indicate that the booster refurbishment process does not require much manpower, expensive hardware replacements or complex inspections.

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 was owned by the provider itself.

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 under the following formula. To facilitate referencing, most symbols have been kept analogous to the work of Koelle, with some exceptions. The parametric CER's described by TRANSCOST are enough for an initial estimate of the operations cost.

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.

### 3.2.4 Direct operating cost

Direct operations costs (DOC) are cost that are linked to the launch itself.

This kind of cost include :

- *Ground Operations*
- *Propellants*
- *Flight and Mission Operations*
- *Transport and Recovery*
- *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.

The following formula are adapted from the TRANSCOST 7.2.

$$Ground\ operations = \mathrm{W} \cdot 8 \cdot M_0^{-0.67} \cdot N^{0.7} \cdot \mathrm{Lpa}^{-0,9} \cdot f_v \cdot f_c \cdot L \cdot f_8 \cdot f_{11} = 10356\ k\$$$

Where:

- $M_0$= Gross take-off weight

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 B.

The propellant cost per launch depend to a certain extent on the vehicle size and also on the annual launch rate. Both determine the required quantity per year and that is according to the ground rules of chemical industry a major influence factor on the specific cost.

$$Propellant\ cost = \frac{M_p}{r+1} \cdot c_f + \left(M_p - \frac{M_p}{r+1}\right) c_{ox} + M_{pres} \cdot c_{pres} = 33\ k\$$$

Where:

- $M_p$= Fuel and oxider mass
- $r$= mixture ratio

$$Flight\ mission\ operations = W \cdot 20 \cdot Q_N \cdot LpA^{-0,65} \cdot f_v \cdot f_8 = 615\ k\$$$

Where:

- $W$= work year cost
- $Q_N$= Vehicle complexity factor
- $Lpa$= Launch per year

$$Transportation\ Costs = T_s \cdot M_0 = 260\ k\$$$

Where:

- $T_s$= Specific transportation cost
- $M_0$= gross take-off weight (GTOW)

The DOC consider only the fee charged per launch. They may be an additional fixed general cost contribution per year, but these cost are part of the Indirect Operations cost.

$$Fees\ and\ insurance\ costs = \frac{I}{1000} + F + c_{payl} \cdot P = 1301\ k\$$$

Where:

- I = Public damage insurance
- $F$= Launch site fees
- $c_{payl}$= Payload charge site fee
- $P$ = Payload capacity

Direct operating Cost = 12,5 M $.

### 3.2.5 Indirect operating cost

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 [30], 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. 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. [30]

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 [30].

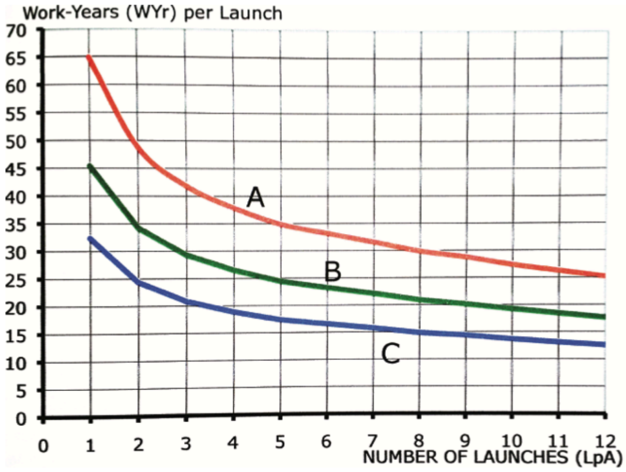


*Figure 25 N of launches – WTr - KOELLE*

A CER for the IOCs was taken for this research from [33] .

The relationship of which is shown in Equation *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 [35], 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.

$$IOC = 40\text{S} + 22{,}5\text{Lpa}^{-0{,}379}W = 5{,}133\ M\$$$

## 3.2.6 Reusability cost

Typically, the refurbishment cost is modelled as a percentage of the average manufacturing cost of a single launch vehicle. This is in line with the metric used by SpaceX official Gwynn Shotwell, who has stated that the cost of refurbishing the Falcon 9 first stage which originally flew the CRS-8 mission was "substantially less than half" of what it would have cost to build a new one. So the refurbishment can vary between 5% and 50%. In this case it's estimated 50% of the average manufacturing cost.

### 3.2.6.1 Recovery cost

This cost item refers only to reusable ballistic first stages and/or booster of fairings which fall into the ocean or come back with vertical landing to launch site.

$$C_{RE} = 0{,}5 \cdot C_{ops}$$

### 3.2.6.2 Refurbishment costs

The refurbishment cost are special category related both to fabrication cost (of spare unit) and operations cost. The refurbishment cost are only relevant for reusable vehicles. No real reference data exist. Yet about this type of costs for space vehicle. The number of flights per vehicle (or reuse) certainly will have an influence on the total refurbishment cost. The possible and most economic number of flights for reusable vehicle is still an open issue: present range of assumptions is between 10-20.

$$C_{RF} = 0{,}5 \cdot C_{man,av}$$

## 3.3 Example

With data found on the internet in the table below is possible to understand how is the earn for Space-x with one rocket with 10 launches.

*Table 4 Example of profit for one launcher with ten launches*

| Flight | 1st stage M$ | 2nd stage M$ | Fairings M$ | Refrub M$ | Fuel+others M$ | Launch M$ | Revenue M$ | PROFIT M$ |
|---|---|---|---|---|---|---|---|---|
| **1** | 30 | 10 | 5,5 | 0 | 5 | 50,5 | 62 | 11,5 |
| **2** | 0 | 10 | 0 | 0,25 | 5 | 15,25 | 50 | 34,75 |
| **3** | 0 | 10 | 5,5 | 0,25 | 5 | 20,75 | 50 | 29,25 |
| **4** | 0 | 10 | 0 | 0,25 | 5 | 15,25 | 50 | 34,75 |
| **5** | 0 | 10 | 5,5 | 0,25 | 5 | 20,75 | 50 | 29,25 |
| **6** | 0 | 10 | 0 | 0,25 | 5 | 15,25 | 50 | 34,75 |
| **7** | 0 | 10 | 5,5 | 0,25 | 5 | 20,75 | 50 | 29,25 |
| **8** | 0 | 10 | 0 | 0,25 | 5 | 15,25 | 50 | 34,75 |
| **9** | 0 | 10 | 5,5 | 0,25 | 5 | 20,75 | 50 | 29,25 |
| **10** | 0 | 10 | 0 | 0,25 | 5 | 15,25 | 50 | 34,75 |
| **TOT** | | | | | | 209,75 | 512 | 302,25 |

In this example in according to the data on internet it's show how should be the profit for Space-x with a reusable Launcher.

So what does it cost SpaceX to launch a Falcon 9? If Musk's marginal cost figures are at least somewhat correct, SpaceX's cost to a launch a newly built Falcon 9 is about $50 million. The company charges $62 million for a standard commercial Falcon 9 launch with a new booster, so the first mission results in about $12 million in profit. The second launch of the same booster then costs only the mentioned $15 million, which include refurbishment of the booster and payload fairings, production of a new second stage, fuel, the cost of operating a naval recovery fleet, etc.

SpaceX charges a little less for launches with a reused booster, so if the second launch carried a payload for a paying client, SpaceX gets $50 million. That means the total revenue from two launches of that booster is $112 million ($62M + $50M), while the total cost to SpaceX is only $65 million ($50M + $15M). So SpaceX would have made a profit of $ 47 million after two launches. These 47 million that can potentially cover the costs of at least three Starlink launches making them free for Space-x itself. If the given booster is launched 10 times in total and an average use of two times is considered for each fairing, the total cost after 10 launches would be approximately $ 210 million.

As an example from the following table, SpaceX could use each Falcon booster for four commercial launches and then the remaining six could launch Starlink satellites “for free”. This is a pretty clear-cut case of booster reusability being worth it.[2][3]

## 3.4 Results and validation

*Table 5 Recap cost estimation*

| **Development cost** | **8 B$** |
|---|---|
| **Production cost** | 59,1 Millions |
| **Direct cost oper** | 12 milion |
| **Indirect cost oper** | 5,5 million |

The Handbook of Cost Engineering uses the following definitions:

- Cost per flight= Total vehicle production Cost + Direct Operation Costs + Indirect Operations Costs = 76.6 milioni
- Price per flight = Cost per Flight + Development Amortization + Nominal profit Amount = 76,6+6,51+9
- Complete user price = Price per Flight + Insurance = more or less 90 Millions

Where:

- Nominal profit amount is 8.5 % of the Cost per Flight
- Insurance = 5% cost per flight = 3,83 M$
-

Results are presented in Table 5. The total development cost are significantly higher than expected. Handbook of cost Engineering used is an old version from 2007 so some formula has been modified and adapted. The engine production cost it's almost in the range of what is expected. About the first and the second stage production the cost is also abnormally high compared to what internet thought. Tototal cost is almost the double compared to the statement of Musk.

# Chapter 4

## 4 Discussion and conclusion

At this point check uses the lower bound for all cost factors in its analysis of the Falcon 9, it is not possible to more closely match the inferred development costs incurred by SpaceX without making improvements to the CERs, and such changes to the Handbook of Cost Engineering is beyond the scope of this thesis. However, if the calculated development costs could be reduced by a factor the new Complete User Cost would be cheaper.

The benefits of cost analysis are relevant both in the planning and business planning phase, and in strategic decisions. If correctly applied and with the necessary control and monitoring tools, the cost analysis contributes to:

- Saving money to the company: the optimal allocation of resources will still be an unattainable ideal, but with an in-depth tool and the overall survey like this it is certainly easier to understand where resources are not showing profitable. Using cost center accounting tools, it is possible to understand which areas, departments or divisions of the company employ the most resources.
- Cut waste: If resources are wasted, if there is any cash flow bleeding, this information will be revealed in this control phase.
- Improve the quality / price ratio, more generally the ratio between resources used and objectives achieved, by type of product offered. Prices revised on the basis of costs, although this strategy is not always the most suitable for the tourism sector, can dare to give a general image of the performance and of the relationship between production factors and pricing decisions.
- Be more competitive in the market. The design and the relevant technology, and as a consequence, the cost are very tighten dependant mission.
  So two kinds of mission must be considered:

- The first one of low energy, LEO is reachable by "simple" TSTO launcher winged like the Shuttle and many "X" vehicles or by conventional designed launcher like Kistler. We may observe that almost all the RLV are designed for LEO orbits.
- The second one, for high energy GTO requires more heavy launcher, 3 stages (or 2 stages with booster) and the recovery of the last stage is questionable.
- The associated question to mission is : what is the commercial market dedicated to each one
- The GTO market is quite well known and quite well predictable, about 20 to 25 satellites by year.
- The LEO market except the one dedicated to ISS servicing (which is not "yet" commercial !) is linked to telecommunication satellites and according "Iridium" collapse the market is very unpredictable. A great dose of optimism is needed to promote a RLV development for this orbit (except for demonstration purpose).

## 4.1 Goals

The main goals of the past decades are the maximum performance strictly connected to the minimum cost.

This means that cost have to be taken as a criteria for all the aspects.

The main aspect to analys is the optimum size of a launcher. The optimum size is evaluated in order to minimized the weight. In particular for the RLV's, maintainability and refurbishment have to be considered already in the early design phase.

Cost engineering is the paradigm for modern launch vehicle optimization with the goal of minimum development and operations costs.

The required vehicle net mass (including landing propellants) is an important costing parameter.

The net mass of reusable ballistic vehicles is about 40% higher than for expendable vehicles with same propellant mass.

This is due to higher safety structural design factors important fort the reusability.

Also thermal protection for re-entry and the additional equipment for integrated check-out or health control systems and the redundancy are important on the total net mass.

The higher mass also required a larger propellant mass which increase the net mass.

The difference between net mass and dry mass is about 22%-25% and this factor is related to the vehicle dry mass that includes the propellant per orbital and landing Maneuver.

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# Appendix A

Conversion table from WYr to USD, Euros and Yen.

This is a copy of the table from the Handbook of cost Engineering

| Year | USD | Euro | Yen |
|---|---|---|---|
| **1961** | 2700 | 18900 | |
| **1962** | 2800 | 20000 | |
| **1963** | 2900 | 21000 | |
| **1964** | 3000 | 22000 | |
| **1965** | 3100 | 23200 | |
| **1966** | 32300 | 24400 | |
| **1967** | 33200 | 25700 | |
| **1968** | 34300 | 27400 | |
| **1969** | 36000 | 29100 | |
| **1970** | 38000 | 31000 | |
| **1971** | 40000 | 3305 | |
| **1972** | 44000 | 35900 | |
| **1973** | 50000 | 38700 | |
| **1974** | 55000 | 43600 | |
| **1975** | 59500 | 50000 | |
| **1976** | 66000 | 55100 | |
| **1977** | 72000 | 60500 | |
| **1978** | 79700 | 65150 | |
| **1979** | 86300 | 71800 | |

| | | | |
|---|---|---|---|
| **1980** | 92200 | 79600 | |
| **1981** | 98770 | 86700 | |
| **1982** | 105300 | 92400 | |
| **1983** | 113000 | 98300 | |
| **1984** | 120900 | 104300 | 14,6 |
| **1985** | 127400 | 108900 | 15,2 |
| **1986** | 132400 | 114350 | 15,8 |
| **1987** | 137700 | 120000 | 16,4 |
| **1988** | 143500 | 126000 | 17,1 |
| **1989** | 150000 | 133000 | 17,6 |
| **1990** | 156200 | 139650 | 18,1 |
| **1991** | 162500 | 145900 | 18,6 |
| **1992** | 168200 | 151800 | 19 |
| **1993** | 172900 | 165800 | 19,5 |
| **1994** | 177200 | 160800 | 20 |
| **1995** | 182000 | 167300 | 20,5 |
| **1996** | 186900 | 172500 | 21 |
| **1997** | 191600 | 177650 | 21,5 |
| **1998** | 197300 | 181900 | 22 |
| **1999** | 203000 | 186300 | 22,6 |
| **2000** | 208700 | 190750 | 23,2 |
| **2001** | 214500 | 195900 | 23,8 |
| **2002** | 222600 | 201200 | 24,4 |
| **2003** | 230400 | 207000 | 25 |

| | | | |
|---|---|---|---|
| **2004** | 240600 | 212800 | 25,6 |
| **2005** | 250200 | 219200 | 26,3 |
| **2006** | 259200 | 226300 | 26,9 |
| **2007** | 268800 | 234800 | 27,5 |
| **2008** | 278200 | 243600 | 28,2 |
| **2009** | 286600 | 252700 | 29 |
| **2010** | 296000 | 261000 | 28,9 |
| **2011** | 303400 | 268800 | 30,4 |
| **2012** | 312000 | 275500 | 31,2 |
| **2013** | 320000 | 285000 | 32 |
| **2014** | 328700 | 292400 | 32,8 |
| **2015** | 337100 | 301200 | 33,6 |

# Appendix B

The liquid rocket fuel prices listed here are adhered to in the research. Their stated cost are in varying eco- nomic years and are standardized to 2015 prices per kilogram costs.

| 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 |

# Appendix C

In this appendix is define the factors that are used in the estimation for Production and development cost.

| Item | Value | justification |
|---|---|---|
| $f_1$ | 0,9 | It's a standard project |
| $f_3$ | 1 | The Falcon 9 team has a new engineer and old engineer with lot of experiences |
| $f_4$ | 0,7 | The stages are simple |
| $f_7$ | 1 | |
| $f_8$ | 1 | |
| $f_9$ | 1 | SpaceX is the lead designer and manufacturer of their components |
| $f_{10}$ | 0,7 | SpaceX has a strong emphasis on cost engineering |
| $f_{11}$ | 0,5 | SpaceX is a commercial venture |

| | | |
|---|---|---|
| $f_v$ | 0,8 | Expendable, liquid-propellant vehicle with storable propellant |
| $f_c$ | | Stages assembled horizontally and transported to launch pad |