Innovative Cost Engineering Approaches, Analyses and Methods Applied to SpaceLiner – an Advanced, Hypersonic, Suborbital Spaceplane Case-Study

by

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ABSTRACT

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When commencing a new program within the space sector, the question of expected program costs has emerged as a most critical criterion to be considered, especially within the context of large and highly complex international programs where multiple domains and disciplines are directly interfaced. Given added technical, economic, and political complexities, the real challenge is to representatively estimate costs during the early program phases where physical, technical, performance and programmatic parameters, requirements and specifications might be scarce, unavailable, or still evolving. Here, the disciplines of systems and cost engineering, as well as program management converge to support the costing function.

Cost estimation is a subset of the cost engineering domain, and a plethora of cost estimation methods (CEMs), models, tools and resources applicable to various space sector applications, exist. However, due to the unique nature and specificity of each mission, project and respectively, program, the available arsenal of costing means can often be too general.

A new class of vehicle has also recently established itself as one of prevalent interest – launcher vehicles with a focus on reusability to render them economically viable, while concurrently offering cost-effective access to space for both cargo and humans. For such manned, reusable launchers (RLVs), a lack of historical data implies that classically assuming a single cost estimate based on a single heuristic parametric or analogy cost estimation alone is, by definition, limited. Thus new ways are needed to address cost estimation for complex,

unprecedented programs in the early program phase where system specifications are limited, but the available research budget needs to be defined. The hypersonic, suborbital, passenger spaceplane SpaceLiner currently being studied at the German Space Center, DLR, is one such vehicle and is selected as a current RLV case-study to model and apply the advanced cost engineering approaches and innovative techniques developed and described in this work.

Within the context of the case-study, the development of necessary processes and application of advanced and modified cost estimation approaches and programmatic principles is demonstrated. After a thorough literature review of current estimating practices in industry, the parametric method is justified as the prime CEM for optimal use during the early program phase. The TransCost statistical-analytical model for cost estimation and economical optimisation of launch vehicles, as well as two cost models, 4cost *aces* and the PRICE software, all of which are parametric, are selected. The transparent TransCost model is then extensively tested against realised development programs with an RLV focus, and consequently calibrated.

Prior to the three models being input with high-level, technical SpaceLiner data, some essential programmatic analyses are performed. The SpaceLiner program is considered from a top level as a global whole, and a detailed work breakdown structure of the required components to be developed and produced, is derived. In conjunction, and in accordance with European Cooperation for Space Standardization standards, a baseline program schedule is also established in order to represent the possible timeframe of the global project, to identify major milestones, and to support model inputs for the costing process.

Based on the WBS, program schedule and selected three models, independent development cost estimates are prepared, and an Amalgamation Approach of the multiple sets of results is then assumed. A final baseline development cost range is ultimately determined for the SpaceLiner, being maximally reflective of all currently available inputs. The cost of production is also considered using parametrics, while the operational scenario is qualitatively outlined, completing the SpaceLiner cost- and economics baseline.

DECLARATION

In accordance with Monash University Doctorate Regulation 17.2: *Doctor of Philosophy and Research Master's Regulations,* the following declarations are made:

In hereby declare that this Thesis contains no material which has been accepted for the award of any other degree or diploma at any university or equivalent institution and that, to the best of my knowledge and belief, this thesis contains no material previously published or written by another person, except where due reference is made in the text of the Thesis.

The core theme of the Thesis is a new cost estimation methodology and approach within the systems engineering framework, focusing on estimating development and production costs for large, complex space systems during the early program phase. The ideas, development and writing up of all work contained in the Thesis were the principal responsibility of myself, the candidate, from the Department of Electrical and Computer Systems Engineering (ECSE) under the supervision of Dr. Y. Ahmet Şekercioğlu, and in cooperation with the co-supervisor, Dr. Martin Sippel, head of the department of Space Launcher Systems Analysis (SART) at the German Aerospace Center, Deutsches Zentrum für Luft- und Raumfahrt (DLR), in Bremen, Germany.

Olga Trivailo
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Retrospectively, the PhD journey is one of oscillating sinusoids. Distinguished by peaks of excitement, exhilaration and an ultimate feeling of achievement, the sinusoid is consistently punctuated and skewed by troughs of challenges, exhaustion, despair and infuriating frustration. However, like our oscillating sinusoid paradigm, when combined, the standalone peaks and single troughs somehow synergise into a melodious and unique little sound-wave – albeit a seemingly insignificant one in the grand scheme of things. But what is beautiful music made of other than from a collection of those same sound-waves, big and little? Contributing but a peep to the symphony of knowledge is most certainly worth traversing that aforementioned journey.

During this PhD phase the peaks were greatly enhanced and the troughs gently dampened by the involvement of some exceptional people. Firstly, I would like to thank my two most outstanding Supervisors, Dr. Martin Sippel and Dr. Y. Ahmet Şekercioğlu, for their unwavering and ongoing support, always wise advice, calming counsel, careful guidance and continued understanding and unwavering encouragement, especially during the challenging times. Furthermore, my sincerest gratitude extends to my distinguished advisor and mentor, Prof. Dr. Bernd Madauss, as well as Mr. Joachim Schöffer, Mr. Herbert Spix, Dr. Fabian Eilingsfeld and Dr. Dietrich E. Koelle for their invaluable input and for so generously sharing their time, expertise and wealth of experience and knowledge to enrich my own understanding. A heartfelt thanks must also be expressed to all my wonderful friends, peers and colleagues, whose staunch support, patience and unconditional understanding were both an incredible motivational driver and an absolutely crucial contributing factor to the ultimate completion of this PhD – I trust that you all know well who you awesome people are.

And finally, to my tiny yet very precious little family circle which so devastatingly diminished during the years that it took to complete this Thesis - even though you may not be with me because of a distance, geographical and divine, I carry you in my heart wherever I may be, always, forever and indelibly so. This particular PhD Thesis and work is, in every way, for you.

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LIST OF TABLES

A/B	*air-breathing*
AA	*Amalgamation Approach*
AACE	Association for the Advancement of Cost Engineering through Total Cost Management International
AAInT	Amalgamation Approach Interface Tool
ACE	Advocacy Cost Estimate
ACEIT	Automated Cost Estimating Integrated Tools
aces	Advanced Cost Estimating System
ADCS	attitude determination and control subsystem
AIT	assembly, integration and testing
AMCM	Advanced Missions Cost Model
APR	Annual Production Review
AR	Acquisition Review
ASPE	American Society of Professional Estimators
ATLO	assembly, test and launch operations
CBS	cost break-down structure
CDR	Critical Design Review
CE	cost estimation
C&DH	command & data handling
CECM	Cost Estimating Cost Model
CEH	Cost Estimating Handbook
CEM	cost estimation methodology
CER	cost estimation relationship
CHATT	Cryogenic Hypersonic Advanced Tank Technologies
COCOMO	Constructive Cost Model
COSYSMO	Constructive Systems Engineering Cost Model
COTS	commercial off the shelf
c/o	cut-off

CSM	capsule solid motors
DDT&E	design, development, test & evaluation
DLR	German Aerospace Center (Deutsches Zentrum für Luft- und Raumfahrt)
DOC	Direct Operating Costs
EADS	European Aeronautic Defence and Space Company
EASA	European Aviation Safety Agency
EBU	engineering build-up (engineering bottom-up)
e.c.	economic conditions
EDC-D	Effective Date of Contract Development
EDC-P	Effective Date of Contract Production
ELV	expendable launch vehicle
EPC	End of Production Contract
ESA	European Space Agency
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulation
FAST 20XX	Future High-Altitude High-Speed Transport 20XX
FTR	Flight Test Review
GAO	General Accounting Office
GLO	gross lift-off
GOTS	government off the shelf
HIKARI	High Speed Key Technologies for Future Air Transport Research & Innovation Cooperation Scheme
HLLV	heavy lift launch vehicle
HST	high speed transport
HQ	headquarters
ICE	independent cost estimate
ICEC	International Cost Engineering Council
IOC	indirect operating costs
ISPA	International Society of Parametric Analysts
ISU	International Space University

JPL	Jet Propulsion Laboratory
LC	learning curve
LCC	life cycle costs
LF	learning factor
LH2	liquid hydrogen
L/L	launch and landing
LOOS	launch and orbital operations support
LOX	liquid oxygen
LPA	launch per annum
LVCM	Launch Vehicle Cost Model
MDR	Mission Definition Review
MECO	main engine cut-off
MESSOC	Model for Estimating Space Station Operation Costs
MICM	Multi-Variable Instrument Cost Model
MRR	Mission Requirements Review
MSFC	Marshall Space Flight Center
MUPE	Minimum Unbiased Percentage Error
NAFCOM	NASA/Air Force Cost Model
NASA	National Aeronautics and Space Administration
NASCOM	NASA Cost Model
NE	North East
NICM	launch and orbital operations support
NMF	Net Mass Fraction
NOx	mono-nitrogen oxides (NO and NO2)
NORP	number of reference points (TransCost handbook)
NRC	non-recurring costs
NW	North West
O&G	operations and ground
OHB	Orbitale Hochtechnologie Bremen
ORR	Operational Readiness Review

PAF	Project AIR FORCE
PAX	passengers
PBS	Product Breakdown Structure
PCEH	Parametric Cost Estimating Handbook
PDR	Preliminary Design Review
PEI	Parametric Estimating Initiative
PF	TransCost programmatic factors (f_6, f_7, f_8)
PFM	Prototype Flight Model
PLC	product life cycle
PM	program/project management
PMO	Project Management Office
PPP	Public-Private Partnership
PRICE	Parametric Review of Information for Costing and Evaluation
PRR	Preliminary Requirements Review
QR	Qualification Review
RAND	Research and Development
RC	recurring costs
REDSTAR	Resource Data Storage and Retrieval Library
Res.	residual
RLV	reusable launch vehicle
ROM	rough order of magnitude
SAIC	Science Applications International Corporation
SART	Space Launcher Systems Analysis Department
SCEA	Society of Cost Estimating and Analysis
SE	systems engineering
SEER	Systems Evaluation and Estimation of Resources
SLB	SpaceLiner booster stage
SLO	SpaceLiner orbiter stage
SOC	Space Operations Center
SOCM	Space Operations Cost Model

SSCAG Space Systems Cost Analysis Group

SPC SpaceLiner passenger cabin / rescue capsule element

SPO System Project Office

SRR System Requirements Review

STSO single stage to orbit

SVLCM Spacecraft/Vehicle Level Cost Model

S/W software

TC TransCost

TFU theoretical first unit

TLC technological life cycle

TPS thermal protection system

TransCost Model for Space Transportation Systems Cost Estimation and Economic Optimization

TSTO two stage to orbit

TT&C telemetry, tracking and command

USCM Unmanned Space Vehicle Cost Model

VQ Vendor Quote

WBS work break-down structure

WYr work year

SUPERSCRIPTS AND SUBSCRIPTS

AA_{MAC}	Amalgamation Approach (macro-mode)
AA_{MIC}	Amalgamation Approach (micro-mode)
AA_{VAL}	Amalgamation Approach (validation-mode)
C_D	TransCost development costs
C_P	TransCost production costs
f_x	TransCost complexity factors
f_0	system engineering / integration factor
f_1	development standard factor
f_2	technical quality factor
f_3	team experience factor
f_4	cost reduction for series production factor
f_5	refurbishment costs factor
f_6	cost growth by deviation from optimum schedule factor
f_7	program organisation (parallel contractor organisation cost growth) factor
f_8	regional productivity factor
f_9	cost impact of sub-contractorship factor
f_{10}	cost reduction by past experience factor
f_{11}	cost reduction through government-free development factor
f_{12}	newly established delta development complexity factor
M^x	component mass with exponent *x* (TransCost)
S_DX	development sensitivity
S_PX	production sensitivity
T_M	maximum mission design lifetime
T_0	Time 0 (reference)
W_E	electronic component weight (4cost *aces* software)
W_M	mechanical component weight (4cost *aces* software)
W_S	structural component weight (PRICE software)
W_T	total component weight (PRICE software)

1 INTRODUCTION

"Going into the unknown is how you expand what is known" – Julien Smith

When commencing a new program within any sector or industry, the question of expected program costs has emerged as a most critical criterion to be considered. Within the space sector, this is also true, being particularly relevant within the context of large and highly complex international programs where multiple domains and disciplines are directly interfaced and where a large budget is usually required. Given the technical, economic, and political complexities, the real challenge is to representatively estimate costs during the early program phases where physical, technical, performance and programmatic parameters, requirements and specifications might be scarce, unavailable, or still evolving. Here, the disciplines of systems and cost engineering, as well as program management all converge to support the costing function.

Cost estimation is a subset of the cost engineering domain, and a plethora of cost estimation methods (CEMs), models, tools and resources applicable to various space sector applications, exist. However, due to the unique nature and specificity of each mission, project and respectively program, the available arsenal of costing means can often be too general.

A new class of vehicle has also emerged and established itself as one of currently prevalent interest – launcher vehicles with a reusability focus to render them economically viable, while concurrently offering cost-effective access to space for both cargo and humans. For such manned, reusable vehicles (RLVs), a lack of historical data implies that using purely the classic heuristic approaches such as parametric cost estimation alone, or analogy, is, by definition, limited. Thus new ways are needed to address cost estimation for complex, unprecedented programs during very early program phase where system specifications are limited, but the necessary budget requires definition. The hypersonic, suborbital, passenger spaceplane SpaceLiner currently under development at the German Space Center (DLR), is an example of a current industry RLV under research, which has been chosen to model and apply the advanced cost engineering approaches and innovative techniques developed and described in this work.

Within the context of the current SpaceLiner case-study, the development of necessary processes and application of advanced and modified cost estimation approaches and programmatic principles is demonstrated. After a thorough literature review of current estimating practices in industry, the parametric CEM is justified as the prime method for optimal use during the early program phase. The TransCost statistical-analytical model for cost estimation and economical optimisation of launch vehicles [100-102], as well as two commercial models, *aces* by 4cost GmbH [2-4] and the PRICE tool and software [152-154], all of which hinge on the parametric method, are selected. The transparent TransCost model is then extensively tested against realised development programs with an RLV focus, and consequently calibrated.

Prior to the three models being input with high-level, technical SpaceLiner data, some essential programmatic analyses are performed. The SpaceLiner program is considered from a top level as a global whole, and a detailed work breakdown structure (WBS) of the required components to be developed and produced, is derived. In conjunction, and in accordance with European Cooperation for Space Standardization (ECSS) standards, a baseline program schedule in also established in order to represent the possible timeframe of the global project, to identify critical milestones, and to support model inputs for the costing process.

Through combination of the WBS, development program schedule and selected three models within context of the Amalgamation Approach (AA), multiple independent development and production cost estimates are calculated, and an amalgamation of the multiple sets of results is then assumed based on stringent analyses and consequent iterations, if necessary. A software interface and tool, AAInT, is especially developed and designed to support the AA function. A final baseline development and production cost range is ultimately determined for the SpaceLiner case-study, being maximally reflective of all currently available program and mission inputs at an early program phase. The operational scenario is qualitatively outlined, completing the cost- and economics baseline for the large, complex industry case-study concept.

1.1 Focus of Thesis

From a historical perspective, attaining maximum performance has been the dominating design criteria for space missions. This ideology, however, has now been rendered outdated with cost becoming the new design criteria of dominance [99]. Limited resources and stringent mission budgets constitute a real, monetary barrier for access to space, meaning that cost must be a major and stringent consideration within the scope of mission planning and management. Here, a particular focus of the work is placed on launch vehicles, the sole means of access to space. The ability to develop, assemble and launch a cost effective, reliable and safe launch vehicle is a key measure of organisational space sophistication and capabilities [191]. For such programs, results of a cost estimate performed during the early program phases represent a determining factor for mission realisation. Hence the need for increasingly accurate cost models, methods and tools within the space sector is key, a difficult task given the highly variable nature, scope as well as scientific and technical requirements applicable to each mission.

1.2 Research Motivation

For all new programs, the estimation of costs during the early study phases, and into design, development, testing and integration phases, is an extremely challenging albeit necessary activity.

The research conducted within this thesis is motivated by the need to develop modified and innovative cost engineering practices and cost estimating approaches, methods and analyses for large, complex, multidisciplinary programs during the early phases. There is a need to synchronise the current cost engineering and estimation arsenals in line with the multitude of changes influencing the space industry in recent years.

One main reason is the space industry evolution influencing shift in space mission applications. Recent evolution of the space industry has seen the scope and purpose of space missions deviating from purely scientific goals, in the direction of cost-effective and economical access to space for a commercial advantage. Furthermore, coupled with rapid advancements and improved capabilities and affordability of space technologies, has given rise to a realistic advent of concepts such as that for hypersonic intercontinental passenger travel and also the realisation of an embryonic space tourism segment. Application of space technologies for manned applications forms a breakaway to traditional space access, meaning that previously applied analyses methods are not as representative.

Another key influence on the space sector has been the effect of recent political and economic conditions on the space industry influencing vehicle design towards a focus on reusability capability. Access to space has lately found a strengthened source of funding from private investors instead of government agencies. This has resulted in the increasing emergence of private, commercial space companies, such as Space Exploration Technologies (SpaceX) [198], Virgin Galactic [218] and Reaction Engines Limited [157], amongst others. Consequently, there has been an influx of new developments for innovative and cost-efficient vehicle concepts, including launcher vehicles, advanced stages, capsules and spaceplanes intended not only for transport of cargo, but for civilian applications. As previously mentioned, reusability of these systems is key for supporting economic success. But while the technology is advancing, analyses methodologies, and specifically, cost estimation methods find themselves lacking, especially for such a new class of vehicles where little precedence exists.

1.3 PROBLEM DEFINITION

There are several problems at hand to be overcome when costing an unprecedented, reusable vehicle for manned applications like the SpaceLiner case-study. Firstly, the concept is still in a preliminary design phase with system and indeed subsystem specifications still being designed, calculated and deduced. Hence any cost estimation method or model would either have to assume a specific subsystem configuration scenario, or alternatively be at a broad system level rather than at a specific sub-system one. Secondly, there is a distinct lack of applicable precedent missions and therefore little relevant historical data can be obtained. So application of existing CERs from the parametric approach contained within TransCost might yield non-representative results.

Furthermore, the cost estimation would have to fit within context of current economics and trends of the space market, another challenging task given that the current political, social, financial and economic environment has changed drastically over the past decade. The dynamic emergence of companies pushing the boundaries of space access with a civilian focus, have emerged, inciting considerable competition for access to space. This competition has consequently underpinned considerable technological progress and therefore both higher anticipated launch rates and logically, consequently lower launcher prices. In turn the lower launch prices feed back into industry competitiveness and the cycle is reiterated.

1.4 ORGANISATION OF THESIS

This Thesis commences with an introduction to the domains of system engineering, cost engineering, cost estimation, with Chapter 2 defining their context, utility and importance within space applications - namely within complex, large scale international programs. A brief historical overview of cost estimation methods (CEMs), models, tools and general and current industry practices is provided. The latter is complemented with an in-depth literature review specifically addressing cost estimation early in space program phases for launcher systems, with a hardware focus. Based on the review, the proposed Amalgamation Approach (AA) for reducing increasing cost estimation confidence, while reducing uncertainty of early program cost estimates is also introduced and explained. This employs the relatively simple concept of result redundancy to arrive at a final consensus, as opposed to the traditional approach of accepting a single source or single value cost estimate.

Expanding on the presentation and discussion of theory, Chapter 3 then outlines the background and progress of a hypersonic, suborbital space plane being studied at the Bremen Institute of Space Systems of the German Aerospace Center, DLR, for ultra-fast point to point passenger transportation. Dubbed the SpaceLiner, this project is introduced and discussed as being a highly relevant and current industry example of a large-scale international program which is largely unprecedented in nature. Knowledge and process shortcomings and gaps for cost estimation of such an unprecedented vehicle are also highlighted, and linked to theory presented in the earlier chapters.

Linking the cost theory and the selected case-study example, Chapter 4 describes the SpaceLiner philosophy in terms of data, factors and technologies which are identified to influence program costs, in particular, development and production program Phases C and D. Accordingly, an in-depth and multi-level work breakdown structure (WBS) for the case-study is developed, and preliminary program schedules devised. Drawing key points from the literature review, Chapter 4 highlights the TransCost parametric model to be used as a focal starting point for further dissemination of the various difficulties associated with costing a vehicle with limited similar precedent. A dedicated TransCost tool is programmed in an Excel interface to support extensive TransCost model testing. Development data from large and complex space launcher programs is entered into the TransCost tool, with a focus on those programs with reusability capabilities. Two prominent examples are the heritage Space Shuttle and the Soviet Buran vehicle development efforts. Through this exhaustive TransCost testing and validation process, a modified model is developed in view of application to the SpaceLiner case-study vehicle.

Additionally, in line with AA_{MAC} theory, the PRICE and 4cost *aces* software models are selected as suitable candidates for incorporation into the AA cost estimation framework.

Finally, synthesizing theory, TransCost model testing outcomes and lessons and the newly developed AA and AAInT tool, a development and production cost estimation is performed on the fully reusable, suborbital hypersonic SpaceLiner industry example. Numerical results are derived implementing the highly analytical and stringent AA_{MAC} mode, and respective cost ranges for production and development are established. A qualitative confidence level for the latter is also discussed and established. Operations and grounds costs addressed qualitatively given the still evolving nature of the SpaceLiner program, with a preliminary breakdown of required resources and infrastructure, also proposed.

The key results, findings and outcomes are analytically discussed and associated conclusions drawn, documented, with ramifications and contribution of the research and work presented within this Thesis extended to other future large, complex, multi-disciplinary programs.

1.5 CONTRIBUTION OF DISSERTATION

Within forward looking industries such as the aerospace industry, large scale, complex, international projects must pass certain preliminary research phases to reach maturity and actualisation. Inseparable and mandatory for every new program proposal, is always an estimate of the expected costs including all foreseen lifecycle costs spanning development through to production and ultimately, program execution and operations. A representative cost estimate is critical to secure a suitable, justifiable program budget, which is consequently key to underpinning program success. Particularly challenging is establishing an estimate very early on, when program details, requirements and specifications are not crystallised, and when changes to technical design, mission requirements and other cost-critical aspects are still occurring.

This Thesis addresses exactly this challenge through a step-wise process, outlining the background in theory and research to the approach and required preparation of a cost estimate and business plan for large, complex, interdisciplinary programs. The acquisition of necessary information and its dissemination is described, after which key activities for program cost assessment are outlined and performed on a suitable case-study, the SpaceLiner. The Thesis introduces, describes and discusses the amalgamation approach (AA) which is used as a tool to ascertain and analyse the resulting cost estimate accuracy and representativeness of the program at an early state through cost estimation result redundancy. Effectively, the Thesis therefore builds upon existing cost estimation practices, and then further explores, defines, explains and extrapolates on this baseline to establishes a new set of processes and necessary steps for producing a first, representative cost estimate early during a program, based on limited, still evolving information. With respect to the case-study selected, this Thesis establishes an unambiguous path for the future application of the cost estimation processes described and developed within, also facilitating for incorporation of new information into an existing and clear cost estimation structure and business planning framework, as it becomes available.

Ultimately, and in line with the contribution of this work and document, the goal of the Thesis is to address the current gaps outlined in Chapter 1.3, and to establish a preliminary but justifiable and defensible development and production cost estimate with a high level of confidence for the chosen case-study, the unprecedented, early-phase, large, complex and international SpaceLiner concept.

1.6 PUBLICATIONS

During the compilation of this document, several publications were made through independent peer-review, as well as through conference papers which were written and presented based on the work contained within this Thesis. These are listed below. Later publications with final results of this work could not be made, since cost results obtained using the PRICE Systems and 4cost *aces* tools were performed under an agreement for limited and exclusive use and dissemination within context of this Thesis only.

Peer-Reviewed Journal Publication

- Trivailo O., Sippel M., Sekercioglu Y. A., *Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning,* Progress in Aerospace Sciences, Vol. 53, pp. 1-17, August (2012).

Conference Paper Submissions, Presentations and Contributions

- Trivailo, O., Sippel, M., Sekercioglu, Y. A., *Review of Cost Estimation Methods, models and Tools Applied to Space Mission Planning Now and in the Future,* 60. Deutscher Luft- und Raumfahrt Congress by Deutsches Gesellschaft für Luft- und Raumfahrt (DGLR), Bremen, 27-29 September, 2011 (*main author and presenter of peer reviewed paper*).

- Sippel M., Schwanekamp T., Trivailo, O., *Progress of SpaceLiner Rocket-Powered High-Speed Concept*, 64th International Astronautical Congress (IAC), Beijing, 23-27 September, 2013 (*co-author of paper*).

- Trivailo, O., Lentsch, A., Sippel, M., Sekercioglu, Y. A., *Cost Modeling Considerations & Challenges of the SpaceLiner – An Advanced Hypersonic, Suborbital Spaceplane*, American Institute of Aeronautics and Astronautics (AIAA) SPACE2013 Congress and Expo, San Diego, October 10-12th, 2013 (*main author and presenter of paper*).

2 COST ESTIMATION IN THE SPACE DOMAIN

"Cost estimating is the translation of technical, programmatic and management specifications into cost." – Joe Hamaker, Cost Analysis Division, NASA HQ, Washington [75]

Historically attaining maximum performance has dominated design criteria for space programs and missions with maximising performance mistakenly once seen as being synonymous with minimising weight. This ideology, however, has now been rendered outdated with cost becoming the new design criteria of dominance. In today's competitive environment, limited resources and stringent 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 for all management decisions and processes. Therefore cost engineering, the new paradigm for space launch vehicle design [99] is an essential component during the preliminary stages of any space program, as well as consistently and progressively throughout the entire project execution. Cost estimation CE and cost modeling are the two elements focal to this Thesis, with the topics being of current, significant interest within industry as seen by the rapid advancements and evolution of the process [72]. The two components have been classified as being key constituent functions within the overall cost engineering and cost control frameworks [107, 203]. In fact conclusions from a cost estimate performed during the early Phase 0/A are often a determining factor for program realisation. Within a research context, and given that research drives progress, a preliminary cost estimate performed at a pre-phase 0 stage can dictate 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 bidding context. Conversely, significant cost under-estimation increases the risk of financial loss and program failure by influencing the decision making process associated with budget allocation [56, 72]. Hence the need for representative and adequate cost estimation during the very early program research, establishment and development phase is obvious. Here it is important to note that a cost estimate

(CE) is a dynamic value rather than a fixed, static one, and as such, should be reassessed regularly so as to absorb and reflect any new information which becomes available. Early in program planning, available specifications may be limited and the resulting CE would therefore have a higher uncertainty than one made later on during the program life cycle. However at this early stage, a representative CE reflective of all available information and data at the given time can optimally support the project funding and underpin allocation of an adequate initial budget.

Most recently, global, social, economic and political circumstances 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 funded origins. As pointed out by Maryniak (2005), governments have been ousted and replaced by markets as the principal engines of technological change [124]. Such political variability and an uncertain financial market have both heralded significant changes and restructure within many international space agencies including America's National Aeronautics and Space Administration (NASA), arguably the most prolific body in the world's organisation and funding of space [67]. Coupled with rapid advancements and improved capabilities and affordability of space technologies, these events have all given rise to the plausibility, design and preliminary implementation of novel concepts such as super- and hypersonic intercontinental passenger travel. Concurrently, space tourism in the form of sub-orbital civilian is becoming an attainable reality and the promise of orbital flights for civilians is also developing strongly from its embryonic phases.

Diverse papers, articles and reports have addressed and explored the topic of space tourism, its advent, current progress and future potential of the industry [5, 23, 35, 38, 66, 67, 104, 106, 125, 146, 150, 197, 200]. Additionally, well summarised by Crouch (2001), numerous surveys and studies to gauge interest and plausibility of a space tourism market have been conducted predominantly in the 1990s across Japan [33, 34], the USA [35, 36, 143], Germany [5], Canada [35], the United Kingdom [19] and even Australia [39]. More currently, several studies are also being undertaken by various institutions addressing the evolving public propensity and openness to space tourism and space transportation for civilians [23, 38, 70, 125, 146, 149, 167, 200]. Generally speaking, findings suggested that conceptually, a significant proportion of respondents were positively inclined towards the prospect of space travel. While such survey results are more speculative than they are conclusive, the common trends observed were relatively consistent and positive, and are well reflected in the conclusions drawn from a key NASA and Space Transportation Association (STA) General Public Space Travel and Tourism study, which states that “serious national attention should now be given to activities that would enable the expansion of today's terrestrial space tourism businesses…in time, it should become a very important part of…[the] overall commercial and civil space business-program structure” [143].

In recognising and adapting to latter trends, an increasing number of private entities prominent companies, entrepreneurs, space transport technologists and other proponents have emerged over the past decade targeting the anticipated space market from a commercial perspective [150]. Prolific examples include Sir Richard Branson’s Virgin Galactic [20, 218], a highly successful synergy of the Virgin Group and Paul Allen and Burt Rutan’s Mojave Aerospace Adventures [61, 218], renowned for its prize-winning suborbital SpaceShipOne spaceplane, Sir Richard Branson’s, has had a significant impact on the technological progress of space technologies as well as on media exposure and public awareness of space access. Other companies actively proving and enhancing the existence of a commercial space market include Space Adventures [77], Armadillo Aerospace [14], and Elon Musk’s SpaceX, whose key organisational goal is “enabling humanity to become a space-faring civilization” [198]. The latter are all major contributors to recalibrating the interest levels in manned spaceflight through heightening exposure and public awareness, as well as pushing barriers of technology and feasibility through competition, while seeking to cost-effectively and rapidly progress manned space travel in the long term, while concurrently capitalising on these activities. Until now, much of the activities have focused on sub-orbital flights, while more recently focus has also turned to orbital civilian ventures [104]. In fact Eilingsfeld (2006) suggests that growth is limited for suborbital space tourism due to very short times to experience space despite relatively high ticket prices [52] compared to the aviation segment. So in order to enhance the business case, he identifies and proposes three options to prolonged the space experience, which are an orbital cruiser, a space hotel or a suborbital spaceplane.

One such particular spaceplane which deviates from a purely space tourism objective, is the SpaceLiner [168, 182, 183, 185, 186], shown below in Figure 1.

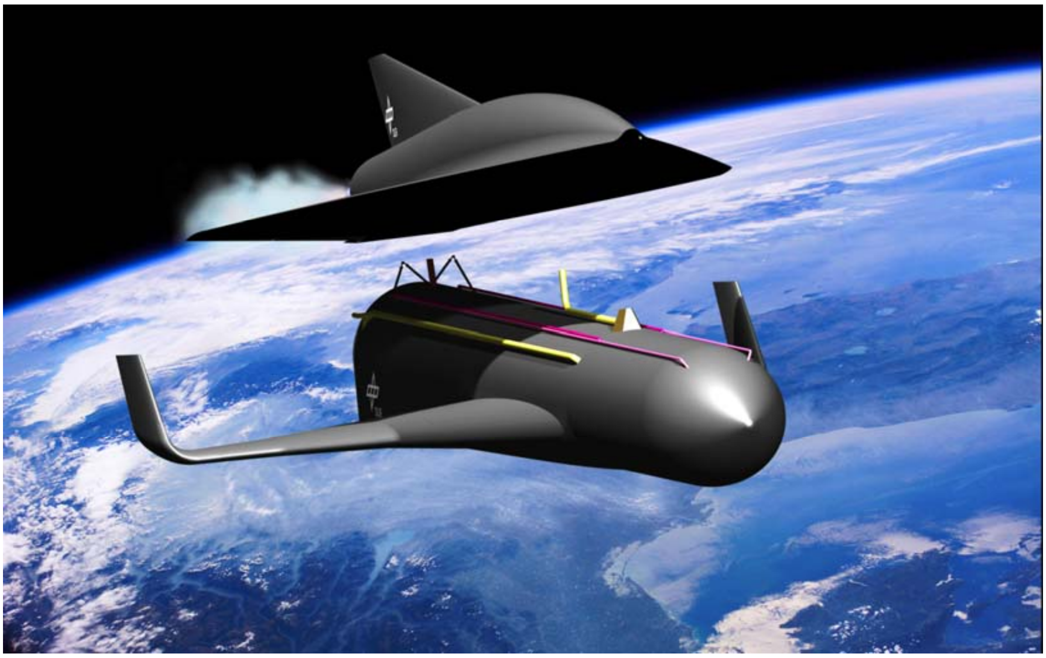


Figure 1: Artist's interpretation of SpaceLiner 7 [82]

This hypersonic, suborbital vehicle, shown below in Figure 1, is currently under preliminary design within the Space Launcher Systems Analysis (SART) department at the German Aerospace Center, DLR. The concept recently received substantial funding within context of the European FAST20XX framework [172], and aims to revolutionise the space market by marrying an ultra-fast means of transportation with the allure of thrill seeking [185]. The SpaceLiner concept aims to transport passengers from Australia to Europe in 90 minutes, an unprecedented speed compared to current civilian aviation sector capabilities.

Directly relevant to the SpaceLiner, in their paper on reusable hypersonic architectures, Kothari and Webber (2008) derive a $500,000 figure for potential orbital space tourism [104]. More generally, however, initial forecasts made by the Futron group [23, 66] indicate that the initial customer cluster will be prepared to pay up to $200,000 for a first ticket to space, while more recent circulating predictions suggest that by as early as 2014, a ticket for suborbital flight is likely to cost between $50,000 and $100,000 [192]. This initially apparent discrepancy can be attributed to lower prices incited by anticipated market competition, and given this phenomenon it is therefore reasonable to expect a growing emergence of public companies competing to make access to space simpler and more affordable in the coming decades [205]. Furthermore fundamental marketing theory of a product life cycle (PLC) can be constructively applied to the case of space access in the form of tourism. PLC describes the expected phases for a given product or service, from its inception, design and development, through to maturity and in some cases, obsolescence [98]. In accordance with fundamental PLC principles, Klepper (1997) describes that a general trend can be observed for the evolution of a particular industry, irrespective of the industry itself. Klepper proposes that any interdisciplinary product life cycle can be segmented into three fundamental phases being an early exploratory stage, which can be further split into development and introduction, followed by an intermediate growth and development stage, and finally by product maturity [149]. A PLC is then represented visually as a relation of volume of sales and profits with respect to time during the associated phases. While differences and deviations to a traditional PLC and its phases are recognised and classified in wider literature to reflect the varying nature of a product [98], Peeters (2010) suggests that the traditional PLC curve, shown qualitatively in Figure 2, can be applied directly to the potential civilian space access and tourism industries [149].

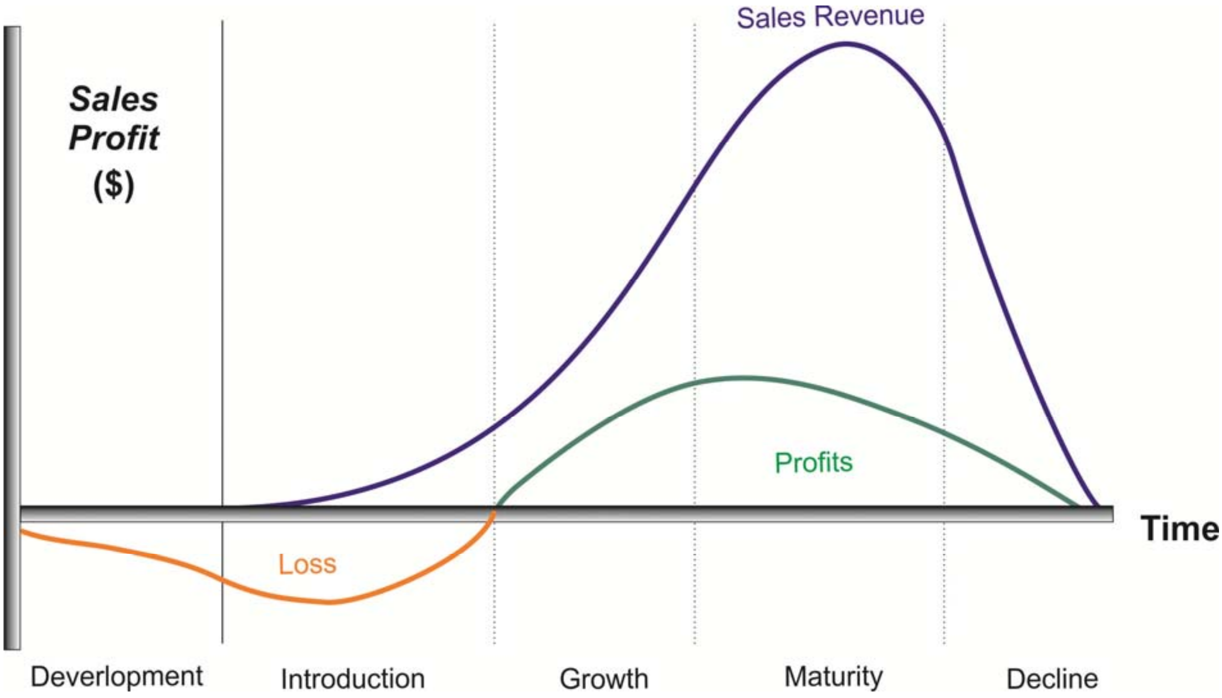


Figure 2: Qualitative traditional PLC curve for potential applicable to the industry of civilian access to space [149] [151]

Working further with the justifiable scenario that space tourism is an attractive and successfully marketable 'product' [106], as has been shown through numerous works and publications [5, 23, 34, 37, 38, 70, 104, 125, 146, 200], and combining this with the trend of increasing volume most prominently seen during the product growth and maturity PLC phases in particular, it is logical to expect launcher production rates to consequentially also increase in the coming decades. In a NASA funded study dedicated to projections of future space-lift systems conducted by the Aerospace Corporation, Johnson and Smith (1998) conclude that in order to achieve a one or two order of magnitude reduction in cost, flight rates must significantly increase compared to the Shuttle [93]. For a 10 × cost reduction, 48 flights per year are proposed and 700 flights per year for a cost reduction of 100 ×. Combining a foreseen increase in launch vehicle demand with an increase in flights, should incite technological enhancements in spacecraft hardware reusability, which at present is fairly limited, in particular for launcher vehicles with manned capabilities. At present, the only projects comparable for this category of space vehicles are the Space Shuttle fleet, which was only semi-reusable , and the Russian Buran orbital vehicle, which performed just one unmanned flight before the program was cancelled due to a mix of political influences and lack of funding [80]. Consequently, higher launch rates should drive launch costs and overall space access costs down, requiring existing cost models to be recalibrated to facilitate the change. As an example, recent suggestions have implied that the SpaceX fleet of Falcon 9 vehicles "break the NASA/Air Force Cost Model NAFCOM" [193]. So with the recently transpired and justifiably foreseen advancements to space access through the advent of commercial space travel spurred on by current space access and space tourism initiatives, it is essential for cost estimators and experts to keep abreast of the technological changes and have the capability to obtain indicative, relevant and justifiable estimates despite implementation of novel, unprecedented technologies.

Returning back from the costs of applications to the costs of the space vehicles and launchers themselves, to foster and accommodate for such progressive trends within the space sector, stringent and consistently applied cost engineering principles and practices are key to ensuring that estimated costs for new, unprecedented programs are representative, justifiable or at the least indicative of expected costs while being reflective of all available inputs and information at the time. As mentioned previously, a CE is a dynamic, constantly varying figure. So while it is impossible to predict exact program costs, consistently applying certain principles, practices and methods, like revising CEs at regular interval throughout the program life cycle to incorporate any changes and reflect new information, supports budgeting decisions and maximally assists in avoiding significant unexpected budget blow-outs [72]. Or if exceeded, helps to ensure that the discrepancy between the existing dynamic estimate, the available allocated budget and the actual cost is minimised. Furthermore, at various program phases the amount of defined information increases as program specifications and requirements crystallise. Here, 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 as defined and reviewed within this Thesis.

Numerous excellent resources exist, which list and describe general and specific cost estimation methods, models and tools applicable to the space sector. Actually many of the most extensive documents have been lengthy government funded projects and studies, a fact which only emphasises the importance of the topic within industry. In 1977 The RAND Corporation released a comprehensive study under Project AIR FORCE aimed at listing and assessing the validity of parametric spacecraft cost estimation methods for current and future applications with a decreased focus on system mass, while stressing the importance of concurrent utility of human logic and reasoning during cost model use and application [47]. Consequently, another two in-depth RAND studies into shortcomings of cost estimation methods were released in 2008 [65, 227]. In the RAND document which addresses cost estimation of space systems within the Air Force Space and Missile Systems Centre (SMC), Younossi et al. incorporated past lessons learnt, while providing future recommendations for improving the processes, methods, tools and resources based on the study's findings [227]. The second, document by Fox et al. is a dedicated handbook reference describing guidelines and metrics needed to review costs associated with space acquisition programs [65]. Both documents list and contain descriptions of some key cost estimation models, such as the Unmanned Space Vehicle Cost Model [214], (USCM), the NASA/Airforce Cost Model (NAFCOM) [170, 171, 188] and Small Satellite Cost Model [7]. More specifically, Meisl (1988) described the cost estimating techniques especially for early program phases [128], while more recently, Curran et. al (2004) provides an in-depth look on aerospace engineering cost modeling [40]. Other documents, such as NASA's Cost Estimating Handbook [135-137] and the online DoD Parametric Cost Estimating Handbook [42] also offer their own lists of various industry-relevant cost estimation tools and methods. Depending on the source, the scope of these lists is typically broad, covering many specific estimation methods for mission hardware and software, development, operations, management and risk analysis amongst others, but usually with limited, brief descriptions per entry. Alternatively, the literature will focus on a very narrow range of select models and methods, while omitting key others.

The remainder of this chapter presents the critical first steps, basic theory and material necessary for logical progression of the rest of this Thesis. It does so through offering a niche, robust summary for the main cost estimation methods, approaches and resources applied within the space sector for space hardware, with key existing commercial off the shelf (COTS) and government off the shelf (GOTS) tools and software products also discussed. Many of the commercially available products feature 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 CE for the anticipated program is nevertheless required to proceed further. For completeness sake, these models are, however, included and briefly discussed within the review. Manuals, handbooks and reports directly applicable to space sector cost estimation with a specific complete system level are also outlined, since they are seen as valuable resources for advanced methodology development for reusable launch vehicles. Furthermore, the Thesis features a hardware focus, and while it is clear that software and associated development, implementation and operations costs are essential for the realisation of every mission, the software-specific cost models are not included within the scope of this Thesis, since this is considered a sub-system component of an overall system. This Thesis approaches cost estimation at early program phase, and therefore from a top system level.

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

2.1 COST VERSUS PRICE

At the commencement of this Thesis work, it is essential to define the accounting terms of cost and price, briefly outline the significant distinction between their meanings, and consequent use of terms both throughout this Thesis, as well as within context of the cost estimation domain.

Cost and price are directly related, although frequently the two are used interchangeably depending on their context, which are not always correct to the definition. Cost is the amount considered from the side of the program organisation, and relates to the total amount paid or payable for the acquisition of all materials, property (goods) and services calculated for the project on the basis of an estimate of required effort, and other direct costs for all additional resources, such as manpower, equipment, real facilities, material, supplies, as well as travel and bought out items [202]. The term 'cost' is then frequently combined with an adjective, for example 'program development cost'. In contrast, price is what the consumer is expected to pay for the product, or the dollar value that a company will sell its product for or commit to a contract, meaning usually the total monetary value of the total project cost, with a calculated profit or fee additionally imposed [202]. In this respect, 'cost' is a sub-set of the term, 'price'.

Very often, the terms price and cost are used interchangeably. And while recognising the difference in the technical definition, in this Thesis, the term 'cost' (or 'costs', both of which are also used interchangeably), is predominantly used to describe how much monetary resources are required to fund the various phases of space programs in the early phases. This is because the perspective of this Thesis is from the producer's position. At the end of most cost estimations and calculations, the profit is also finally built in, thus technically making that value a 'price' value. However, whenever a profit margin is included in a presented figure, this point is always clearly identified and stated. Therefore, in recognising the technical difference between price and cost, the term 'cost' is adhered to throughout this work, since the area of research is cost engineering, and cost estimation, and the bulk of the resulting figures which are calculated, manipulated and analysed, are indeed costs, unless otherwise indicated.

2.2 SPACE SECTOR COST ENGINEERING & ESTIMATION

2.2.1 Cost Estimation in a Cost Engineering Framework

Cost estimation features prominently, essentially and diversely across all industries and domains in today's competitive and profit-driven environment. From small-scale, private, commercial initiatives such as how much a holiday or the purchase of a house might cost, right through to multi-billion dollar project bids within the construction, building and infrastructure industries – the question of cost firmly dominates and dictates business activity, initiatives and undertakings, and ultimately progress.

Within the aerospace industry, this is no exception. From cost figures simply being made up, like in the initial instance for the Concorde program [221], to labour hours and materials being tediously tallied to obtain crude cost estimates during World War II to advanced models and tools which have been developed and applied today, cost estimation is an integral element of program planning, management, overall system design and the cost engineering framework.

While cost estimation and cost engineering are distinct and separate disciplines, the two are intimately related. Cost engineering itself is a multi-faceted 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 [40, 84, 161]. By applying this definition, cost estimation is therefore a constituent component or subset of the larger cost engineering framework [107, 203], and is defined as the process of prediction of forecasting of product or output costs, resulting in an estimate [162]. A CE in itself, however, is not a static or deterministic value. On the contrary, it is a living variable which 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 to unforeseen factors and events which cannot be factored in during formulation of the estimate. Nevertheless careful, realistic budgeting is a crucial first step to underpin future program success, the basis for which is derived from a preliminary program CE. Hence it is logical to state that a justifiable, competent, informed CE reflective of all the data which is available during the early program planning is a solid foundation for an adequate and supportable program budget [212]. In turn this increases chances for a program's timely and efficient execution and ultimately realisation. An initially excessively high estimate may result in a lost contract award, while an underestimated figure would lead to cost overruns during project implementation [132]. So while there may be preliminary, limited, or insufficient information available regarding configuration, mission or environmental parameters of a mission early during a program, a pronounced need still exists for reasonable, justifiable estimates to be achieved. During such estimates, analyses performed assist in identification of key cost drivers which may be specific to each mission. In 1988, Meisl proposed that a 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 draws upon past experience and knowledge while adjusting for differences between the new and historical data [128]. And within the space industry even today, such a heuristic approach still forms the fundamental backbone of most cost estimation methods and models [72].

Here, during early mission phases, effective schedule management also directly integrates into the cost estimation framework, since the two are directly interdependent. It is clear that time delays result in increased costs not factored for in an initial CE, and therefore in cost overruns. With supporting processes and practices in place aiming to optimise available resources, facilities, funds and materials, careful and strategic schedule definition and management, both essential elements within cost engineering, determine the success of a program [56]. The ultimate objective is to meet project deadlines and thus cost targets while attaining required technical performance.

Overall, however, essentially three key elements can be identified to accommodate for effective cost estimation practice [128], as shown graphically in Figure 3. The most challenging includes access to reliable, detailed and complete input data. The second component is an appropriate mix of effective tools, methods and models to perform the estimate, which must be consistent with program phase and system definition at the time of the estimate [128]. 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 well as scientific and technical requirements applicable to each mission. This decision ultimately hinges on the program phase, the accuracy required, available information and risk analyses and is the responsibility of the program manager, and consequently the estimator themselves. Finally, a skilled cost estimator with sufficient knowledge and estimating experience is required to bring all the elements successfully together. The estimator is then responsible in amassing the right data, polling adequate information, asking the right questions and ultimately translating the latter into model inputs [128]. If any single part of this process chain or any key elements are missing, a cost estimate is unlikely to be indicative of program cost, and therefore not useful.

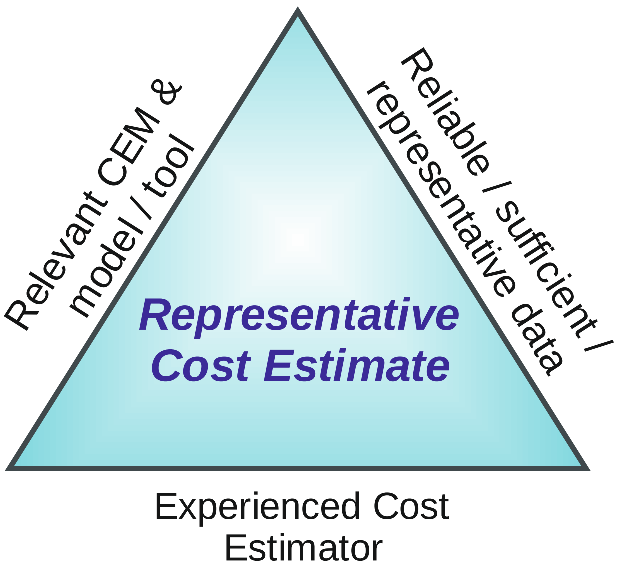


Figure 3: Key elements essential for a representative, robust and justifiable cost estimate [128]

2.3 COST RISK ASSESSMENT & UNCERTAINTIES

In addition to careful scheduling, to minimise the likelihood of cost overruns 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 CE, when a detailed understanding and assessment of potential cost risks is essential. Here it is important to define the meaning of 'risk' and differentiate this from 'uncertainty'. Risk addresses the probability of a certain event occurring and its consequent impact on a project, and therefore risk can be in part preempted for and factored in within an estimate. Uncertainty, however, relates to an unforeseen, unexpected event which becomes known only after it has occurred [173]. So while potential risks for a project can be identified, analysed, planned for and managed, the uncertainty element for unexpected costs during project lifetime is impossible to fully address during the early program phase. Furthermore, risk and uncertainty are not mutually exclusive, with the modeling of uncertainty directly translating into risk [42]. Therefore any given project can never be entirely risk-free, although various cost risk quantification analysis methodologies, strategies and approaches exist to address this aspect. So while cost risk estimation is an extremely important element within the cost estimation process and cost engineering framework, it is not delved into in great detail within the scope of this work. Interested readers may refer to the following references for further details on cost risk assessment and management [13, 42, 65, 137, 175, 212].

Another type of uncertainty not directly associated with unexpected events arising during a program relates to a formulated CE itself. This uncertainty is associated with the development or implementation and thus usefulness of any cost model underlying the estimate, and includes factors like omission of a key cost driver, data inconsistencies, and model limitations and simplifications due to lack of data [42]. Additionally, this uncertainty also encompasses an estimate's accuracy based on available program data, and also the correlation with a program's phases. Normally, early in a program only few specific mission details are available based on which a first CE can be formulated. Therefore uncertainty around the initial estimate is high. As the program advances through development and into implementation, specifications and mission requirements begin to crystallise. Concurrently, the initial CE should be treated like a dynamic figure, reassessed regularly and updated with actual costs. In this way the cost uncertainty associated with the first preliminary estimate is reduced with every iteration, supporting the management function to make informed decisions with the best available information. It has also been shown in practice that costs are more likely to overrun than under-run [211], with the initial cost estimate baseline generally tending to increase as the program develops. Here, the baseline cost refers to the most likely CE figure given no abnormal problems occurring and normal working practice.

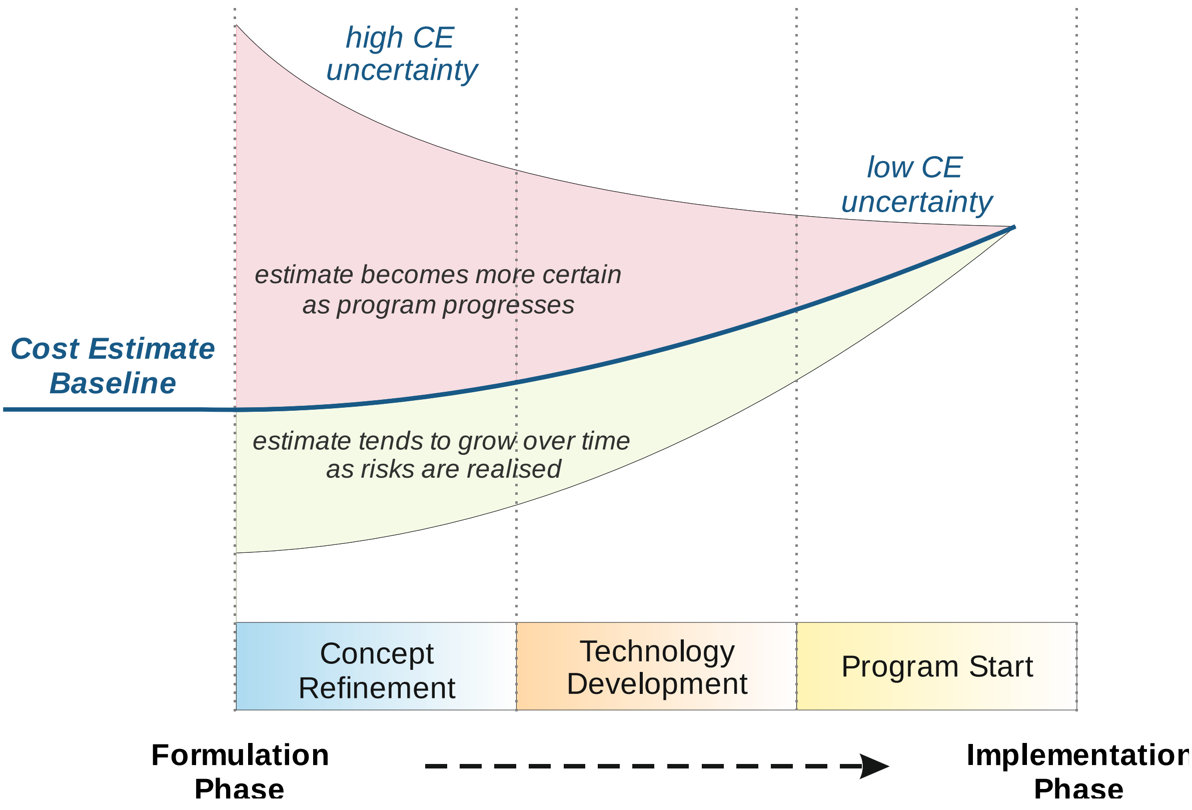


Figure 4: Cone of uncertainty illustrating estimate uncertainty associated with baseline cost estimates as it is iterated throughout the program phases [212]

The latter processes and principles are graphically illustrated below in Figure 4 in what is referred to as the cone of uncertainty [211], where the horizontal axis represents project milestones and phases, while the vertical axis indicates estimation uncertainty and variability. It can be seen that underrun of costs during early program phase is significantly less likely than a cost overrun.

2.3.1 Cost Estimation Diversity within the Space Sector

Cost estimation within the space sector must be able to encompass a diverse scope of missions ranging from simple satellites to reusable launch vehicles and manned spacecraft. Each project is then further broken down into its technical system and sub-system deliverable elements as well as organisational components. Therefore at various stages of a program, separate cost estimates are required to address program development and manufacture of both hardware and software, operation costs, life cycle costs (LCC), management and organisation costs. Other cost assessments, such as advocacy and independent cost estimates (ACE and ICEs) are also required, which are separate, although associated with or embedded within the context of an existing LCC estimate [136]. To facilitate for all these cases, proper selection of appropriate estimation methods and tools is vital, since this positively impacts overall project costs. Many variables and considerations dictate this choice, including available technical definition detail and program phase, the scope of the effort to be costed, availability of historical cost data and program maturity coupled with the cost estimator competency and experience [135]. While it is important to recognise these differences, the methods and processes themselves remain fairly consistent.

To address the diversity for cost estimation purposes, numerous proprietary, dedicated models exist to estimate various aspects of mission costs for both software and hardware. These include cost models for subsystems and space instruments (SICM, NICM, MICM) [65, 74, 135], systems engineering processes (COSYSMO) [29], operations and processing (SOCM, MESSOC)

[134, 174, 194], as well as ground development and risk assessments (ACEIT, Crystal Ball, @Risk) [136]. Even a model for determining the cost of performing a cost estimate has been addressed [47, 159]. This Thesis, however, specifically focuses on commercial off-the-shelf (COTS) cost estimation approaches applicable on a more global system level for an overall space flight project with a hardware focus. The methods of focus here are normally best suited and particularly necessary and applicable during the initial phases of program development and mission planning.

2.3.2 Cost Engineering Oriented Organisations

The importance of effective, efficient and accurate cost engineering practices, as underpinned by effective cost estimation throughout a program life cycle, is unquestioned. Yet despite this fact, cost estimation methods and practices within industry remain largely undefined, with a lack of understanding stemming from limited education, training and support available to the cost engineering community. It is logical that an ability to control costs directly hinges on closely adhering to set guidelines and learning from previous projects while simultaneously reacting to current circumstances efficiently and effectively [123]. Yet prevailing organisational inconsistencies concerning the absence of formal structure, documentation and processes for cost estimation methods and practices [161] combined with ineffective retention of past experience, knowledge and 'lessons learned' continuously results in inefficient outcomes. And with deadlines and competitive bidding for projects adding time pressure to the mix, unstructured, hasty cost estimations result in repeated significant budget overruns, particularly within larger organisations and agencies like the US DoD [226], ESA [43, 44], and NASA [210].

These issues and inconsistencies have underpinned the emergence of numerous professional, industry and Government cost estimation groups and organisations whose core fundamental philosophy and aims are to promote the standardisation of cost engineering principles within industry. This is done through encouraging effective knowledge management and retention, and pooling available resources to establish and maintain a common basis and standards for cost engineering practice. Amongst others these include the International Society of Parametric Analysts (ISPA) [90] and the Society of Cost Estimating and Analysis (SCEA) [189] (both of which merged together in November 2012 to form the International Cost Estimating and Analysis Association (ICEAA)[88]), the Space Systems Cost Analysis Group (SSCAG) [196], the Association for the Advancement of Cost Engineering through Total Cost Management (AACE) International [16], American Society of Professional Estimators (ASPE) [11], Association of Cost Engineers (ACostE) [204] and the International Cost Engineering Council (ICEC) [87]. While having a slightly different focus, fundamentally all of these organisations share the common goal of cooperating and promoting better, more consistent cost engineering principles and cost estimation practices and standards.

2.4 COST ESTIMATION METHODS

Predominantly, four main, commonly accepted and staple cost estimation methods (CEMs) form the backbone of tools applied for cost estimation within the space sector being:

- Engineering Build-Up
- Analogy
- Parametrics
- Expert Judgement

The detailed engineering build-up (also known as bottom-up) estimation approach encompasses the synonymous techniques of engineering build-up, grassroots or detailed cost estimations. Analogy and parametric cost estimations are then part of the top-down methods or statistical approaches and can be classed as gross estimation methods. The Rough Order of Magnitude (ROM) approach is also outlined in the NASA Handbooks as a commonly utilised method. Finally, expert judgment (EJ), arguably, is another method commonly relied upon to generate cost estimates, although there does not appear to be a clear consensus on whether or not it constitutes an official method [83].

Several of the techniques can also be strategically combined to formulate a hybrid estimate. Alternatively, if this is possible, an existing tool or model can be taken and potentially 'tailored' to a particular mission's specifications through manual input or calibration. Given recent radical advancements to space access and technologies with the political environment encouraging commercial space access coupled with the advent of space tourism, it is more important than ever to have the capability to obtain representative cost estimates. Currently, given the promising advent of commercial launches [58, 205], ultrafast space transportation [52, 104, 167, 183, 191, 208] as well as the potential for space tourism [5, 23, 37, 70, 71, 106, 143, 146, 149, 167, 197, 200], this applies particularly to launch vehicles with manned capabilities.

Yet a lack of precedent and consequently very limited data exists for this category of spacecraft, limiting the suitability and application of the most commonly implemented CEMs within the space sector.

The key CEMs, including the core three, as well as the supplement ones currently recognised and utilised within the space sector are concisely summarised below, and their respective attributes, strengths and shortcomings also provided.

2.4.1 Parametric Cost Estimation

Parametric cost estimation is applied prolifically within academic, research, industry and government applications, offering a means to economically approach proposals, negotiations or basic program cost assessments which hinge on cost or price data and estimation. More specifically, the parametric approach is extensively applies in advanced planning studies, contractor proposal validation, as well as commonly being used within planning and budgeting during acquisition processes [42] with the CEM having official acceptance by the Federal Acquisition Regulation (FAR) for proposal preparation [59]. It is also the foundation of numerous key models and software used for early phase cost estimation of space programs, such as the TransCost Model [100-102], the USCM [214] and NAFCOM [171, 188]. A particular distinction of this approach is that it can be used when little is known about the design to be costed, or when a readily applied validation or consistency check of an existing estimate is required.

Best applied within early program phases, a top-down approach is assumed since only basic requirements are usually available, while more detailed system and subsystem criteria are not yet established. Only basic inputs which can be easily projected before concrete of final design and specification information is available, and which logically relate to cost, are required. Such often preliminary inputs are then sufficient to provide adequately representative cost results

[81]. A series of mathematical relationships called cost estimating relationships (CERs) are then determined based on historical data. CERs seek to relate cost to physical, technical and performance parameters that are known to strongly correlate with program costs. Complexity factors, or specific manually defined user inputs can then be applied to address deviations from underlying CER parameters and a particular mission of interest.

However while it is commonly believed that early mission costing cannot be done effectively in any other way, a difficult aspect of parametric cost estimation is the actual CER formulation itself. A cost model is only as robust and reliable as its underlying database of projects, so database quality and size impose limitations on CER credibility [60]. Significant amounts of time and resourced are devoted to the collection of quality raw data, which then usually needs to be adjusted for consistency, or normalised, to make it comparable and compatible with other relative data. The challenge lies in obtaining sufficient, representative quantities of cost data, yet alone in finding accurate, relevant and sufficiently detailed numbers and figures. The DoD Parametric Cost Estimating Handbook [42] identifies nine main data sources which include basic accounting records, contracts, cost reports and proposals, historical and technical databases, other information systems and organisations, and functional specialists. Here, a key difficulty concerning access to data arises due to the classified nature of most projects within context of a competitive space industry. In fact the data collection process is often the most time-consuming, strenuous and costly aspect in cost estimation and for accurate CER formulation [137]. Even extracting data retrospectively from projects poses challenges relating to contractual and administrative complexity [100]. Furthermore, all developed CER credibility must be verified through comparison and sufficient correlation to existing projects. The interested reader is directed to consult references [42, 89, 212] for more detailed information and discussion about quality data collection, adjustments and normalisation for CER development.

In addition to the challenges of CER formulation, the CERs, once developed, may not be relevant when new technologies or requirements beyond normal boundaries of the underlying

CERs are introduced [109]. In this respect, assumptions must be made that historical data are representative of future conditions, rendering CERs only effectively applicable to projects similar in nature as the CER data itself. A solution here is to employ an alternative estimation method which can be used as a sanity check, or to combine several approaches if it is possible to segment the cost estimate into constituents which can be each addressed by various approaches.

2.4.2 Engineering Build-Up

Known synonymously as engineering build-up (EBU), bottom-up, grassroots or detailed cost estimation, this very specific analytical approach is generally applied to a mission when all parameters at system and sub-system levels are known and clearly defined. Cost estimations are then performed at the lowest level of detail, and require a breakdown of the overall project into smaller work packages, taking the form of a Work Breakdown Structure (WBS), which also provides the reference for the Cost Breakdown Structure (CBS). The low level cost estimates usually come directly from the engineers and experts performing the designated work, the sum of which then constitutes the overall cost estimate for the program. It is common for labour requirements and non-labour 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 [135, 136]. Therefore EBU is inherently an extremely resource-intensive approach with significant associated costs, time and effort. Extremely careful attention must be paid to the organisation of the WBS to avoid duplications and omissions of tasks, which would then reflect directly on costs [173].

Inability to quickly adapt to scenario changes or specifications, requirement and design alterations, which are frequently made during early planning phases, is a weakness of this CEM. Given any modifications, new estimates must then be built up again. So ideally, detailed and advanced low level specifications are necessary for application of EBU. These are usually not available during the beginning stages for mission planning, which renders the approach unsuitable for application during early project phases.

However if applied during later project phases (i.e. Phases A – D) when sufficient details are available, the resulting cost estimate can be extremely accurate since it is unique to the specific industry and application [212]. Credibility is established since the total cost can be broken down into constituent cost elements, providing clear insight into major cost contributors, making elements of the estimate reusable within individual project budgets, and making the cost estimate defensible [135]. Insight is also gained into major drivers and contributors to overall cost, which can be useful for program review and analysis.

2.4.3 Estimation by Analogy

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 costed [137]. Intensive analyst judgment is required regarding the similarity of two projects, followed by adjustments made for any differences, such as project size, complexity, team experience or technologies, between them. Although necessary, such judgment is often considered subjective [212]. Application of the method is also limited since identifying a suitable analog or adequately detailed technical, program and cost data are often an extremely difficult task. If successfully identified, reliance for the comparison is then based on a single data point only. Therefore sufficiently detailed data of the 'compared' system as well as the 'new' system under consideration is essential. The method then hinges 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 various program phases at minimum cost, since analogy can be applied even before specific program specifications are known. And if a close suitable analog is found, the resulting estimate is then based on sound factual historical data and is defensible.

Analogy can be further broken down into Loose Analogy (LA) and Close Analogy (CA). LA requires only few 'loosely similar' data points not closely related to new project, and adjusts relevant past broad experience for moderate changes in complexity. CA requires very similar data points from either another program or through technical development studies, and calls upon direct past experience with adjustments made for only minor changes in complexity [109].

2.4.4 Estimation by Expert Judgement

Expert judgment (EJ), or expert opinion, is a commonly applied approach despite being subjective in nature of the assumptions and assessments which are formulated by the estimator based on their own experience and knowledge. According to ESA's Engineering Costing Techniques specifications, EJ is classed as an cost estimation method [72], contradictorily as both the backbone and limitation of the analogy approach [60], as knowledge based cognition [130] and simply guessing [97] in other literature. A widespread feeling exists that the EJ approach is particularly intuitive and as such, consequently liable to personal knowledge bias and sensitive to political pressures [83]. Yet while frequently criticised and often misunderstood by those outside the cost estimating community [161], EJ is consistently and extensively applied in the generation of cost estimates [72, 163]. Applicable during all project phases, EJ can be beneficial when historical data are scarce or unavailable. While gathering a group of experts may require some resources, once achieved, EJ requires comparatively minimal effort, time and cost and is often used as a sanity check for CER results where implemented data are significantly beyond the CER data ranges [212]. In fact various more advanced techniques have been designed with EJ at their core. One example, the Delphi method, relies solely on group engineering EJ obtained from several professionals, to provide the cost estimator with latitude in their cost prediction [135].

Another useful approach is the Analytic Hierarchy Process (AHP) developed by Dr. Thomas Saaty [164, 165]. AHP decomposes a problem into a hierarchy of specific criteria and alternatives. Expert judgment is then employed to determine and assign specific rankings, or priority scales through pairwise comparisons to the established criteria [73, 95, 165], and after some normalisation of the rankings, an overall relative score can be deduced per option. An advantage of AHP is its capability to significantly reduce complex, multi-faceted decisions to a series of simple pairwise comparisons, in this way capturing and reflecting the subjective and objective aspects of a decision [164]. Another strength is the method's applicability to a decision process despite the absence of quantitative ratings, since assessors and experts are always capable of determining which criteria dominate over other criteria within a pairwise comparison context [95]. A recognised weakness pertains, however, directly to the same weakness as that of the EJ element itself, namely the fact that the EJ involved can be inconsistent or prone to knowledge or experience bias. Ways to gauge any inconsistency and improve the EJ element of AHP are challenging [95]. Despite this, AHP constitutes a powerful tool for comparisons of alternative design concepts based on qualitative and quantitative criteria.

2.4.5 Rough Order of Magnitude Estimation

The NASA Cost Estimating Handbooks [135-137] define the rough order of magnitude (ROM) estimation as one of 'four generally accepted estimating methodological approaches' [137]. Also referred to as a vendor quote (VQ), this 'first order' methodology is useful early in mission planning phases to estimate costs via 'rules of thumb' that are either already known from past experience, or readily available based on polling of current industry-wide data [109]. Applications of the ROM method for cost estimation include hardware, facilities and services, usually when a project has not been started and when requirements are not explicitly specified.

2.5 COST ESTIMATION METHODOLOGY SELECTION

In order to initiate a relevant, indicative and valid cost estimate for a mission, identification of the most appropriate CEM which can most realistically indicate program costs on a case to case basis is essential. While the method by which the cost estimation will be performed is normally decided by the project manager, the responsibility to understand, select and verify the pedigree and applicability of a suitable model which utilises the chosen method, then falls on the estimator and is essential to the accuracy of the estimate [137].

Throughout the program life cycle, information, the levels of details and sometimes key requirements and specifications relating to the project change. Concurrently with each phase change, it is necessary to reevaluate the cost estimate and update this to incorporate the new information which comes to light. The various CEMs available are to varying degrees appropriate for use during the different program phases. This suitability and adaptability of the different CEMs is qualitatively shown below in Figure 5, which particularly focuses on the essential pre-phase A activities, and does not extend beyond the production Phase D. Here, relevant to the focus of this Thesis work, we identify the CEMs suitable to the early, pre-phase A development. As is highlighted in red in Figure 5, flexible, system-level CEMs are applicable during the early stages, while it may be premature to use the more detailed and resource intensive approaches like EBU. As can be seen, the main CEM during the early phase of interest is the parametric approach. ROM and analogy estimates are also featured, while EJ is applicable consistently throughout the entire program lifecycle.

2.5.1 Cost Estimation Handbooks, Reports, Manuals & Sources

Various different sources for cost estimation approaches, models, practices and standards exist. In addition to official commercial models and software, a selection of detailed manuals, handbooks, reports and other various sources exist addressing cost estimation..

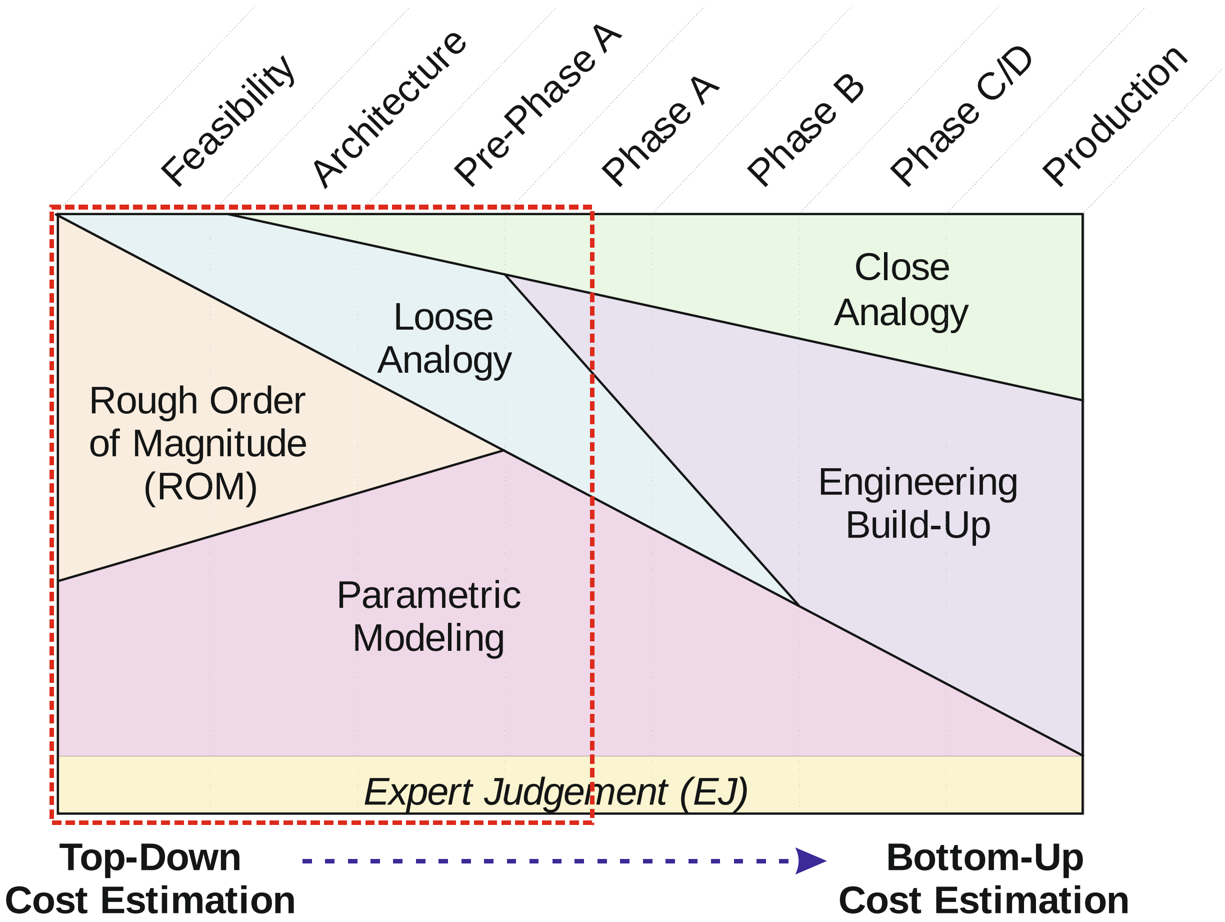


Figure 5: Qualitative application of CEMs according to project phase [109]

Prominent handbooks include the NASA Cost Estimating Handbook versions [135-137] the SSCAG Space Systems Cost Risk Handbook [137], the FAA Life Cycle Cost Estimating Handbook [60], the ISPA Parametric Estimating Handbook [89], the DoD Parametric Cost Estimation Handbook [42], the RAND Project AIR FORCE Reports [47, 65, 227], and the GAO Cost Estimating Assessment Guides [210-212], amongst others. These numerous sources, however, generally tend to focus on particular elements of cost, such as cost risk or life cycle, or a particular approach, as relevant to their most common application.

As a part of this Thesis, a comprehensive literature review of relevant literature was conducted and published to determine CEMs and consequently tools, models and resources which utilise them. This review can be found in ref. [209] for the interested reader, and allowed the identification and selection of methods, as well as tools, models and resources for application to large scale, complex programs during the early program phases. Extracting information from this research, relevant models and tools were identified for effective practical application to the SpaceLiner industry case-study.

2.6 THE AMALGAMATION APPROACH TO COST ESTIMATION

The wide scope of available cost estimation resources means that cost estimators must select the most suitable cost assessment means for a given project during a specific program phase. Such choice is subject to constraints including laws and regulations, as well as license and subscription fees for most software packages. The cost estimator must be capable to justify their choice of cost model, as dictated by project purpose and level of design details available [135].

Here, two important things should be emphasised. The first being a distinction between a cost estimation methodology (CEM) and a cost estimation tool or model. CEMs refer to an underlying approach or principle of performing a cost estimate, like the parametric or analogy approaches. In turn, tools like PRICE-H or 4cost, or the various available models like TransCost, refer to commercial or government products which are based around a specific underlying CEM. It is essential to again stress that while a suitable method, model or tool is key for an estimation, the science of cost estimation also incorporates the elements of good data, as well as an experienced, knowledgeable estimator. Together, the three elements combine to produce a robust, justifiable estimate to support a representative, realistic project budget, as previously shown in Figure 3. Within this chapter, the development, logic, structure and application of the new Amalgamation Approach, as developed through the work conducted within this Thesis, is introduced and explained.

2.6.1 Multiple CEMs, Models & for Cost Estimation

In order to obtain an overall 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. Any associated profit margins should then also be incorporated to obtain the price (see Chapter 2.1). The CEMs and range of available models, tools and resources available are more suitable in varying degrees for use in particular circumstances and for specific applications during different project phases, as has been demonstrated in Chapter 2.5. It is therefore common for estimators to loosely combine multiple different CEMs and also tools to obtain cost estimate for an overall system. It is known that this approach can maximally support the various associated engineering tasks involved for large projects, while also allowing for the comparison of cost models [203]. For example, in their paper which compares ESA and NASA cost estimation approaches and end results for a human mission to Mars, Hunt and van Pelt (2004) list the CEMs of parametric CERs, PRICE-H, SEER-H, historical analogies and vendor quotes as the chosen methodologies to arrive at a preliminary estimate [85]. However, although applied and described in select research papers, until now, such a combination approach has remained predominantly, highly intuitive, with no formal structure being outlined nor defined for its application.

2.6.2 Amalgamation Approach Definition & Application

Many of the significant cost estimations, in particular for large scale complex projects like those undertaken within the space sector, rely on one main cost estimation source, model, tool or CEM, with perhaps a loose sanity check from another estimating source [60], and sometimes also numerous models and tools. The AA definition hinges on a cost estimate, whether at a macro- or micro level, being derived through a formalised cross-check with multiple other means, whether through a different CEM or tool and model. In any case, a minimum of three cost estimate results are required and contrasted amongst each other. In this way, multiple points can be used by the estimator as reference, with strategic analyses then employed to justify selection of a most representative cost estimate or range. In this instance, simply a pairwise comparison would be no different to a sanity check, and given a significant cost estimate delta, might make it challenging to determine which out of two estimate holds the most uncertainty. Three estimate results which are thoroughly and strategically executed, however, should allow for the cost estimator to make an easier identification of where any inconsistencies or issues might originate from.

This Thesis therefore proposes a formalised standard, the AA, for such an approach, which harnesses a strategic combination of multiple, justifiably selected CEMs and consequently models or tools to increase the reliability and representativeness of the cost estimate. Through AA, an added redundancy is incorporated into the cost estimate through multiple results which can then be analysed and contrasted. Such a seemingly basic comparison process increases the cost estimation fidelity through elimination of factors such as human error, while concurrently reducing uncertainty and cost risk, which might arise when a previously applied method has specific limitations known by the estimator, which undermines credibility of the resulting cost estimate. In essence, AA can be paralleled to life critical engineering systems within a mechanical and hardware sense, or, for example, avionics networks on manned space craft, which must always feature system redundancy. A similar concept and redundancy configuration, albeit relevant within a financial context to the budget of a space program rather than human life, is therefore proposed for cost the estimation function, through utility of AA.

Furthermore, AA is designed specifically for application during early program phase when uncertainty of the estimate is inherently very high in accordance with the cone of uncertainty principles already presented in Figure 4. At this stage, also, the relevant CEMs, as well as models and tools are also relatively fast to implement, thus accommodating for relatively quick and simple changes of parameters since inputs are generally higher-level ones.

Here, it is assumed that given the respectively large budgets associated with international, complex programs in the space industry, due to the large scale of investment and ramifications of failure, that sufficient resources are available to adequately support a solid cost engineering team and its cost estimation experts, with funding allocated for necessary resources. Core requirements are a sufficient quantity of staff to effectively execute the cost estimation function, as well as resources for acquisition of any necessary cost estimation tools or models (license fees).

The proposed AA technique can ideally be utilised for three different although complimentary purposes, at three different 'modes' of function. These are introduced below:

- AA contribution within the formulation of cost estimate on a micro-scale, internal to that estimate (AA_{MIC})
- Formulation of an independent, stand-alone, 'prime' cost estimate at a macro-level based on AA (AA_{MAC})
- AA application to an existing cost estimate to serve as a sanity check or validation for that existing estimate (AA_{VAL})

For each different purpose and mode of application, however, slightly different standards, rules and requirements apply, as defined and outlined in more detail in the following sub-chapters below.

2.6.2.1 Sub-element AA Cost Estimation

The first application of AA, AA_{MIC}, would be a sub-function within context of formulation of a single cost estimate which is already based on a certain CEM, and deals with the unique requirements and specification for a particular project. In this case, internal to that estimate, different CEMs might be able to better address the individual and various project elements, components or processes to be costed. An example of this is where a system model, such as the Small Satellite Cost Model (SSCM), a parametric-based tool, is applied, but where the resulting cost estimate is expressed as a sum of constituent sub-system cost estimates at lower levels. Here, the estimator may opt to take out particular sub-system estimate components and replace them with, for example an analogy or bottoms-up estimate if more in-depth details are available for that particular sub-system, or if past experience can offer a more representative cost for that segment. This is an example of AA application on a micro-scale (AA_{MIC}), contributing to a more reliable estimate in a manner internal to that estimate. This principle is illustrated graphically in Figure 6. A typical SSCM output is shown, but where selected cost elements (in this instance, the propulsion sub-system) estimate as calculated by the initial SSCM parametric model based on inputs, is replaced by costs (in this instance, cost) obtained through other CEM or tool known to be more representative. In this example, the analogy CEM is applied, where the propulsion engineer might know of a similar propulsion module which already exists and costs $18.5M, based on firmly known data. The SSCM model-calculated cost element is thus removed, and replaced by the AA-deduced value. All consequently affected values, shown crossed out in red in Figure 6, are then revised and adjusted. While the example shows only one element being affected by AA_{MIC}, more elements can be influenced and revised, and more than one CEM or even tool, can be used.

For the AA_{MIC} the sub-system nature of the initial cost estimate to which AA_{MIC} is internally applied to, might imply that this initial estimate must be a bottom-up estimate, and therefore only possible to be formulated later on during a program phase. However, even with the case of the high-level system TransCost parametric model which can be applied even during very early phases, a basic component breakdown to at least a secondary level of detail (i.e. engine, rocket stage, booster etc.) AA_{MIC} can still be applied when one of the component costs produced by the baseline cost model is known or shown to be different through application of another CEM or tool or model.

As the program develops through into the later program phases, the AA_{MIC} method is rendered less applicable. As the WBS breakdown becomes more detailed, encompassing lower system levels, and the EBU CEM increases in relevance, by its definition, each sub-item is then costed independently in line with the definition of this CEM.

	Estimate (FY13$K)				% of	% of
	Non-rec	Rec	Total	Std Error	Sub-level	Sys-level
Spacecraft Bus Subsystems						
Power	1.563	2.345	**3.909**	2.244	7,2%	
Structure	4.089	3.626	**7.715**	3.302		
ADCS	2.085	2.170	**4.254**	1.251		
Propulsion	~~6.099~~	~~9.540~~	~~**15.659**~~	5.724		
TT&C*	3.813	3.520	**7.333**	9.964		
C&DH*	7.402	6.833	**14.234**	0	26,3%	
Thermal	546	484	**1.029**	502	1,9%	
Spacecraft Bus	~~**25.597**~~	~~**28.517**~~	~~**54.114**~~	**12.239**	**100%**	61,4%
IA&T*	5.738	5.902	**11.641**	6.837		13,2%
PM/SE	8.451	9.156	**17.607**	10.212		0%
LOOS*	0	4.755	**4.755**			5,4%
S/C Development & First Unit	~~**39.787**~~	~~**48.329**~~	~~**88.116**~~	**17.344**		**100%**

Known cost through analogy CEM
18.500

Value to revise

Figure 6: Example of AA_{MIC} application within context of the parametric SSCM cost estimation, where the analogy CEM is used to replace the initial cost estimation model output [7]

2.6.2.2 Prime, Independent AA Cost Estimation

A second and most substantial and intensive application of the AA, the AA_{MAC} mode, is the formulation of an independent, stand-alone cost estimate at both the macro- and micro-levels. Multiple CEMs and/or tools and models are used concurrently, to arrive at their independent cost estimates, which are then contrasted, analysed and consolidated in a justified manner to achieve a representative cost estimation range.

While multiple tools and models should be applied, they should always be applicable to the program phase, as shown previously in Figure 5. Hence, it is common that the same CEM underlies at least two, or even all of the multiple models and tools. This is perfectly in line with cost estimation theory since during early program phases, the prominent CEM of choice is the parametric method. Other CEMs, such as analogy and EJ can also be combined and applied within the AA_{MAC} context. The multiple results are then analysed, and consolidated, with any discrepancies noted and addressed. Here, second to the cost estimation per tool or model, the analysis process itself forms the bulk of the work, and often results in numerous iterations of calculations before a reasonable consensus and firmly justified synthesised cost range is achieved. The skill, knowledge and expertise of the cost estimator are essential during this process. The cost consolidation and result synthesis process should comprise of a concise and thorough description of analyses conducted, assumptions made and respective, detailed justification for the final cost range selected. Being an early phase CE also indicates that a point figure is inappropriately precise at such an early stage.

In order for AA_{MAC} to be effective, (unlike AA_{MIC} which has no minimum number of cost results for effective application of the method), a minimum of **three** separate CEs are required to address the case where significant discrepancies exist between cost estimation results. In the case of only two results, while redundancy is implemented, it would be very difficult to identify the source of uncertainty given only a pair-wise comparison. However, with three values for comparison and analyses, yet another added degree of redundancy is achieved between three independently derived results, making it easier to analytically identify the source of any discrepancies or significantly large variations. Besides, significant variations or discrepancies between results would indicate a higher uncertainty of the final CE, which is an important finding and outcome in itself. Such discrepancies indicate to the estimator to seek and identify reasons behind the non-consensus, focusing on where and why they night arise. And if results differ dramatically, then the further analysis which is elicited leads to a synergy of multiple results based on analyses of the cost engineer. This higher level of analyses and more solid justification are enforced through AA_{MAC} than would result from a single-source estimate value. If a clear consensus and consolidation of the multiple AA_{MAC} cost results reflected through a reasonable cost range are still difficult to attain, either a larger CE range might be appropriate, or a higher uncertainty interval associated with a more narrow cost range, might be assigned. Both outcomes would nevertheless provide vital, transparent information to program management about the accuracy and reliability of the final estimate. This element is usually missing, or not as explicitly and clearly reflected in standard, single, stand-alone CEs. Alternatively, a greater uncertainty, or larger cost range might incite an increased urgency to re-valuate and reassess the results as soon as new, more specific information about the project becomes available.

For efficient use of $AA_{MAC,}$ a WBS of the program is required to allow for a cost breakdown to be established at a high program level, but also at a lower WBS level, if needed. Here, it is also necessary to establish an AA_{MAC} interface which supports the AA function. As such, a simple yet highly effective Excel-based tool, the Amalgamation Approach Interface Tool (AAInT), was designed and developed within the scope of this Thesis to address the need for a clear, simple and specialised interface which facilitates for entry and quick analysis and dissemination of at least three sets of results in line with the AA_{MAC}. This interface is able to show the multiple cost results in a convenient and clear way that allows the cost estimator to make a convenient and fast comparison and consequent analysis of multiple figures. AAInT is also flexible and can be customised by the user to incorporate WBS structures of various depths depending on the scale of the program. Furthermore, and more essentially, the AAinT supports importation of cost data directly from the source into dedicated spreadsheets at the discretion of the user, to avoid the potential for human and other transcription errors. Caution must nevertheless be exercised when linking the input cells on the main calculations sheet to the various cost figures in other sheets. A more detailed description of a customised AAInT example is provided later in this Thesis in Chapter 4.8.1 with respect to the chosen case-study.

A drawback of AA_{MAC} is that the derivation of three values using three different methods or models is of course more resource consuming, especially if more than three values are derived through application of different CEMs, models and tools and the costs compared and analysed. However this is then a question of trade-off between the increase of resources and expected increase in CE certainty, and should be decided on a case-to-case basis, with consideration to given available resources for the cost estimation function.

The AA_{MAC} process and the associated steps for a minimum of three tools are shown in Figure 7. All key AA elements which are new to standard cost estimating practice are highlighted in purple. At the highest AA_{MAC} level, and reiterating theory presented previously in Figure 3, the three elements required for a justified CE are shown, being reliable, representative and sufficient program data, suitable models or tools to support estimate execution, and a competent cost estimator. The data then supports the estimator in creating a program breakdown of elements to be costed (usually in a WBS format) at the necessary level of detail. Cost calculations are performed using multiple models, and results entered into an AA interface, AAInT, after which they are contrasted, compared and any significant cost deltas analysed to determine the reason. If the analyses determine an inconsistency or error, this is corrected and another cost run done via a crucial iterative process. Thus, when the final result it reached, any inconsistencies or errors are maximally eliminated. Not all cost deltas necessarily indicate an error as they could result from different model mechanics. All cost estimator conclusions, reasoning, logic and justifications should be fully documented and explained. The final step is then consolidation of multiple results into a cost range based on the analyses performed and on the latter reasoning, justifications and conclusions to reach the ultimate AA_{MAC} result.

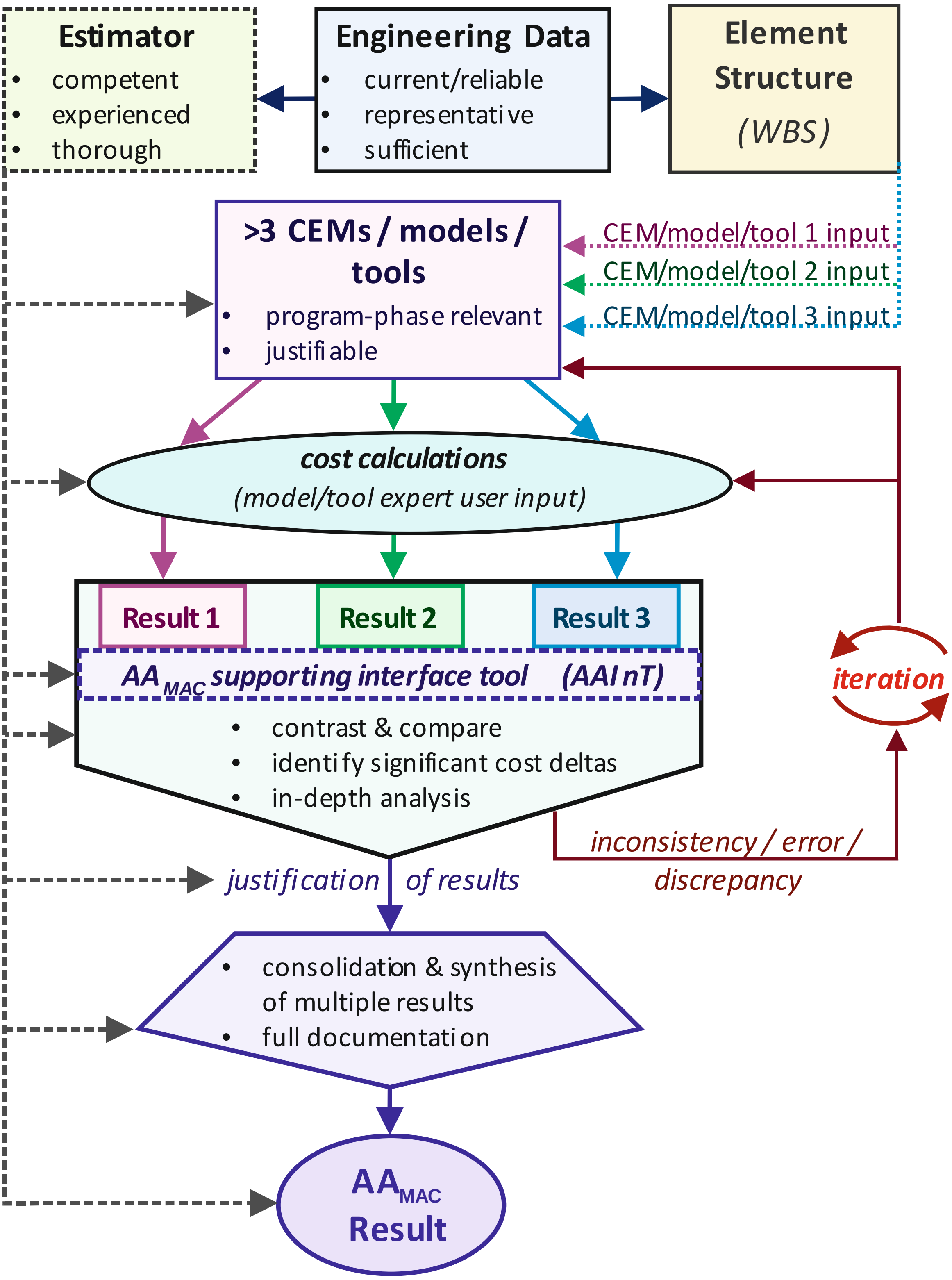


Figure 7: Graphical representation of AA_{MAC} showing key inputs, logic and processes

2.6.2.3 Validating AA Cost Estimation

Alternatively AA can be implemented as a sanity check or validation (AA_{VAL}) to an already existing estimate which might need to be validated or confirmed. The assumption here is that such an existing estimate was compiled through use of the standard single CEM, method or tool. Here, uncertainty may arise when the previously applied method has specific limitations known by the estimator, which undermines credibility of the resulting CE.

As previously described, in line with the AA_{VAL} process, other CEMs, methods or tools are then applied to existing, identical inputs used during formulation of the initial CE, and the result of the second cost estimate, compared and analysed alongside the already existing figure. Here AA acts as a staunch sanity check for order of magnitude of the original estimate, to support it, or if the difference is significant, may indicate that an alternative CEM or tool should be applied, or that the original estimate should be questioned or reconsidered if the two are drastically divergent. Although here, it is important to be aware that the divergence could lie in the sanity check method itself, in which case this distinction lies to be made by the estimator based on available data as well as their expertise and experience, two of the identified elements for a representative cost estimate.

2.6.3 AA Key Requirements

For the AA_{MIC} and AA_{VAL} modes of AA there are no specific requirements or limitations, other than first the selection of an appropriate CEM, followed by choosing a relevant model or tool, if necessary. For the standalone AA_{MAC} approach, however, and as already outlined in Chapter 2.6.2.2 above, a minimum number of three models or tools must be identified and acquired to allow concurrent estimation of program costs. Out of the three AA modes, AA_{MAC} is the most structured, formalised and resource intensive mode. After this, the individual costs and model results are contrasted, compared and analysed in what is essentially a cost estimate redundancy process. With a high level of analytical activity necessary once the first multiple set of results is obtained, AA_{MAC} can evolve into a highly iterative process where initial analysis uncovers any inconsistencies. Inconsistencies identified may be related to human error, EJ bias, the inaccurate translation of technical details into model/tool parameters, among others, and need to be rectified. At each iterative loop, however, the cost result uncertainty is reduced, and the final results honed in upon.

Since numerous CEMs exist, many combinations of different methodologies are possible, in addition with various combinations of the available tools and models based on them. Decision of which particular methods to combine and apply, remains the responsibility of the project manager in close coordination with the cost estimator themselves. Here, the experience and knowledge of the estimator is of crucial importance [128]. Such a decision hinges on a number of determining factors which include the available information with respect to program definition, specification and requirements, expected level of cost estimate detail, and availability of resources such as costing tools or models, available data, finances, personnel 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. In addition, close attention must be paid 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 translate into a more accurate estimate if the methods applied are not suitable for the program, or in accordance to program phase, or are wielded by an inexperienced estimator.

Furthermore, as already described in Chapter 2.6.2.2 an essential requirement and element of the AA_{MAC} framework is a simple, effective and flexible AA interface which can be tailored for the unique nature of each program being costed with AA. In addition, a WBS is also usually required. Depending on the nature of the program being costed, as well as the depth of cost estimation, this usually delves into at least three if not four levels of WBS elements, which should be achievable albeit only at a preliminary level even during the early program phases.

2.6.4 AA Advantages

Regardless of the mode, there are multiple benefits associated with the amalgamation approach. All these points have already been mentioned respectively per individual AA mode in the preceding chapters. Since each of the advantages is linked or feeds into the other advantages due to their close relation and logical effect, the points are shown in a succinct point form below.

- Cost estimate redundancy check / validation
- Immediate identification of significant cost variances between methods
- Assists quick and effective identification of human error data input
- Increases fidelity of data accuracy for model input
- Increased final cost estimate robustness, representativeness and reliability
- Reduced cost estimate uncertainty and thus associated risk
- Clear indication through result discrepancies, if a cost estimate needs to be reassessed or revised
- AA framework supports and elicits further analyses and clear, detailed justification of any assumptions made during cost estimation formulation

Overall, AA offers a powerful, effective and efficient redundancy check, validation or consolidation of an existing cost estimate within context of a formalised procedural program management framework. It helps to reduce cost estimation uncertainty and consequently financial risk, while increasing the estimate's representativeness, robustness and accuracy. In addition, if a significant deviation between multiple results is observed, this outcome already indicates the level of uncertainty, which the cost estimator can then seek to address through further, deeper analyses to determine the underlying reasons. If discrepancies are considerable (order of magnitude delta), then often, several iterations and revisions of cost calculations may be necessary to arrive at a final, logical and justifiable consensus.

2.6.5 AA Drawbacks

Several drawbacks of AA can be identified, and are dependent on the AA mode being used. These are:

- Increased resource requirements (i.e. time, work effort, cost) associated with:
    - cost estimate calculation using multiple models/tools
    - analyses of multiple cost estimates, at top, and lower project WBS levels
    - performing multiple cost estimate iterations if necessary, in case of significant result variations to justify the reason
    - tool/model acquisition (licensing fees and processes) and professional model/tool user recruitment / involvement

- variability of models/tool and consequently internal model/tool mechanics (additional requirement for cost estimator to have a basic understanding of each AA tool's key model mechanics)

The following sub-chapters offer a more in-depth explanation of the drawbacks, and how these should be addressed and minimised.

2.6.5.1 Increased Resource Requirements

The main drawback of AA is that the derivation of multiple values using numerous different methods or models is of course more resource consuming, requiring more time, effort amount and consequently resulting in increased costs for compilation of a cost estimate. Of course more than three values can always be derived through application of different CEMs, models and tools. However whether this approach is taken is then a trade-off question between the increase of resources (and costs) and expected increase in cost estimate certainty and reliability. This should be decided on a case-to-case basis.

In addition, in the common case of considerable cost discrepancies, various cost estimation iterations might be required, once again being costly in terms of the time dimension. However, it is exactly through these iterations, that sound justifications for any contradictory figures, and thus an increased cost certainty are also achieved.

Additionally, costs for any licensing fees of commercial tools and models which are required, might also be incurred. In addition, if multiple models and tools are utilised, and, as is common, if these are specific, complex, multi-dimensional models, the involvement of a professional model/tool user might be required to enter all associated inputs and ensure all data are effectively translated into the model-specific parameters. After all, cost estimate reliability is a direct function of the experience and model familiarity and proficiency of the user, and their ability to translate mission specifications into specific model or tool inputs. However, compared to the enhancement of the resulting cost estimate in terms of representativeness and reliability, and given the very high order of magnitude costs associated with the aerospace industry programs which the cost estimation process relates to, the increase in resources at the critical stage of cost estimation compilation is seen as proportionate. After all, establishing a sound, realistic and sufficient initial program budget is essential to underpin future successful program progression and execution.

2.6.5.2 Variability of Model Mechanics & Model Experts

The AA stipulates that several models or tools, as well as possibly CEMs need to be applied. If multiple models and tools are used, then careful attention needs to be paid with respect to maintaining a consistent input of the same program data between different models/tools to ensure comparability of results.

Another complication here is that most commercial tools, such as the PRICE and 4cost *aces* models require an experienced user to conduct the proper input of data and translation of technical parameters into model- or tool-specific inputs due to their specificity and definitions and complexity of structure. The decision whether to involve a professional model/tool user remains up to the prime cost engineer, relating also to the available early-phase program budget. Here, if an expert user needs to be employed, then another consideration is the potential scope for personal knowledge and expert judgement bias with respect to translation and interpretation of technical program inputs into model/tool numerical values. The expert interpreting and entering ultimate data into a cost tool/model should have knowledge of the space domain, and work closely with the cost estimator. Here, the expert judgement and subjectivity of interpretation of program data which is then translated into complexity factors, directly influence cost results. But while it is important to note this drawback, the issue of subjective judgement is fairly prolific within the cost estimation domain. After all, the EJ CEM shares the same problem, but is still nevertheless widely applied and accepted within the aerospace industry. It is therefore extremely important for the cost engineer to clearly and consistently communicate with the model/tool expert throughout the entire process of data entry. It is also essential to clearly record and document in detail all assumptions and logic behind inputs, the subjectivity of which may potentially result in a respective reflection on final results. In this way, a clear logic-log and transparent record must be kept of all decision making processes.

Even if expert model/tool user is involved, the prime cost estimator must nevertheless be sufficiently familiar with the mechanics and workings of the selected cost estimation models/tools, their mechanics and basic input and output variable definitions to ensure either their own effective input or alternatively clear communication of technical, program and mission specifications and to the expert user into the model/tool inputs. This is essential to facilitate for commonality of model/tool calibration (if applicable), and transferring technical details into representative complexity definitions relevant to whichever tool/model being used. In addition, a basic model/tool understanding also assists in final analysis, result interpretation and consolidation of the multiple AA results into a single range, allowing for clear identification of possible reasons for result discrepancies, if any.

While fundamentally similar, the various existing early-phase models and tools have different complexity factors, both qualitatively and quantitatively, feature different interfaces and allowances for inputs, and also can make different baseline assumptions, which much all be familiar to the cost estimator to ensure effective AA application and consistency of inputs between various models and tools. Therefore if data entry for a specific tool or model is achieved with assistance of an external expert user, the constant, consistent, unambiguous and clear communication between the two parties throughout the course of the estimate calculation is absolutely crucial.

2.6.6 Amalgamation Approach Summary & Conclusions

The structured approach and key principles of the proposed Amalgamation Approach in its three defined modes of application have been defined - namely AA_{MIC}, AA_{MAC} and AA_{VAL}. The main aim of AA is to effectively achieve a redundancy framework for cost estimation results, just like redundancy is implemented in mechanical and technical applications for life-critical systems, with AA replacing the usual industry approach of reliance on a single cost estimate source. The cost redundancy goal is either achieved through conducting a separate cost estimate to confirm or challenge an existing one (AA_{MIC} and AA_{VAL}), or in the case of the AA_{MAC} mode, through utility of multiple CEMs or tools to either to create a brand new and stand-alone estimation. A specially designed Excel-based tool, AAInT, has also been developed and introduced for effective application of AA_{MAC} to complex space programs, based on inputs from a program’s unique WBS and constituent sub-systems. This interface facilitates for data input at various levels of program and WBS detail, while remaining sufficiently flexible to accommodate the various specificities inherent to each program, particularly of a complex and international nature.

Overall, AA constitutes an effective method to reduce uncertainty associated with an initial, single cost estimate, and is ideally suited for application during early phases when cost risk associated with an estimate is high. While AA (especially AA_{MAC}) to a cost estimate is more resource intensive, the reduced uncertainty and increased justification and representativeness through result redundancy may often warrant the latter given the large scale of space programs.

3 SPACELINER - AN INDUSTRY CASE-STUDY

"Nothing ever built arose to touch the skies unless some man dreamed that it should, some man believed that it could, and some man willed that it must." – Charles Kettering

In 2005, a strategic, innovative and visionary concept was proposed by the German Aerospace Center (DLR), with the potential to not only enable sustainable low-cost space transportation to orbit [176, 179, 180], but also to revolutionse the status of currently viable passenger point-to-point transportation. Based on statistics extracted directly from the aviation industry, it is clear that ultra-long haul travel between the world's key locations and business centers is a substantial and mature market. Since the termination of Concorde's operation in 2003, intercontinental travel has been restricted to low-speed, subsonic and long-duration flights. An interesting and attractive alternative, therefore, to conventional air-breathing hypersonic passenger airliners in the context of designing and developing intercontinental passenger HST vehicles of the future, would be a rocket propelled suborbital craft. Such a concept, dubbed the SpaceLiner [168, 182, 183], has been proposed, and is currently under investigation by the DLR Space Launcher Systems Analysis (SART) group at the Institute of Space Systems in Bremen, Germany. This two stage RLV would be capable of traveling ultra long-haul distances such as Europe – Australia in 90 minutes, while other intercontinental routes between business centers located in East Asia, Europe and the East and West coast of North America, could be reduced to flight times of slightly more than one hour [168].

A perfect hybrid between the space and aviation industries, the SpaceLiner design is based on using well established rocket technologies in order to benefit from the existing safety standards established within the space industry, rather than having to establish a track-record for completely new and untried technologies.

Figure 8: The SpaceLiner vision of an ultra-fast, rocket-propelled intercontinental, point-to-point passenger transportation spaceplane [82]

Here, repeated studied have shown that estimates for developmental projects containing only "modest technical advances" have a tendency to be more accurate than projects which incorporate totally novel ideas and concepts, thus pushing the development threshold substantially [31]. And with the vehicle reaching speeds of up to Mach 25 during flight, safety is of the utmost priority to the concept and the potential for its future commercial success. The SpaceLiner's main purpose would be to service the point-to-point, intercontinental passenger transportation segment, which, as previously touched upon, is foreseen to be considerable. With the new space age depending on the combination of reusability and high traffic levels civilian space access is the new market most likely to demand these high traffic levels [15].

This utility overlaps neatly with the latest deviation of space access into the space tourism and ultra-fast long distance passenger transportation domains, giving SpaceLiner the potential to revolutionise the launcher market with both high production and launch rates per year, and consequently significantly lower costs.

An important distinction which needs to be made within context of the SpaceLiner, is that this vehicle, in terms of technology and application, is new in the sense that it is a hybrid between the aviation and space domains. Basically, a space technology has been proposed for application to a standard civilian application and function of passenger transport. This characteristic influences the development and production processes and approaches for such a vehicle, as well as the associated costs. Development would be more in line with space industry standards, while the high number of serial production foreseen for the vehicle would resemble more the aviation industry. This is further elaborated upon in more detail, later on in the Thesis.

3.1 SpaceLiner Configuration Development & Launch Sequence

First proposed in 2005 [179], the SpaceLiner concept has been and continues to be under constant development as technical requirements crystallise. Numerous papers detailing progress of the iterative design process have been regularly and consistently published and presented to the wider aerospace community [169, 180, 182-184, 187, 208].

The SpaceLiner baseline design concept consists of a fully reusable booster and passenger stage, both of which are arranged in a piggy back configuration, as seen in Figure 8. The vertical launch system is powered by rather conventional LOX/LH2 staged combustion engines, all of which should be functioning from lift-off until main engine cut-off (MECO). The booster stage is predominantly the cryogenic propellants vessel with its own engines. The passenger stage, referred to synonymously as the orbiter, encapsulates and carries the passengers in a cabin configuration. Passengers embark horizontally, as they would a standard aircraft, after which the capsule is integrated into the orbiter for a vertical system start. This passenger cabin element of the SpaceLiner vehicle is a highly complex sub-system in its own right. Furthermore equipped with a solid propellant propulsion system, the cabin is also designed to functions as the passenger escape capsule in the unlikely event of an emergency [21].

A fundamental characteristic of the concept is its full reusability, which should allow for low turnaround times between flights of each vehicle. Both the booster and orbiter, including engines, are designed to be fully reusable and equipped with wings for a gliding return flight. After the launch, the vehicle climbs to an altitude of approximately 73 km, at which point the booster separation occurs. During the entirety of the ascent phase, a propellant cross-feed from the booster to the orbiter is foreseen right up until separation between the stages to reduce overall size of the orbiter. After separation, the booster makes a controlled re-entry and is transferred back to the launch base by a patented ‘in-air capturing’ method. This has been investigated at the DLR through simulations in the past, and has been proven feasible in principle [177, 178], while further research and future work pertaining to the topic is also planned.

Meanwhile, the orbiter continues to accelerate to a velocity of 6.7 km/s and an altitude of 80 km using its own propulsion system. After the passenger stage main engine cut-off (MECO), the powerless gliding flight phase begins. Initially, the SpaceLiner was designed to use a so-called skipping trajectory which was believed to maximise the range and thus reduce propellant and mass. However, it was also found that this trajectory leads to comparatively high heat loads, and increases the mass of the thermal protection system. Most recent trajectory optimisations have obtained a smooth trajectory devoid of any skipping, while greatly improving passenger comfort and reducing heat loads [187]. Here, a small increase in propellant mass for the new trajectory profile is more than balanced by a lower TPS mass. In addition to the trajectory improvements, the vehicle shape has also changed.

Since the first design, different configurations in terms of propellant combinations, staging, aerodynamic shapes, and structural architectures have been analyzed. A subsequent and respective configuration numbering scheme has also been established for all investigation phases.

The genealogy of the different SpaceLiner versions is shown in

Figure 9. The configuration trade-offs within the FAST20XX studies performed in recent years support the definition of the latest and most current reference configuration, SpaceLiner 7, which, up to date, has advanced through to the version SpaceLiner 7-3.

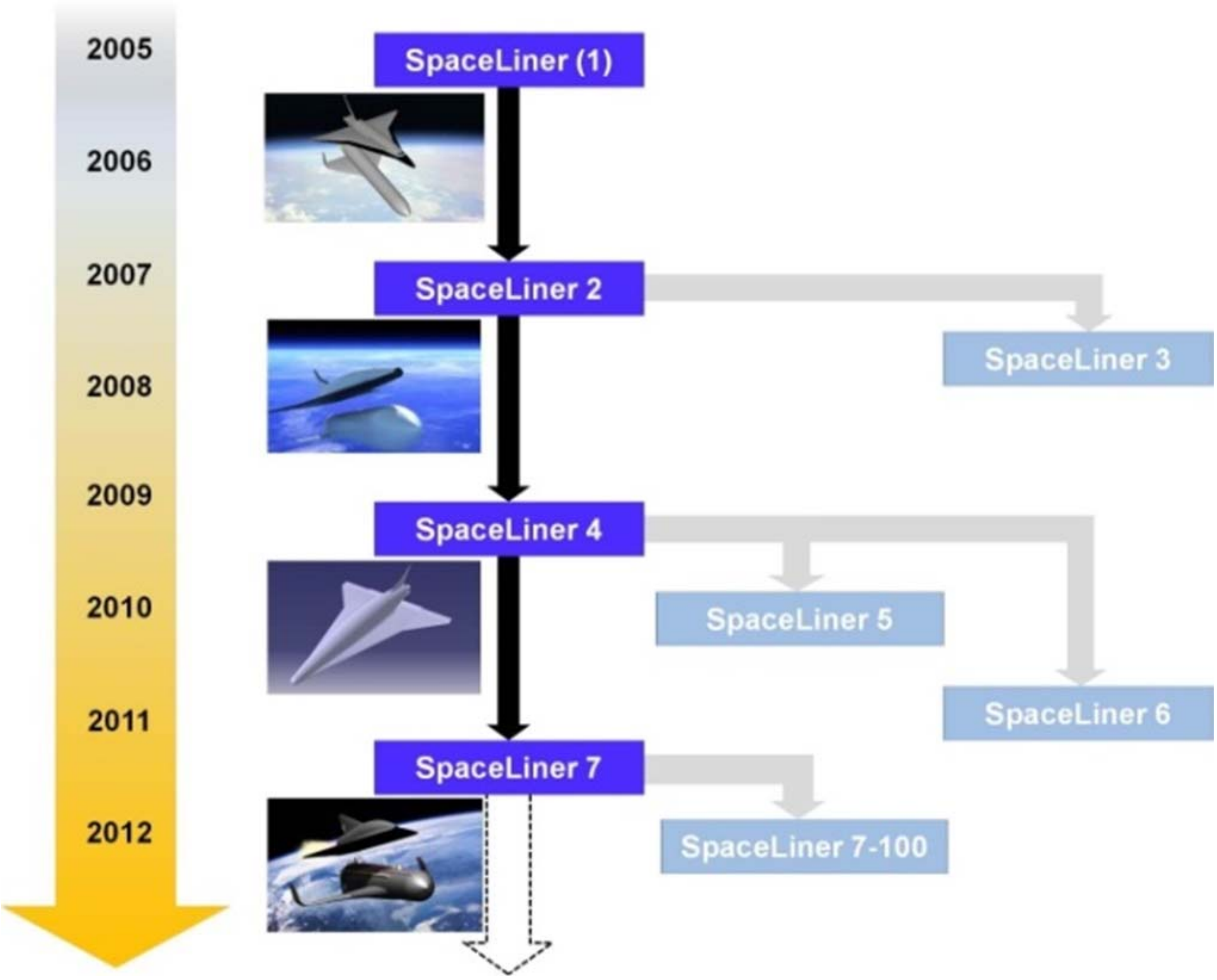


Figure 9: Evolution of the SpaceLiner concept [186]

The SpaceLiner is a highly dynamically evolving concept with advancements and progress being made throughout the course of the writing of this Thesis, and indeed in real time. As such, it is vital to point out that for the sake of the analyses and calculations presented in this Thesis, at one point it was necessary to select and effectively 'freeze' one specific version, which, at that time, was the most current available. This version is SpaceLiner 7-1. Therefore, although a more current version is currently under investigation, and work is continuing on the concept advancement, all calculations and analyses presented in this Thesis, pertain to SpaceLiner 7-1

3.2 MISSION DEFINITION

Since investigations on the SpaceLiner began, the ambitious westbound Australia – Europe route has been defined as the reference case. Using the mission range as a fundamental criteria, the connection between Australia (Sydney) and Western Europe, has been calculated to be the longest at roughly 17,000km [186, 216]. The effect of the surface rotation of the Earth influences the chosen direction of travel, with a positive effect observed for all trajectories flying towards the East. As a result of the selection process, the westbound Sydney to West Europe route is identified as being the most demanding, and thus has always been taken as the SpaceLiner design reference mission. It is therefore the reference trajectory that has been most extensively studied to date. It is proposed that this flight distance will be traversed on a daily basis in each direction by a spaceplane, carrying 50 passengers (PAX) onboard. Several other, shorter intercontinental missions have also been defined, which have the potential to generate a larger market demand. For this reason, a SpaceLiner derivative configuration with the capability of transporting up to 100 PAX over the shorter intercontinental distance has also been studied [169]. In order to keep the number of different stage configurations at the lowest possible level, the potential flight destinations of interest have been divided into three classes, and could be flexibly serviced by a suitable combination of four vehicles (50 PAX orbiter stage, 100 PAX orbiter stage, nominal booster, shortened booster), all with a high commonality of fundamental components and sub-systems, such as engines and avionics, despite differences in size.

- *Class 1:* Reference mission (up to 17,000 km) Australia – Europe with 50 PAX orbiter and large reference booster
- *Class 2:* Mission (up to 12,500 km) e.g. Dubai – Denver with increased 100 PAX orbiter and large reference booster
- *Class 3:* Mission (up to 9,200 km) e.g. Trans-Pacific with increased 100 PAX passenger orbiter and reduced size booster

3.3 SPACELINER 7

The current arrangement of the two stages at lift-off is presented in Figure 10. The stage attachments are in accordance with the classical tripod design. The axial thrust of the booster is introduced through the forward attachment from booster inter-tank into the nose gear connection structure of the orbiter. The aft attachment takes all the side and maneuvering loads.

Figure 10: Visual representation of the latest SpaceLiner 7 launch configuration with passenger stage (top) and booster stage (bottom) with stage attachment [183]

The booster is a large, unmanned tank structure powering the SpaceLiner system at launch with its nine engines, and providing propellant cross-feed to the orbiter until stage separation. Two integral tanks with a diameter of 8.6m are used with separate bulkheads. The configuration resembles that of the Space Shuttle External tank layout, modifications to which include the ogive nose (for aerodynamic reasons and for housing subsystem), a varied propulsion system, and the wing structure with landing gear. Key parameter data for the configuration is shown in Table 1. The SpaceLiner passenger stage shape and internal structure configuration, including two engines and the passenger cabin/rescue capsule, are graphically shown in Figure 11. Some key parameter data are also given in Table 2 for the SpaceLiner 7 passenger stage.

Table 1: Key parameters of SpaceLiner 7 booster stage

Length [m]	Span [m]	Height [m]	Fuselage Diameter [m]	Wing Leading Edge Angle [deg]	Wing Pitch Angle [deg]	Wing Dihedral Angle [deg]
83.5	36.0	8.7	8.6	82/61/43	3.5	0

Table 2: Key parameters of SpaceLiner 7 orbiter stage

Length [m]	Span [m]	Height [m]	Fuselage Diameter [m]	Wing Leading Edge Angle [deg]	Wing Pitch Angle [deg]	Wing Dihedral Angle [deg]
65.6	33.0	12.1	6.4	70	0.4	2.65

As the structural pre-design is not yet finished, all dry mass data are still based on empirical estimation relationships derived from launch vehicles or hypersonic transport studies. These data are shown in Table 3. System margins of 14% (and 12% for propulsion) are added to the estimated mass data. Based on available subsystem sizing and empirical mass estimation relationships, the orbiter mass is derived as listed in Table 4. The total fluid and propellant mass includes all ascent, residual and RCS propellants and the water needed for the active leading edge cooling. The stages' MECO mass is approximately 161.8 Mg.

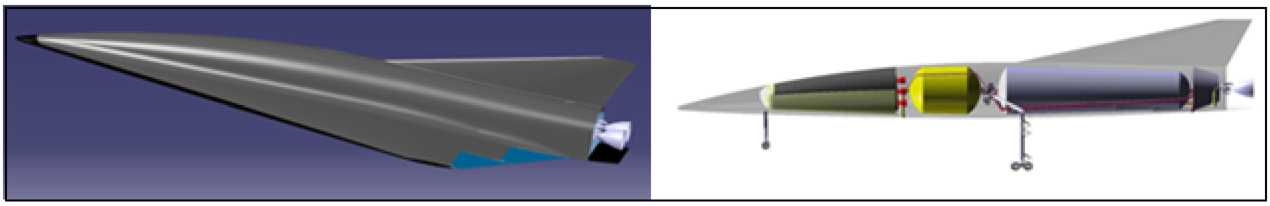


Figure 11: Latest SpaceLiner 7 orbiter shape (left) and CAD drawing of the reusable SpaceLiner 7 passenger stage (right) showing configuration of cabin, propellant tanks and landing gear [22, 182]

Table 3: Mass data of SpaceLiner 7 booster stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total Dry Mass [Mg]	Total Propellant Loading [Mg]	GLO Mass [Mg]
91.7	36	21.6	22.8	172.2	1290	1462

Table 4: Mass data for SpaceLiner 7 orbiter stage

Structure [Mg]	Propulsion [Mg]	Subsystem [Mg]	TPS [Mg]	Total Dry Mass [Mg]	Total Propellant & Fluid Loading [Mg]	GLO Mass [Mg]
56.2	10.1	43.5	30.8	145.4	229.6	376.8

The SpaceLiner 7 gross lift-off (GLO) mass exceeds 1830 Mg for the Australia – Europe reference mission. To put this relatively large value into perspective, however, using the analogy method, it is still below the mass of the Space Shuttle STS of more than 2000 Mg, and is therefore considered to be technically feasible.

Table 5: Mass data for SpaceLiner 7 launch configuration

Total Dry Mass [Mg]	Total Propellant Loading [Mg]	GLO Mass incl. PAX / Payload [Mg]
312	1520	1839

3.4 SpaceLiner Considerations & Challenges

A significant amount of work has already been performed on studies, analyses and simulations of the SpaceLiner system since the concept's inception in 2005. The SpaceLiner concept was awarded funding within the framework of the EU-funded, international FAST20XX Seventh Framework Programme under Theme 7- Transport, Aeronautics [172]. As a direct result of the extensive ensuing investigations by a conglomerate of international partners, significant progress of the concept status was made. Concurrently, during the detailed preliminary investigations, various challenges spanning across the technical, logistical, commercial, socio-political as well as economic domains have been encountered, identified and explicitly defined. Key points are listed below:

- Acoustic noise and sonic boom
- Launch and landing site selection
- Routes, destination and city-pairs
- Trajectories and TPS
- Environmental impact
- Operational considerations
- Door-to-door passenger transport network
- Reusability
- Reliability and safety
- Business case considerations

The latter key issues and challenges as per the present status of research and have been categorically outlined in separate works belonging to the course and progression of this Thesis work [208]. The challenges arising for the SpaceLiner program are directly and irrevocably linked and interrelated in a complex network of technical, logistical and programmatic dependencies. Many outputs from various disciplines directly provide inputs and influencing other categories. Nevertheless, ref. [208] describes each aspect and issue separately. It is beyond the scope of this Thesis to define explicit solutions, but rather to hone in on the particular area of interest, being the cost considerations and cost modeling of large, complex space systems in an international context.

Consideration and estimation of life cycle costs (LCC) of any new and proposed program, and in this case, the SpaceLiner case-study, is an extremely important task. More specifically, the aspect of performing a cost estimation during the early program phase for an unprecedented, large and complex program is indeed the kernel of this Thesis. The classical LCC categories of the non-recurring development and the recursive production costs are addressed, while operations and the associated recurring costs are discussed in a more qualitative manner in line with the early case-study program status. This will be elaborated upon in greater detail in subsequent chapters.

In terms of the cost of the service to passengers themselves, immediately it is clear that tickets for such a journey will considerably exceed that paid for standard airline tickets of today. This cost increase is reflective of an entirely new level of technological application, and is the premium assigned to the time savings of SpaceLiner's ultra-fast mode of travel. Such logic automatically narrows the potential target market for SpaceLiner, honing in on the current aviation segment's 63 million business class and first class travelers who flew in 2012, and generated more than €72 billion ($95 billion USD in revenues) [166]. Congruent with this definition of the initial target market niche, the underlying assumption is the increased propensity of the consumer to travel and also enhanced ability and willingness to expend money for an enhanced travel experience, making them ideal consumers of the service which SpaceLiner encompasses.

The consequent Chapter 4 is dedicated to the development and discussion of effective and novel cost estimation approaches and processes (AA_{MAC} mode), resulting in a preliminary cost range for SpaceLiner development and production. More importantly, a structured cost estimation framework is established to allow for future refinement of the initial cost estimations as more information and technical details of the program become available.

4 SPACELINER CASE-STUDY COST ESTIMATION

"Man must rise above the Earth- to the top of the atmosphere and beyond – for only thus will he fully understand the World in which he lives." – Socrates

In this chapter, the challenge of formulating a representative early phase cost estimate for an unprecedented vehicle is considered directly through a practical application of cost engineering principles and cost estimation approaches on a selected case-study - the SpaceLiner. Using the cost engineering and estimation theory which has already been introduced, developed and discussed in earlier chapters as a baseline, the following chapters outline in detail the tailored and strategic approach undertaken to produce a cost estimate for a large, complex and unprecedented vehicle concept which is in an early pre-phase A stage. A pivotal tool to this approach is implementation of AA, in particular, the AA_{MAC} mode, as discussed in Chapter 2.6.2.2. From now, any mention of AA can be assumed to be with reference to the AA_{MAC} mode.

During the early phases of the program, an initial cost estimation is necessary to determine the various life cycle cost (LCC) elements, establish a funding scheme and to formulate a desirable and representative business case. The latter three elements are not mutually exclusive, but in fact, heavily related. The final program cost is almost always guaranteed to vary from the initial estimate due to dynamic program evolution, as well as unforeseen events which cannot be factored in for during formulation of that estimate. Here, adequate and representative risk and uncertainty, between which a clear distinction should be made [209], play a very important role and should also be assessed at program commencement. This topic, however, is not a focus of this Thesis, as it constitutes an own extensive field of study and research. Still, realistic budgeting, the basis of which is derived from a preliminary program cost estimate of development, production and operation costs, is a crucial first step to underpin future program success. 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 supportable program budget [212]. Synergised implementation with strong project and schedule management functions further increases chances for a program's timely and efficient execution and ultimately realisation. So despite preliminary, limited or incomplete information regarding configuration, mission or environmental parameters, as is the case for the still evolving SpaceLiner case-study, a pronounced need still exists for reasonable, justifiable and representative cost range to be achieved, early in the program.

4.1 THE SPACELINER COST PHILOSOPHY

Although SpaceLiner does not use any fundamentally new or exotic technologies, the integration and adaptation of these heritage elements is within a new context, and results in revised requirements such as reusability, and stringent standards for a civilian application. Thus the concept is unprecedented and novel in nature, making application of only existing cost estimation models and methods based on data derived from historical programs, a challenge.

From purely a technical perspective, SpaceLiner is very much a launch vehicle, so one must therefore look at historical projects in the launch vehicle segment. The only realised projects to date which are comparable for this specific category of space vehicles are the Space Shuttle Fleet, which was only semi-reusable [93], and the Russian Buran orbital vehicle, which performed just one unmanned flight before the program was cancelled due to a mix of political influences and insufficient funding [76]. In terms of the recent launcher markets, current launch rates have continued to steadily increase, arguably due to increased competition and changes to newly emerging commercial companies. And the higher launch rates influence launch costs, generally driving the costs of space access down, and requiring that existing cost models to be recalibrated. As an example, recent suggestions have implied that the SpaceX fleet of Falcon 9 vehicles "break the NASA/Air Force Cost Model NAFCOM" [193], a cost estimation tool commonly used in the space industry. So in order to keep up with the deviating space economy trends and space market changes, it is essential that future cost estimations have the capability to obtain indicative, relevant and justifiable estimates despite implementation of novel and unprecedented concepts, furthermore integrated within new company structures [209].

4.1.1 SpaceLiner WBS Definition & Development

For all systems, and in particular for large, complex ones, like the SpaceLiner case-study, the principle of successive refinement given the divide-and-conquer strategy is an essential component of effective program planning at project commencement. During this decomposition process, complex systems are successively and strategically segmented into modular, less complex pieces, until they are simple enough to be conquered [175]. From this, generally two structures emerge, namely for describing the product system itself, as well as a structure to describe the system which produced the product system. This is the prime goal of a work breakdown structure (WBS), which is a necessity for logically, categorically and systematically addressing all project phases, and in particular the development and production Phases C and D. A WBS and the work package definitions provide the reference for a detailed bottom-up cost estimation and budget formulation, since the cost breakdown structure (CBS) is then directly linked to the content of the WBS [115, 175]. After all, costing smaller, more tangible units is significantly more achievable and traceable, allowing for more stringent control and increased transparency than when the cost of a whole agglomerated system comprising of already very complex sub-systems is considered at an overall top level. In addition, the project is immunised with improved visibility of management data such as schedule, cost, and technical performance, amongst others [112].

Therefore, the first critical step to the logical commencement and progression of cost analysis for any large-scale, international complex space program is the establishment of an adequate and representative WBS. The development of such a WBS, incorporating the model philosophy (see Chapter 4.1.3, Table 8 and Appendix A) is an iterative top-down process defining lower level elements until the work package level has been reached. This WBS then forms the backbone for not only program organisation and execution, but indeed also for cost estimation and control of actual costs and schedule throughout all project phase [112, 115, 202]. As such, upon consultation with topic-specific literature, a specific and detailed WBS for the SpaceLiner case-study Phases C and D was developed, as shown in Figure 12, and to a deeper WBS level in Appendix A. Establishment of the WBS was a very intense, dynamic, iterative and time-consuming process requiring many loops, changes, modifications and rearrangements of elements between groupings before the final breakdown, as it is shown in Appendix A, was achieved. Here, the interaction, communication and open dialog between project management experts and case-study engineers and specialists in their respective SpaceLiner domains was essential to establish an efficient break-down of the overall complex program into its logical substituent units strategically. The author wishes to acknowledge Professor Bernd Madauss from ISU for his invaluable guidance and sharing his knowledge and expertise for the compilation of the case-study WBS.

Firstly, the SpaceLiner concept, as a whole, was segmented into logical sub-level constituent modules which conformed to the group of non-recurring development and the recursive production costs.

- SpaceLiner fly-back Booster (SLB)
- SpaceLiner orbiter passenger stage (SLO)
- SpaceLiner main engine (SLME)
- Passenger cabin / passenger rescue capsule (SPC)

While the engine SLME belongs to the lower-level of SLO and SLB components, it was identified separately as a key element, and the 'heart' of the SpaceLiner vehicle which would incur development costs, as well as consequently, production costs.

A WBS was consequently derived for the multi-element SpaceLiner case-study to provide a logical outline and vocabulary that describes the entire project and integrates all available information in a strategic, transparent and consistent way [175]. The sub-system inputs and categories were based on existing SART in-house Space Transportation Systems Mass (STSM) software package [45] inputs and outputs for both constituent system elements and the respective element masses. The latter were consequently strategically segmented into appropriate SpaceLiner categories of SLO, SLB and SPC in line with WBS requirements and standards.

In line with theory for successful WBS development, multiple iterations were then required, and will continue to be required throughout project advancement. This is because the full extent of the work and tasks is often not evident at commencement, but rather evolves during the WBS formulation and consequent project execution phases [175].

While quantitatively, the derived SpaceLiner case-study WBS ideally describes the top-level system components, which were necessary for application of the AA, attention was also paid to extrapolating the systems into accurate descriptions of their constituent sub-elements and components. This was challenging since many sub-system elements are still works in progress and being dynamically defined prior to their ultimate crystallisation. Nevertheless, sub-system SpaceLiner components were defined qualitatively, thereby providing an essential and thorough structure and framework for more detailed, bottom-up estimation of the concept to occur as it matures in the future.

The SpaceLiner is a two-stage launch vehicle system comprising of the main fly-back booster stage (SLB) and the passenger orbiter stage (SLO). Furthermore, unlike any vehicles which are used as reference projects within the TransCost manual, the SLO stage features an integrated passenger capsule which has a hybrid function, and also doubles as a passenger rescue capsule (SPC) in case of emergencies. Its prime goal is to eject from the SLO body, and autonomously and safely return the passengers back to the ground. In this regard, the SPC features its own solid propulsion system which requires a minimum of development effort since all the technology already exists.

In terms of the SpaceLiner propulsion, while based on standard cryogenic propulsion technology, the SpaceLiner main engine (SLME) would need to be newly developed in view of the passenger-transportation context, with the key challenge here being the required reusability component. SpaceLiner assumes engine reusability of 25-50 times, as is explained later in Chapter 4.1.5. For the sake of the cost estimation, it is also assumed that the SLB and SLO use the *same* cryogenic engine. Mechanically, the engines are identical, although having different size nozzles. Being a traditional, heritage LOX/LH cryogenic engine technology, assuming an 100% new development effort for a single engine is sufficient to address the development of both SLO and SLB propulsion. This important assumption has already been defined and outlined in detail also in the Chapter 4.1.5.

To reflect all technical information, the resulting WBS has seven top-level WBS elements from 1000 through to 7000, which are further expanded overall to three levels of detail. The top three levels are shown in Figure 12, while the full four levels of detail can be found in full in Appendix A.

The kernel of this Thesis predominantly focuses on development and application of novel and innovative new cost estimation approaches and strategies aimed at calculating development and production costs of physical hardware elements of complex space systems during the early pre-phase A phase. The chosen complex and unprecedented SpaceLiner case-study constitutes an ideal candidate for application of the new cost estimation models, approaches and theory developed within this Thesis work, as it is clearly still in the targeted early pre-phase A stage. As such, however, assessing and estimating costs for the WBS ground and operations elements in detail is still deemed too premature as the requirements and key, necessary details are not yet clearly defined. This holds similarly true for the software component, both development and production, of the SpaceLiner case-study. So while these WBS elements are not explicitly estimated, they are logically integrated into the WBS structure and nevertheless considered at a basic component and element level. The *italic* blue font shown for WBS elements 6000 and 7000, as well as 2500-4500 identifies this distinction visually.

When more mission information becomes available, it can be expected that the WBS will need to be updated and expanded respectively to reflect this accordingly. However, in the presented baseline SpaceLiner case-study WBS, the structure of all necessary WBS elements for such a large-scale and complex program, and the approach taken to derive these classifications and groupings, is presented within context of a real-life practical industry application.

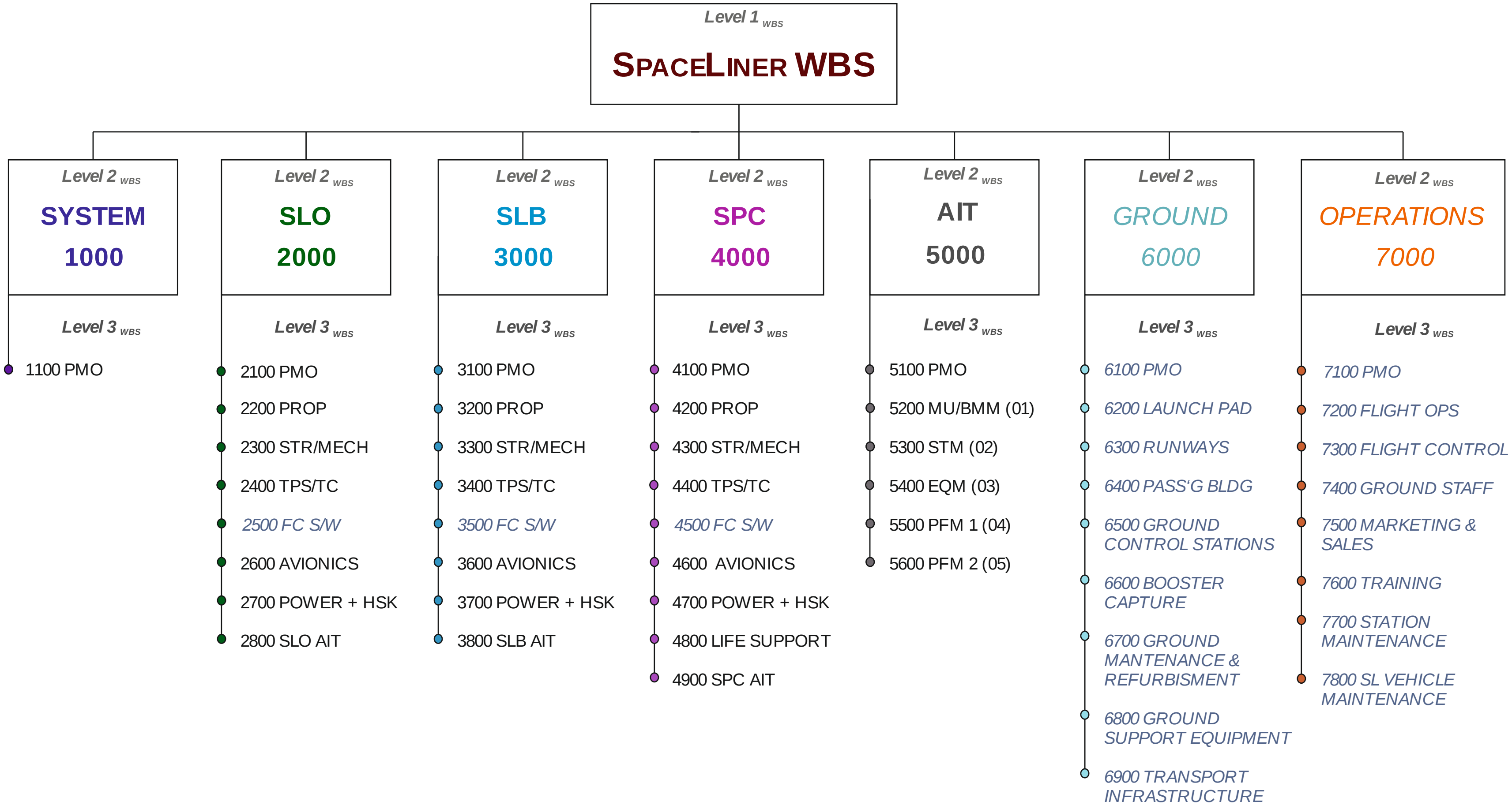


Figure 12: SpaceLiner WBS for development Phase C showing three levels of detail

4.1.2 SpaceLiner Program Schedule & Milestones

Despite the early phase of the program, and to complement the developed WBS, it was important to establish a preliminary and realistically executable, expected program schedule to determine and define key dates, some necessary milestones and the distribution of program phases with respect to time. While slightly different systems and terminology can be adopted between international space agencies, the European Cooperation for Space Standardization (ECSS) standard for project planning and implementation [57] was relied upon as a baseline for this work. This Standard outlines seven distinct program phases, as shown below:

- Phase 0 – Mission Requirements
- Phase A – Concept & Feasibility
- Phase B – System Definition
- Phase C – Design, Development & Verification
- Phase D –Production
- *Phase E –Utilisation*
- *Phase F – Disposal*

The last two Phases E and F, shown in *italics*, are not addressed in this Thesis, since the development and production phases are the key focal elements of this work. Analogy and the EJ methods were then employed to estimate and predict the expected, realistic duration of each program phase drawing on previous large-scale space program examples. Consolidated information and expert opinion was extracted from direct discussions with top experts from both academia and industry specialising in the program management function of the space domain to determine ROM representative timeframes for the various scheduling phases, keeping in mind the considerable scale, scope and high complexity of the SpaceLiner concept. With the mission analysis of Phase 0 presently underway, Phase A could commence already in 2015, which, given that the Mission Definition Review (MDR) is executed during 2015 or 2016, presents a realistic and current scenario. Phase B, the preliminary program definition which precedes final definition may be estimated to then take approximately eight years. The design and development of Phase C could then commence in 2025, realistically lasting up to ten years. The consequent production Phase D is preliminarily assumed extend over 15 years.

The resulting preliminary schedule, which assumes T_0 to indicate the time reference for program commencement, is shown qualitatively (not to scale) in Figure 13 below. The logical sequence and progression for each milestone, activity and review as well as preliminary phase durations assumed for the SpaceLiner case-study, are also included in *italics* with reference to T_0.

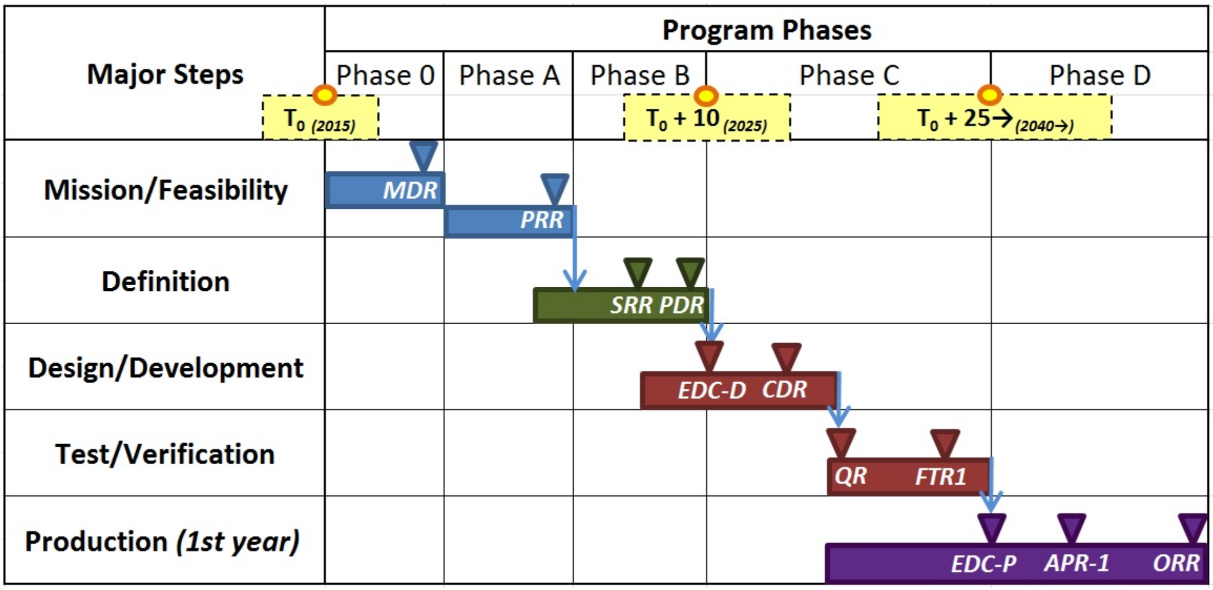


Figure 13: Preliminary SpaceLiner case-study program schedule

Additionally, and in close consultation with the European Cooperation for Space Standardisation (ECSS) guidelines [57], the aim of which is to be applied for the management, engineering and product assurance in space projects and applications, the following milestones associated with the various program phases have been identified as necessary for effective and thorough execution of the SpaceLiner program:

Pre-Phase A – Mission Requirements

- Mission Definition Review (MDR)

Phase A – Concept & Feasibility

- Preliminary Requirements Review (PRR)

Phase B – System Definition

- System Requirement Review (SRR)
- Preliminary Design Review (PDR)

Phase C – Design & Development

- Effective Date of Contract Development (EDC-D)
- Critical Design Review (CDR)
- E/QM Qualification Review (QR)
- PFM1/2 Flight Test Reviews (FTR1/FTR2)

Phase D – Production

- Effective Date of Contract Production (EDC-P)
- Annual Production Reviews (APR1 to APR15)
- Operational Readiness Review (ORR)
- End of Production Contract (EPC)

While the ECSS standard stipulates that the QR and FTR (also interchangeable with the acceptance review, AR) milestones are associated with Phase D, in line with the SpaceLiner philosophy presented in Chapter 4.1.3, it is deemed that any prototype activities belong firmly within the Phase C development phase, and as such, both the QR and FTR case-study reviews are thus segmented to Phase C. The classical 'V Model' is demonstrated throughout a program's review sequencing. Commencing from Phase A and the PRR to the Phase B PDR, a top-down process is observed beginning at the highest level with the customer and top level supplier, and flowing down through the customer-supplier chain towards the lowest levels. From Phase C and the CDR to the APRs of Phase D, however, the review sequence is reversed to a bottom-up direction, starting with the lowest level supplier and their customers, and ascending up the customer-supplier chain back again to the top level customer. This V-Model mechanism and principle is illustrated below in Figure 14.

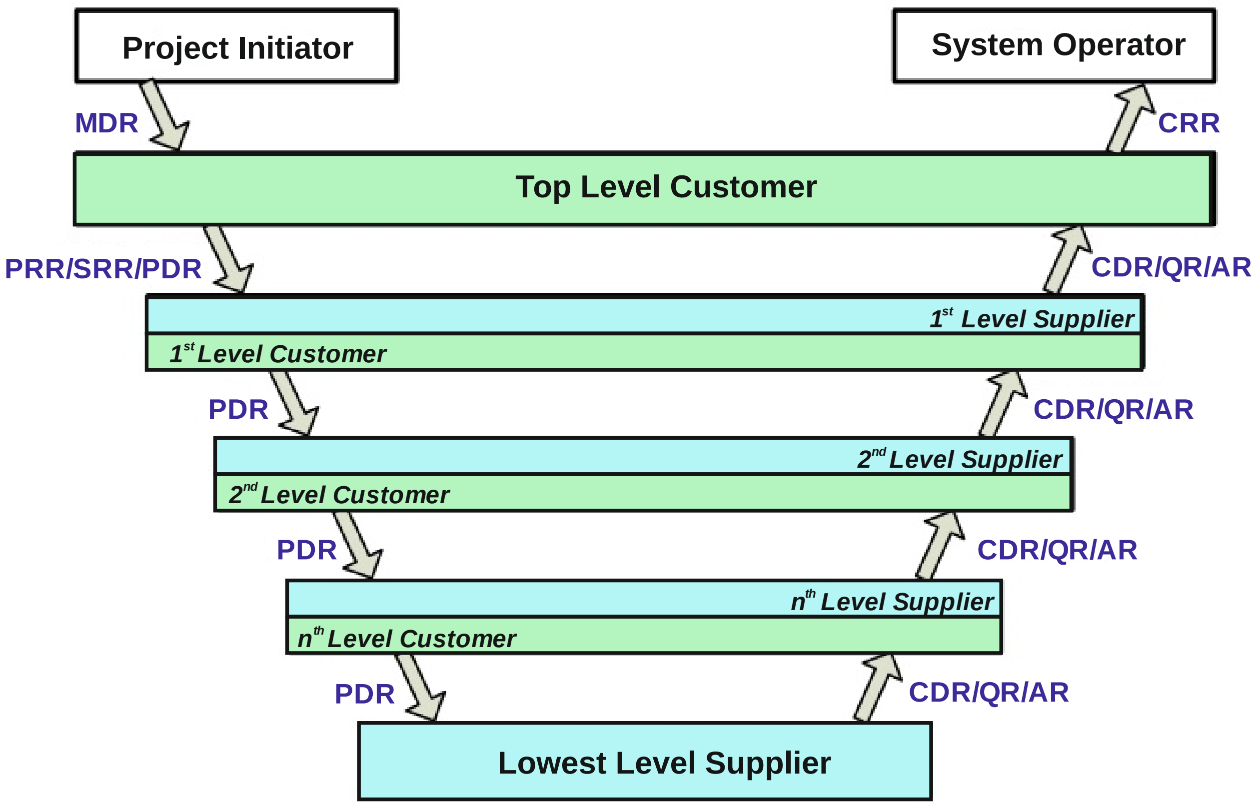


Figure 14: Review life cycle showing various program reviews within context of the V-Model structure [57]

It must also be pointed out that despite the template of milestones and project reviews outlined above, the program management must remain flexible to incorporate additional reviews into the project planning schedule to address the specific and unique project needs of every program [57]. With context for the SpaceLiner case-study, it should be noted that due to the safety-critical nature of the vehicle, in line with stringent safety requirements, additional reviews and audits may well be incorporated into the preliminary schedule structure presented within this Thesis.

Here, it is not the aim of this work to describe the specific features, key objectives, structure, logistics and requirements for each of the above milestones and reviews, although full information, detailing aims and goals of each review, can be found in the ECSS Standard in ref. [57], on pages 21-28.

4.1.3 SpaceLiner Development & Prototype Modeling

Space is undeniably a risky business. Therefore building development models and prototypes to verify the design and proper function through test in flight in the development phase, is of the highest priority to establish a strong safety and solid reliability baseline. This is particularly crucial for unprecedented vehicles like the SpaceLiner case-study. In fact, the risk for such a vehicle increases due to the high number and untrained nature of its civilian passengers for a spacecraft. Implementing a stringent testing campaign, as well as increasing the number of SpaceLiner prototypes flown, as well as test-flight hours prior to commercial implementation should therefore increase and establish a particular reliability standard, and reduce risk. At this stage it is ambiguous to attempt to numerically capture and quantify this risk, however it is clear that the more development models and prototypes which are built and successfully, respectively tested, the better the safety record, and the lower the perceived risk. The SpaceLiner technology is from the space domain, while its application resembles an aviation scenario. Classic space components have fewer prototype units than those within the aviation industry, with many of those being on a sub-system level rather than at a full system level. However, given the safety-critical nature of the SpaceLiner program, the aviation industry analogous prototype quantity philosophy was largely adopted for definition of the development phase prototype philosophy applied to the SpaceLiner case-study example. Research was conducted to ascertain both the aviation and space industry approaches for prototype and testing standards and regimes.

Within the aviation domain, a focus was placed on large, current aircraft programs from the leading aircraft manufacturers like Airbus and Boeing, and existing literature was extensively consulted. While detailed internal program information is usually difficult to locate as it is rarely made public due to confidentiality constraints, several reliable sources were nevertheless identified and referred to [10, 62, 63]. The Airbus A380 program had five fully operational prototypes which clocked a total of 2,500 hours of flight tests to achieve certification with both the European and US airworthiness authorities, the European Aviation Safety Agency (EASA) and the Federal Aviation Administration (FAA), respectively. Similarly, the recent A-350 program also incorporates five prototypes, MSN001-MSN005 with another 2,500 flight-test hours. The sequence of flights is designed to use the flight-test aircraft exactly like a potential airliner would, training the associated processes accordingly and assessing general handling qualities, operational performance airfield noise emissions, and systems operation in nominal mode.

Within the space industry, prototype philosophy differs given that flight duration of most launchers is significantly shorter, and as such, flight hours are not as important a parameters, as the number of successful launches and landings, where appropriate. Similarly, the flight and mission dynamics of a program like SpaceLiner would be rather different, operationally, to standard civil aircraft. Long haul carrier airplanes frequently fly long routes lasting up to 16 hours, and as such, a test regime which incorporates extenuating durations of flight hours holds relevant. The SpaceLiner vehicle would only fly a maximum duration of 90 minutes in accordance with its reference mission requirements. Therefore here, at a top system level, a much more relevant and representative statistic for SpaceLiner prototype units would be with the number of successful launches and landings, especially with the vehicle being fully reusable. On a sub-system level, the number of engine test-firings would be a solid statistic for the prototype and testing regime.

However, prior to having fully functional flight prototypes, numerous preceding mockups, test and engineering models must be constructed and tested. Furthermore, various standards exist for the various sub-systems, which define different requirements and goals per sub-system. For example, a recent 2014 NASA standard for ^the critical structural design and test factors (NASA-STD-5001B [140]), stipulates that "*The standard accepted practice for verification of launch vehicles and human-rated spaceflight hardware is the* ***prototype*** *approach in which a separate, dedicated test structure, identical to the flight structure, is tested to ultimate loads to demonstrate that the design meets both yield and ultimate factor-of-safety requirements. An acceptable alternative for verification of spacecraft and science payloads is the* ***protoflight*** *approach, wherein the flight structure is tested to levels above limit load but below yield strength to verify workmanship and demonstrate structural integrity of the flight hardware* ." Here, we see that from a structural perspective, the space industry stipulates a low number of components to achieve verification of a system through the prototypes. It can also be seen that the *prototype* approach incorporates an extra level of test hardware prior to flight. However the *protoflight* verification approach is advantageous in that it does not require a dedicated test unit, since qualification testing can be performed directly on the flight hardware, although here, a margin over flight limit loads must also be demonstrated be test [140]. Choice of which method is applied depends on the available budget, which, if insufficient, might force the program to adhere to the protoflight method [120]. It must also be noted that electronics and software for such a large system adhere to a completely different testing standards, requirements and processes.

The aim of this Thesis is not to delve into low-level testing and validation requirements for the SpaceLiner case-study. Instead, it is essential to establish and clearly define an initial top-level prototype philosophy and preliminary schedule in order to proceed with the AA approach and cost estimation of program development. Upon consultation and intensive discussions held with numerous highly experienced, seasoned industry professionals and space domain experts, as well as in line with current ESA industry practice for rocket vehicle testing (ECSS-E-10-03A [55]), a five-model prototype philosophy was developed and adopted for the SpaceLiner case-study [121]. The model philosophy consisting of three development and two prototype models and their definitions, is outlined below:

- ***01 MU/BMM - Mockup & Breadboard Model***
  Full scale mock-up dimensionally true of the expected SLO/SLB/SPC configurations, including engines, structures, tanks, electronic units, control mechanism, etc.

- ***02 STM - Structure & Thermal Model***
  Structural model to be tested under environmental conditions such as thermal, vibration, noise, shock, acceleration loads, etc.

- ***03 EQM - Engineering & Qualification Model***
  Model applied for qualification testing and initial flight tests including landing having fully representative parts or integration spares of lower fidelity standard.

- ***04 PFM 1 - Proto/Flight Model 1***
  First flight-worthy, high-fidelity standard prototype for flight tests program including landing and total system acceptance.

- ***05 PFM 2 - Proto/Flight Model 2***
  Second flight-worthy, high-fidelity standard prototype for flight tests program including landing and total system acceptance.

Inputs of prototype units for the 4cost *aces* and PRICE commercial models can be decimal numbers to reflect different effort requirements. For any other production inputs, however, fractions cannot be entered. A consolidated approach to assign a representative prototype-model philosophy for the SpaceLiner case-study had to be determined. Extensive discussion with highly experienced aerospace experts were held, and published ESA guidelines [155] were identified. Table 6 below shows a direct excerpt which recommends a baseline allocation of fractional weightings for *typical* prototype-model items.

Table 6: ESA Standard prototype counting values for various prototype-models

Prototyping / Test Model	# of equivalent PFM
Mass Dummy (MD)	0.1
Bread Board (BB)	0.2
Structural Model (SM)	0.4
Engineering Model (EM)	0.5
Structural Thermal Model (STM)	0.6
Engineering Qualification Model (EQM)	0.7
Qualification Model (QM)	0.85
Protoflight Model (PFM)	1.0

Upon further in-depth discussions with experts [121], and based on close accordance with the typical ESA standard presented in Table 6, the specific weightings of the five SpaceLiner development and prototype models were altered in accordance with program specificity, and consequently assigned as shown in Table 7 below. It can be seen that the SM represents a full prototype model of value 1.0, although it is only a structural model. Additionally, it can be seen that both PFM 1 and PFM 2 also have 1.2 fraction values of full prototype units. This is because by their definitions, these models will be extensively tested beyond their limits, requiring increased effort and therefore cost, compared to any consequent standard performance prototypes. For a vehicle such as the SpaceLiner in particular, the testing requirements for the various system elements including the SLO operation and landing, and also the SLB return to the launch site following an in-air capture maneuver, the increased values are more than warranted. The overall prototype total is thus 4.7 SpaceLiner units.

Additionally, Table 7 can be further broken down and considered from a lower level, on a main component basis per SpaceLiner SLO (including SLME), SLB and SPC elements. For each of these three lower-level components (introduced in Chapter 4.1.1 and fully detailed in Appendix A), a model matrix is developed and presented. The SLO model matrix is shown in full Table 8 below depicting necessary quantified part-units per prototype stage. The full model matrices for the SLB and SPC are consequently found in Appendix B.

Table 7: Numerical values derived for SpaceLiner five-model prototype philosophy

Model Index	SpaceLiner Prototype Model	# of equivalent PFM
01	Mass Dummy (MD)	0.5
02	Bread Board (BB)	0.8
03	Structural Model (SM)	1.0
04	Proto/Flight Model 1 (PFM 1)	1.2
05	Proto/Flight Model 2 (PFM 2)	1.2
∑	**TOTAL**	**4.7**

It is also important to be aware that due to the early pre-phase A stage of the SpaceLiner program, the suggested prototype schedule should be considered preliminary in nature, with significant uncertainty regarding the prototype philosophy. The philosophy should remain flexible to be further refined in line with the evolution of the program during consequent project Phases A/B. Any modifications or updates to specifications and requirements, as well as funding availability should be reflected. The scope of each development model listed above is also prone to change according to specific challenges of the system design which are still fluctuating [120]. To mitigate some of the prototype philosophy uncertainty, a more conservative approach it adopted. The established baseline prototype-model total of 4.7 units is revised upwards to a value of 5 to reflect a more extreme scenario. This value is also in line with the aviation industry standard for large aircraft of 5 prototypes as discussed previously in this chapter

Table 8: SLO Model Matrix quantitatively showing model philosophy components

	Type →	Test Models			Prototypes		
	Proto Fraction →	*paperwork*	*0.5*	*0.8*	*1.0*	*1.2*	*1.2*
	Model Code →	00	01	02	03	04	05
D-2000 Orbiter (SLO)	WBS Element ↓	DES	MU/BBM	STM	EQM	PFM1	PFM2
Propulsion (SLME)	**2200**	100	x	x	x	x	x
Engine Assembly	*2210*	100	x	x	x	x	x
Engine Support Structure	*2220*	100	x	x	x	x	x
Feed System	*2230*	100	x	x	x	x	x
Structures & Mechanics	**2300**	100	x	x	x	x	x
Main Tanks Assembly	*2310*	100	x	x	x	x	x
Upper I/F Adaptor	*2320*	100	x	x	x	x	x
Lower I/F Adaptor	*2330*	100	x	x	x	x	x
SLO Equipment Bay	*2340*	100	n/a	x	x	x	x
Body Flaps & Actuators	*2350*	80	x	x	x	x	x
Landing Gear	*2360*	100	n/a	x	x	x	x
TPS/TC	**2400**	100	x	x	x	x	x
Thermal Protection	*2410*	100	x	x	x	x	x
Active Thermal Elements	*2420*	100	n/a	x	x	x	x
Flight Control System	**2500**	80	n/a	x	x	x	x
ADCS	*2510*	80	n/a	x	x	x	x
RCS	*2520*	100	n/a	x	x	x	x
Flight Control Software	*2530*	100	n/a	n/a	x	x	x
Avionics	**2600**	80	n/a	n/a	x	x	x
On-board Computer	*2610*	COTS	n/a	n/a	x	x	x
Comm. Equipment	*2620*	COTS	n/a	n/a	x	x	x
Health Monitoring	*2630*	80	x	x	x	x	x
Power & Housekeeping	**2700**	100	n/a	n/a	x	x	x
Batteries	*2710*	COTS	n/a	n/a	x	x	x
Converters	*2720*	80	n/a	n/a	x	x	x
Cabling & Connectors	*2730*	80	n/a	n/a	x	x	x
Sensors	*2740*	COTS	n/a	n/a	x	x	x
SLO AI&T	**2800**	100	n/a	x	x	x	x

4.1.4 The Development & Production Industry Analogue

For the SpaceLiner, two of the three classical key components of the overall program cost, being the non-recurring development and the recursive production costs. It was deemed to preliminary to calculate operation costs due to the early phase of the program, and no clear operations scheme having being determined as yet. Here, given the hybrid nature of the vehicle, it is the philosophy that the development effort lies in the space-realm, since all technologies to be designed and tested are space-based. After the initial flight test units, production then resembles production processes of the aviation industry. The high quantities of the SpaceLiner vehicles expected to be produced is analogous to the rates of modern production of large airlines, like the Airbus A380 [9], or Boeing's B777 Dreamliner [30]. The cost of consequent units of production is thus considered based on assessment and analyses of the aviation industry to determine the potential production learning curve for SpaceLiner. These latter assumptions translate themselves into associated numerical complexities when calculating development and production costs for the SpaceLiner case-study.

4.1.5 The Main Engine Development

SpaceLiner features two cryogenic engines – a Booster (SLB) stage engine (nine engines per SLB stage), and a second engine for the passenger "orbiter" (SLO) stage (two engines per SLO stage). Here, it is vital to note that the SLO and SLB engines, mechanically, are the same, except for the nozzle extensions, as shown in Figure 15. As such, the SLO net engine mass is larger than for the SLB engine, having a larger nozzle. To attribute specific percentiles of novelty to two separate engines of the same technology, but of different scaling, would also be unreasonably precise at this early stage. Being identical mechanically, it is therefore assumed that only **one** development cost is incurred for the heavier SLO engine, thus providing a most extreme, 'worst case' cost, but which is then considered to also cover the development cost of the smaller SLB engine.

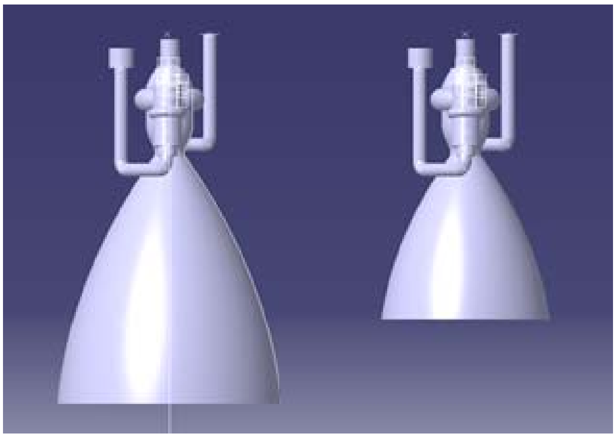


Figure 15: SpaceLiner Orbiter (left) and Booster (right) engines with different nozzle extensions [225]

4.1.6 Cost Estimation for Software Effort

The science of cost estimation between software and hardware, although interrelated functionally and operationally, is nevertheless very commonly segmented and addressed separately [42]. The software category of costs, both development and production, is largely synonymous across the phases, with 'production' comparative to software testing and enhancement once the core code has been compiled. And while interacting with hardware, the software cost category is no different to estimation of any other element, except that several aspects of the process are distinct, peculiar and unique [42]. Software costs are also very challenging to estimate for depending on the nature of the software as a product, which is essentially intangible, invisible and intractable. This makes the end product difficult to quantify [28, 202], with NASA referring to software cost estimation as constituting a "tar pit" [42] within context of their Space and Missiles Center experience.

One of the first essential steps in any estimate is to understand and define the system which is to be estimated. So while hardware requirements are well advanced, for the SpaceLiner case-study, software requirements have not yet been sufficiently defined, rendering them in the extremely early pre-phase 0 stage. As such, accurate costing an unspecified effort is an impossible task. After all, premature estimates are one of the contributors to inaccurate software development costs [202]. As such, software costs were not considered for the SpaceLiner concept at this stage.

4.1.7 SpaceLiner Production Quantity

For calculation of the SpaceLiner production costs, an interesting figure is the theoretical first unit (TFU) cost produced. Particularly for the TransCost model, the TFU cost is then used as the basis for calculation of all serial production costs for a batch of items to be produced. By definition, the TFU is the first unit in the serial production of multiple vehicles and as such, should incur the highest production cost out of the batch to be produced. Usually, production quantity is directly dependent on a clearly defined business case. In turn, the latter incorporates not only a clear, overall program schedule, but also flights rates, which inherently assumes the clear defined launch/landing (L/L) sites and consequently determines the total revenue from expected flights to be sufficiently profitable resulting in financial gain, and a sufficient return on investment (ROI) for its investors. For the SpaceLiner case-study, such a business case has not been yet established, since the technical details, as well as key programmatic data are not yet finalised. As such, a basic assumption had to be made.

Taking the established SpaceLiner program schedule already introduced in Chapter 4.1.2, we see that the operational timeframe has been assumed and set as being 20 years. Although some L/L sites have been proposed, with the reference mission established being Australia to Europe, it can be assumed in a conservative approach that L/L pairs may be located in China and the USA as well (see also Chapter 4.11 for a more detailed discussion). Assuming that between these L/L pairs, four routes are established, those would be flown daily, in each direction, equating to eight SpaceLiner flights per day. Daily flights would need to be ensured to allow passengers the freedom and flexibility of travel to tailor their travel needs and short travel times.

With eight flights per day, this equates to 2920 flights per annum. And with SpaceLiner baseline core vehicle element reusability (excluding engines) of 150 times, this results in a required SpaceLiner production rate of 20 vehicles per year. Adding an additional 5 vehicles as a margin to this amount (one additional SpaceLiner per L/L pairing, with one further additional safety-margin vehicle) results in a required production rate (with margin) of 25 vehicles. Consequently, over the 20 year proposed production phase, this results in a total of 500 SpaceLiner vehicles produced.

4.1.8 SpaceLiner Reusability Impact on Production

Being designed as a fully reusable vehicle means that a single SpaceLiner vehicle can be flown multiple times, a capability which is strongly aligned with cost effective space access. This reusability has a technical limit, which is specific as being 150 flight cycles for the SLO (and SPC) and SLB elements. For the eleven SLMEs per SpaceLiner vehicles, it is assumed that a baseline engine reusability will be 25 times given technical restraints and the current capability of existing rocket engines. Despite being known to be a technical challenge for rocket engines, the relatively high reusability rate is, however, not deemed impossible. For example, the Russian Kuznetsov NK-33 engine, currently utilised in the first stage of Orbital Sciences Corporation's Antares launchers, albeit in a modified version, are rumoured to have been successfully fired on a test-bench well above 30 times [54, 141]. In view of this, a further interesting and plausible sensitivity analysis for 50 times SLME reusability would be relevant, and is indeed considered later in this Thesis in Chapter 4.10.9.3, although realising this goal this will depend on technical capabilities and limits, which can only be determined through prototyping and extensive testing.

With an SLME/(SLO/SPC/SLB) reusability ration, it is also clear that the varying rates of reusability for parts in a single, common vehicle also directly influence production rates, since engines would have to be replaced during vehicle maintenance six times during the lifetime of a single SpaceLiner vehicle. This consequently influences production rate of SLMEs as well as the overall production costs during the program lifecycle. For production, 500 SpaceLiner units are considered. Each vehicle requires eleven engines, which must then be replaced six times. Therefore 66 SLMEs need to be supplied per SpaceLiner vehicle to match the reusability lifetime of each key component.

4.1.9 SpaceLiner Cabin / Rescue Capsule

The SpaceLiner passenger cabin and rescue capsule life-critical system (SPC) is the sub-system which constitutes the most novel and unprecedented and therefore challenging of technologies within the SpaceLiner case-study. Initially the structure is separated, allowing passengers to embark in a normal horizontal configuration. It is then integrated into the SLO main structure on the launch pad prior to launch. In case of emergencies during the flight, the cabin functions as a rescue capsule, capable of returning the passengers safely to Earth in an autonomous manner. The SPC and its integration within the SpaceLiner stage are shown in Figure 16.

While some loosely analogous rescue capsule systems based on a similar premise do exist, these are mainly observed within the aviation industry, including the B-58 Hustler, the XB-70 Valkyrie, the high-speed F-111 aircraft (2 crew), and the early prototypes of the Rockwell B-1 Lancer aircraft (4 crew). However for all of those aircraft, the scale and crew-carrying capacity of these capsule structures deviates extremely to the SPC requirement of being able to transport 50 passengers. Looking into the space domain, historically, the Gemini (2 crew), and Apollo (3 crew) capsules from the mid-1960s, as well as the Mercury program, and the more recently proposed Orion capsule (4 crew) once again transport only a very limited number of crew compared to SpaceLiner case-study requirements. Therefore, directly using any aviation and space analogues forms a weak basis for a representative comparison of technologies, and therefore expected costs, within context of the SpaceLiner case study. Therefore conceding that there are differences between historically available precedent programs to the SPC component of the SpaceLiner program is a very important point for later analyses and discussion of development and production cost results based on the AA and parametric model calculations.

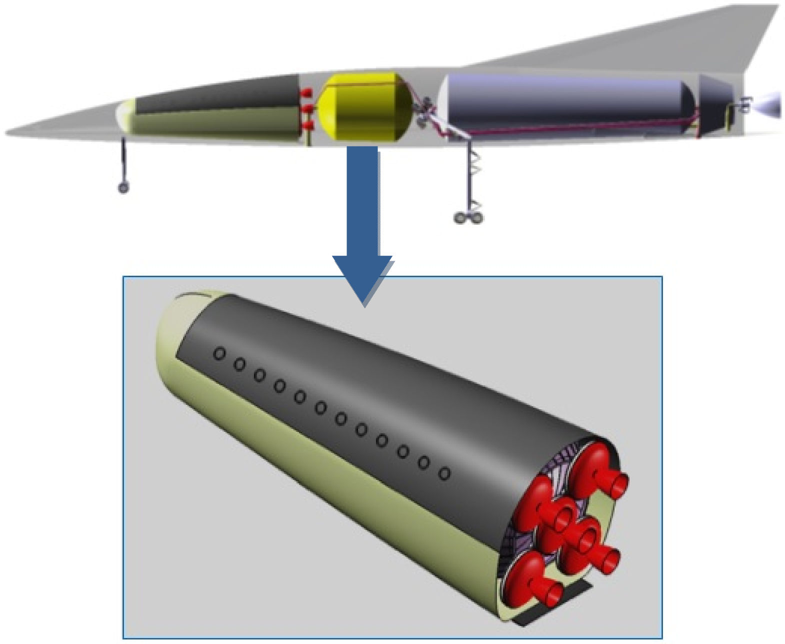


Figure 16: SpaceLiner SPC passenger cabin and emergency escape capsule [22]

4.1.10 SpaceLiner Operations & Ground Costs

While both operations and ground (O&G) cost considerations are, of course, critically important to complete the total LCC analyses for an overall program, at this stage the SpaceLiner operational concept and therefore the processes as well as exact ground infrastructure requirements remain largely undefined as they are still evolving. More crystallised information regarding flight routes, L/L sites and environmental impact is required to obtain a reflective and fixed regime and thus inputs and cost estimation for operations and the ground segment infrastructure requirements and schematic. As such, both the operational and ground infrastructure scenarios are described quantitatively only, in Chapter 4.11, with some numerical estimates and assumptions provided. However, these LCC components specific to the SpaceLiner case-study and application will need to be investigated further in particular as the technical and mission specifications and requirements of the concept continue to emerge to a maturity and into fruition.

4.1.11 SpaceLiner Cost Risk Analysis

In addition to the importance of representative scheduling, which seeks to minimise the likelihood of cost overruns and scheduling delays, the effects of potential risks must be considered during initialisation of a program through risk analysis. While this topic has already been briefly introduced theoretically in Chapter 2.3, it is discussed in greater depth, albeit at a qualitative manner, in the consequent chapter.

In his classic 1982 book entitled *Augustine's Laws*, Norman R. Augustine famously stated that "two types of uncertainty plague most efforts to introduce major new products: known-unknowns, and unknown unknowns" [18]. This is particularly relevant to the chosen SpaceLiner case-study. Given the magnitude and expanse of the SpaceLiner program, here, close assessment of the known unknowns, the cost risk assessment element, is especially crucial. Risk bears a negative connotation, implying a detrimental effect of an unforeseen or unexpected event on the program execution, scheduling and therefore, cost. It is therefore very important to conduct various risk analyses and assessments prior to program commencement, to try and address, capture and identify possible risk factors and elements which may impact a program, and seek to quantify the cost ramifications.

Risk is defined as the uncertainty of successfully achieving any of the technical, programmatic and/or cost targets of a project [116]. Within this definition, and with reference to the SpaceLiner case-study, technical, scheduling, programmatic, financial (cost) and operational considerations all contribute a certain degree of risk [202]. As shown in Figure 17 below, the single common denominator for the various risks introduced through the latter program elements, is cost. Thus, it is imperative to be able to translate any identified potential program risk into a cost, to integrate within program budget. Implementation of effective risk mitigation techniques allows for this cost to be minimised.

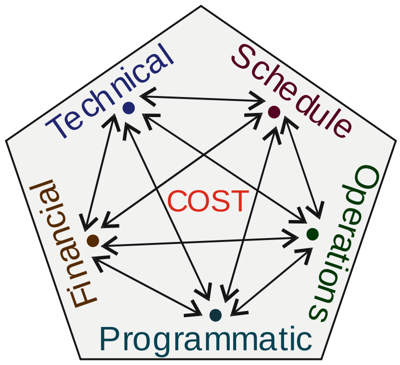


Figure 17: Interrelation of program elements which introduce risk and uncertainty [116]

While only internal factors are under the direct control of program management, risk is frequently imposed due to external factors. Nevertheless, all risks still require identification and careful and strategic management. Here, risk assessment seeks to quantify the probability of a certain event occurring and its consequent impact on a project, in which way risk can be in part preempted and factored in for within a cost estimate. All projects, and in particular large-scale, international programs with an increased number of interfaces and increased complexity like the SpaceLiner case-study, contain a certain amount of risk. The actual process of active risk assessment has bene defined in a multitude of ways, depending on the project. However, the basic steps include planning of risk management, identifying the risks, performing qualitative and quantitative risk analyses, and planning risk responses as a mitigation action [156]. Madauss also outlines a more comprehensive approach to achieve the same goal in four steps, as shown and outlined in Figure 18.

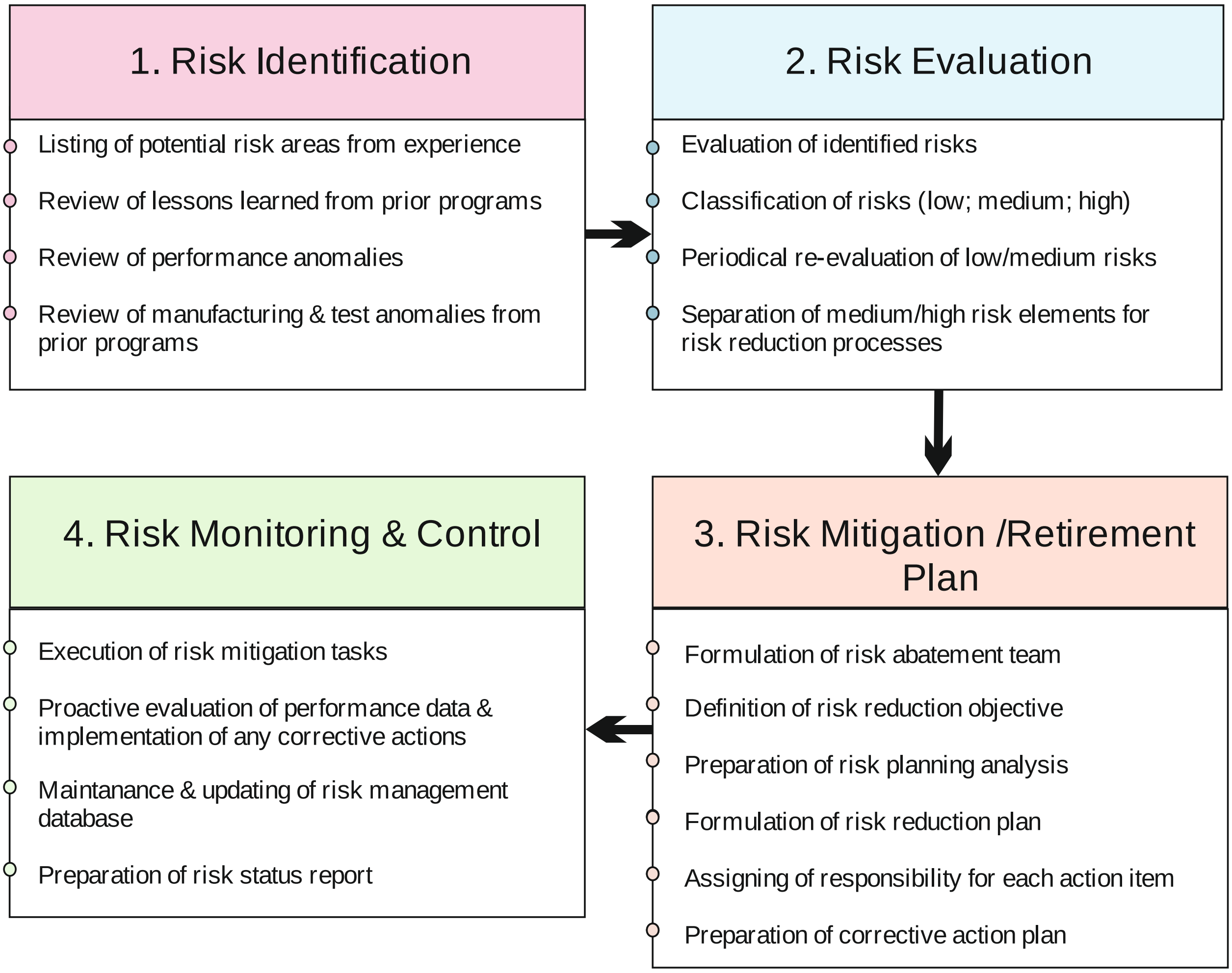


Figure 18: Four step process to risk assessment and mitigation [69, 115, 116, 133]

From the beginning of the project phases all potential risks must be identified, evaluated, mitigated and constantly monitored in line with the four step risk management and mitigation approach. For the SpaceLiner concept, since the operational scenario is not yet determined, operational and programmatic risks remain difficult to assess. Technical risks and challenges for the case-study vehicle have, however, been identified and well documented [208], although these too are dynamically evolving concurrently with SpaceLiner's definition of technical details and specifications. Here, and from a technical and logistics perspective, the aim should be that any remaining technical risks will be minimised to a level which is acceptable for successful integration into the commercial passenger transportation niche, being comparable with standards enforced within the aviation industry. To address this, a key philosophy of the SpaceLiner design concept is to base the design on state-of-the-art technologies in order to keep the potential technical risks as low as possible. In addition, a passenger rescue capsule has also been integrated into the design with the aim of improving the significantly lower safety factor of the space domain.

Here, a critical engineering challenge for all passenger transportation vehicles is to reach a high reliability status through low technical and operating risks (see Figure 17). In this respect, the rocket SLB, SLO (SPC) elements should be man-rated to achieve a much higher reliability and a well proven safety record of close to 100 percent, similar to the aviation industry. This, however, cannot occur until the elements have been fully developed, and performed regular, successive, intensive and successful flights to prove the reliability of the technologies involved. When a firm reliability record is established, it can be expected that passenger demand based on the feeling of security, as well as funding sources, are likely to increase [6]. More information of SpaceLiner case-study technological, logistical and operational risks can be found in detail in ref. [208]. Here, key SpaceLiner case-study challenges are identified to be the safety and reliability of the system, acoustic noise and sonic boom, launch and landing (L/L) site as well as routes, destinations and city pair selection, a door-to-door passenger transportation network, trajectory optimisation and thermal protection system (TPS) ramifications, environmental impact, as well as operational considerations [208]. Each aspect would require a risk assessment, to translate into a cost equivalent. At this stage, this has been achieved through a global margin imposed for costs for all models applied within the AA context.

A baseline SpaceLiner case-study schedule and timeline has also been proposed in Chapter 4.1.2, although this is also of a preliminary nature, hinging on future elements such as production quantities, which in turn depend on flight location pairings, and a business case which considers flight frequency and how many vehicles should be in concurrent operation. To achieve such a preliminary schedule, various assumptions had to be relied upon, all of which have also been fully documented to support justification. When concrete information becomes available, in line with the four step risk assessment plan, assumption should be replaced with fixed program data.

In terms of the financial risks for a complex system as the SpaceLiner concept, assessment and quantification is a challenging task given the multitude of influencing factors. However it is well known that estimating confidence hinges directly on the detail and status of program definition, which makes early program phase cost estimation such a challenge. It is therefore of great importance to develop and crystallise realistic and clear technical specifications and requirements as a solid basis and prerequisite of a reliable cost estimation.

In summary, risk assessment must be implemented across all major WBS element categories. The introduction of risk assessment actions and the attempt to eliminate all risks related to cost estimation is the primary formal means for risk control, at this early stage of the SpaceLiner case-study, the assessment of risks was performed at a very top system level through a judgement of the overall estimating confidence, as will be discussed in Chapter 4.12. The hardware cost estimation for the development and production phases of the SpaceLiner case-study which are performed and discussed in this Thesis are optimally based on all currently available preliminary technical definitions, a systematic baseline project structure demonstrated in consolidation of a WBS, as well as establishment of a preliminary project schedule.

For more information on the diverse field of risk assessment, the interested readers may refer to the following references for further details on risk and uncertainty assessment and management across the various program aspects [13, 31, 42, 65, 94, 115, 133, 137, 156, 212].

4.2 CASE-STUDY COST ESTIMATION APPROACH

This sub-chapter details the challenge and the process used to arrive at an initial SpaceLiner case-study cost estimate for the SpaceLiner case-study vehicle development and production for both the theoretical first unit (TFU) as well as consequently for a proposed serial production schedule. The focus of this work is predominantly the initial development costs, which are typically very high, especially for large, complex aerospace systems [222]. And for such a largely unprecedented and integrated launch system as the SpaceLiner, it is not unreasonable to expect that the largest obstacle to its actual operation will be finding investors for the prospectively significant development cost. Preliminary production costs are also calculated with a relatively high degree of certainty through implementation of AA, while operational processes and ground infrastructure are considered qualitatively at this preliminary stage.

The task of establishing an early phase SpaceLiner cost estimate was broken down into the following five steps, as illustrated in Figure 19. The following individual sub-chapters describe the first four steps in more detail. The final fifth step is then relegated into an own chapter since this constitutes a large proportion of the cost analysis work of this Thesis.

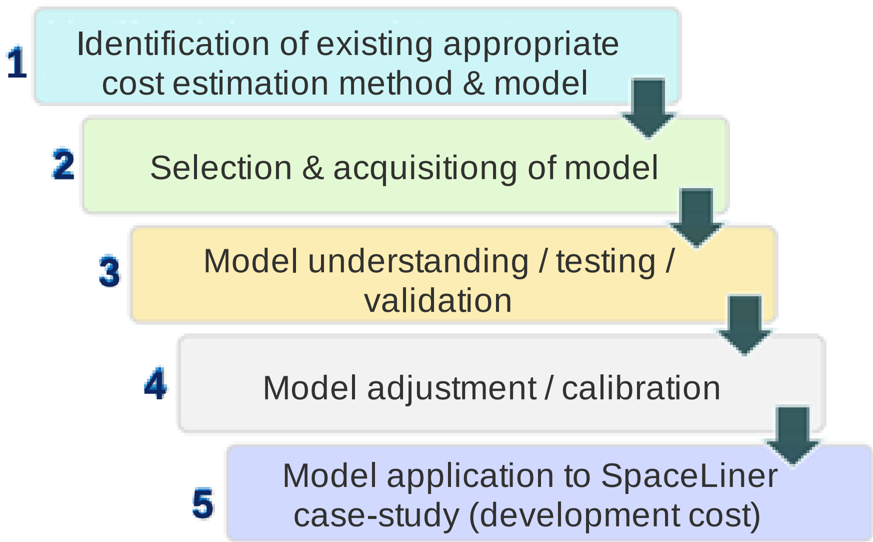


Figure 19: Framework for SpaceLiner development costs estimation processes

4.3 COST ESTIMATION METHODOLOGY IDENTIFICATION

As introduced and described in Chapter 2.6.2, the Amalgamation Approach will be implemented and demonstrated within this Thesis within application of a current and actual industry case-study, the SpaceLiner concept.

Furthermore, as previously established and detailed in Chapter 2, various key cost estimation methods (CEMs) exist for application within the space industry. Suitability of each CEM is strongly dependent on program phase. With every advancement and change to any aspect of a program, it is essential to re-evaluate and update the latest cost estimate to incorporate changes and reflect new information as it becomes available. In this way cost estimation is a dynamic process ongoing throughout the entire program lifetime.

SpaceLiner is in the early development phases, and more specifically, currently classed within the pre-phase A stages. As such, reflective of the active research and concept advancement and incorporation of technological progresses within context of the program, the concept is dynamically evolving. Flexible, system level CEMs are applicable to this early stage, while more detailed and resource intensive approaches, like EBU, are inefficient and thus inappropriate.

Consequently, the firm theoretical cost engineering baseline established through the intensive literature review found in ref. [209] could be applied to a current and real industry example of a large, complex and international space program in its early phase – the SpaceLiner concept. Through application of key findings from analyses already presented in Chapter 2 and through dissemination of cost estimating principles presented in Figure 5, the parametric approach was selected for predominant utility and application to the SpaceLiner. Analogy as well as the EJ and ROM CEMs were also identified as being relevant during this phase.

In line with the AA_{MAC} structure requirements and theory, three tools and models were identified for application to the case-study example chosen within the context of this Thesis. As already introduced in Chapter 4.4, two space-industry prominent and highly utilised commercial off-the-shelf models and tools were chosen, being PRICE and the 4cost *aces* parametric and data-empty models. In addition, the high-level, dedicated launcher systems parametric TransCost handbook and model was also selected. The TransCost Model is available for ready purchase in the form of a textbook. The PRICE and 4cost *aces* models, however, all require varying annual license fees.

For the purpose of this work, the 4cost *aces* software was used under an agreement to support the aims and goals outlined in this Thesis with the unwavering and excellent support of Mr. Joachim Schöffer and Mr. Herbert Spix. The PRICE software was utilised under an academic license from the International Space University (ISU) in Strasbourg under the guidance of the distinguished Professor Bernd Madauss, with outstanding assistance offered by Mr. Fabian Eilingsfeld.

All three models of TransCost, 4cost *aces* and PRICE selected for AA_{MAC} mode utilisation in this Thesis are outlined in greater detail in the consequent chapters.

4.4 AA_{MAC} COST ESTIMATION MODEL & TOOL SELECTION

CEMs form the backbone of various existing cost estimation tools and commercial models relevant to the space sector which exist. These were also identified and listed in the literature review [209]. Three such parametric tools and models were identified and chosen and in line with AA principles and based on their suitability to the SpaceLiner case-study. These comprise of the dedicated TransCost model for launch vehicles, as well as the commercial 4cost *aces*, and PRICE tools. These are briefly introduced and outlined below.

4.4.1 TransCost Model

The parametric TransCost Model for Space Transportation Systems Cost Estimation and Economic Optimisation was chosen as one of three models within the AA framework for the SpaceLiner case-study. TransCost is a dedicated launch vehicle system model encompassing cost categories of expendable (ELV) and reusable (RLV) launch vehicles. It is therefore of interest within the context of this review. The model itself is integrated into the Handbook of Cost Engineering for Space Transportation Systems. Conceived initially as a cost engineering tool, TransCost uses the parametric CEM with underlying CERs derived from a vehicle and engine database of cost data of European and US space vehicle and engine projects within the 1960-2009 timeframe. As such, TransCost is referred to as a 'data-full' model to reflect its inclusion of project-related data for space programs.

TransCost breaks down the costs of a program into three clear categories, being development costs, production costs (incorporating the learning factor, f_4) and operations costs. This latter group of costs is more generally defined categorically, since operations costs are mission-specific, making universal formulae difficult to establish. In this sense, TransCost sets out categories, areas and classes of costs for individual consideration and determination on a case to case basis.

Designed specifically to be applied in the initial conceptual mission design phases, TransCost was an extension of the 1971 dissertation work of D. E. Koelle and is now a very commonly used space transportation cost model within industry, perhaps due to its low cost and ready availability, simple handling, and transparent cost estimation relationships (CERs) and data which underlie the model. Data from historically recorded missions is used to derive a regression line of best fit. Such a regression line is then represented mathematically, in the form of a CER. It is then assumed that any future missions of similar characteristics can be modeled by this trend line. TransCost features dedicated CERs for various vehicle categories, with any differences between underlying CER data and the mission being estimated (i.e. complexities, technology novelty and other deviations), adjusted for by specially defined complexity factors. TransCost effectively features twelve complexity factors (f_x), from f_0 to f_{11}, which can be applied to the existing basic CERs to adjust for variations between the underlying CER and the program which is being costed. These factors are defined and summarised in Table 9 below, while a full list of all the complexity factors, their definitions and values are also included in Appendix D for completeness and the self-contained autonomy of this Thesis as a stand-alone document.

Being a dynamic model, both the database and CERs are continuously updated, and the latest model available since October 2010 is TransCost Version 8.1. Minor variations in CERs exit between the modified TransCost versions, the latest three of which are comparatively shown below in Table 9. While some minor variations of TransCost value ranges can be observed between the three TransCost versions, this shows the dynamic and evolving nature of the Handbook and cost estimation model which seeks to keep up to date with current trends and developments within the space launch vehicle sector.

The model itself addresses three areas of the launch vehicle life cycle costs, being development, production and operations costs. Each category is further broken down into sub-categories, each with its own unique respective CERs, which address distinctly identified categories of ELVs, RLVs and craft, and include solid propellant boosters, liquid propellant, pressure-fed as well as turbo- and ramjet engines, and crewed capsules and space systems. Different factors underpin each CER, and focus on vehicle mass, number of launcher stages, number of units produced and the expected launch rate.

Furthermore, a range of twelve additional complexity factors exist, to be assigned in accordance with what is being costed. These factors, collectively denoted as fx, address the impacts of varying technological advancements and quality level, team experience, regional productivity, series production, effects from increased number of participating contractor organisations, subcontractor-ship or Government involvement, optimum schedule deviations and past technical experience, as well as, more recently, the commercial element to development and production. A visual representation of the TransCost Model structure breakdown is presented in Figure 20.

Table 9: TransCost Complexity Factors defined for three TransCost versions

TC Factor	Definition	TC 7.3 Formula / Values	TC 8.1 Formula/ Values	TC 8.2 Formula/ Values
f_0	System engineering/integration factor	1.04^{N*}	1.04^{N*}	1.04^{N*}
f_1	Development standard factor (*dev. costs*)	0.4 to 1.4	0.4 to 1.4	0.3 to 1.4
f_2	Technical quality factor (*dev. costs*)	system/element specific	system/element specific	system/element specific
f_3	Team experience factor (*dev. costs*)	0.7 to 1.4	0.7 to 1.4	0.7 to 1.4
f_4	Cost reduction factor for series production (prod. costs)	0.7 to 1.0	0.7 to 1.0	0.7 to 1.0
f_5	Refurbishment/maintenance cost factor (ops. costs)	mission specific	mission specific	mission specific
f_6	Cost growth by deviation from optimum schedule (dev. costs)	see Appendix D	see Appendix D	see Figure 49 in Appendix D
f_7	Program organisation / cost growth factor for parallel contractor organisations (*dev. costs*)	$n^{0.2**}$	$n^{0.2**}$	$n^{0.2**}$
f_8	Regional productivity model (dev. costs)	see Appendix D	see Appendix D	see Appendix D
f_9	Cost impact of sub-contractorship	see Appendix D	see Appendix D	see Figure 50 & Appendix D
f_{10}	Cost reduction by past experience, technical progress and cost engineering application	0.7 to 0.85	0.7 to 0.85	0.75 to 0.85
f_{11}	Independent development w/o government contract's requirements & customer interface	0.55 to 0.65	0.3 to 0.45	0.45 to 0.55

*) *N= number of vehicle stages*
**) *n= number of parallel contractor organisations involved in program*

A particular feature of the model is the use of the 'Work-Year' costing unit, which provides firm cost data transcendent of inconsistencies due 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 stated as being within ±20% of cost data range [102]. The open nature of TransCost also means that it can be easily implemented within various programming environments, such as Excel©, which will be demonstrated further in this Thesis.

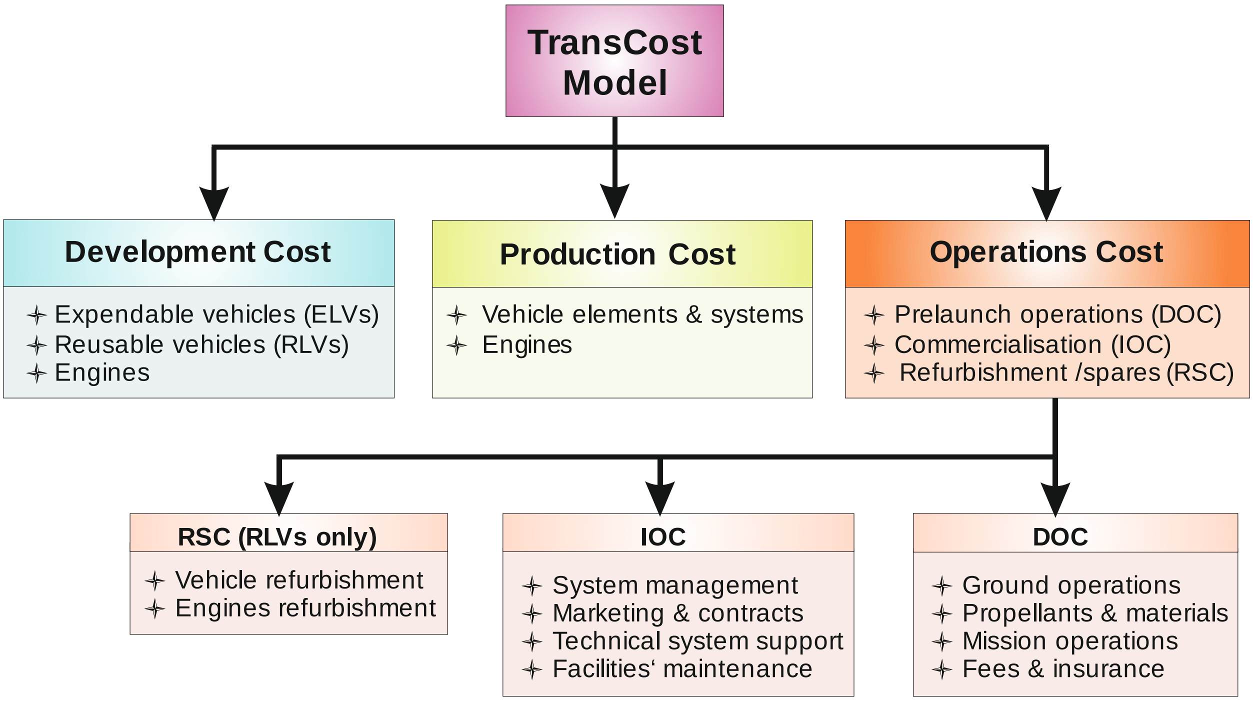


Figure 20: TransCost Model category structure for CERs and costs

4.4.2 TransCost Selection Criteria

In summary, the TransCost model is a dedicated launch vehicle cost model which covers launch vehicle development, production and operation for both expendable (ELV) and reusable (RLV) launch vehicles. A key feature is a detailed and transparent cost database of reference programs for European and US space projects over the past five decades, based on which underlying CERs are derived from. Each cost category is further broken down into sub-categories with their own unique, respective CERs addressing various ELV and RLV technology categories of stages, solid and liquid propellant boosters, pressure-fed and turbo- and ramjet engines, and crewed capsules and space systems. Different complexity factors underpin each CER, and address system-level parameters including mass, number of launcher stages, number of units to be produced, and expected launch rates. Complexity factors are then further assigned as necessary to factor for aspects like technological level, team experience, regional productivity, series production, and program funding structure. A particular feature of the model is also the use of the 'Work-Year' (WYr) costing unit, which provides firm cost data transcendent of inconsistencies due to international currency conversion rates and annual inflation fluctuations. The effort figure can then be converted to any currency, for any year's economic conditions (e.c.).

Therefore the TransCost model applicability and selection for the SpaceLiner project was justified for the following main reasons:

- **Dedicated** cost model for launcher vehicles (ELVs and RLVs).
- **Updated** database from **52 years** of program history for Europe, USA, and Japan.
- **Transparent**, open CERs with **identifiable and visible reference missions** behind each formula shown in a graphical display of reference points.
- Ideal applicability at high, **total system level**
- High suitability for use during **early, conceptual inception and design phase** while technical and mission details are still emerging
- Uses of effort **"WYr" unit to quantify cost**, which overcomes possible exchange rates, currency, inflation and timeframe conversion fluctuations and inconsistencies
- High relevance also to **advanced**, **reusable space transportation** concepts

Therefore the TransCost model was selected as the basic, kernel model and tool for the baseline SpaceLiner LCC calculations of development and production. In particular, dedicated CERs applicable to these two cost categories were targeted for utility. Operations costs (WBS element 7000) could be disseminated largely in a qualitative only, with some numerical figures provided, although backed mainly by analog or EJ CEMs. In addition, ground infrastructure (WBS element 6000) was also loosely estimated based on the EBU, analogy and EJ approaches. due to the still early program phase of the SpaceLiner concept, the final version of these two LCC aspects will need to be reconsidered at a later stage when final program details and requirements are concrete. Therefore, the non-recursive development costs, and the recurring production costs were focal to this study.

Based on theory, other supporting CEMs including analogy, EJ and the ROM approach were also deemed relevant, concurrently employed, and often relied upon as sanity checks during the costing process.

The overall cost estimation ranges for SpaceLiner development and production are therefore a result of the CEM amalgamation approach (AA) which has been strategically established, developed within this Thesis, and applied to a current actual space program in line with efficient cost engineering principles and practices.

4.4.3 PRICE Systems PRICE-H

The PRICE-H cost estimation model was developed by Frank Freiman in Moorestown, New Jersey, with its origins in military space applications. Based on his studies of statistical quality control, in 1969 he invented parametric cost modeling for hardware systems development and acquisition [12, 152]. The PRICE-H Model was then established commercially by Mark H. Burmeister at the former RCA-Astro organisation, now Lockheed Martin in 1975 [152]. Being developed to assist with bidding on payloads for military systems to DoD on intelligence satellites, the PRICE Systems Solutions now constitutes a market leading software distributed by

PRICE (Parametric Review of Information for Costing and Evaluation) Systems internationally. A subscription for the software is required.

The PRICE® Systems Solutions is based on the parametric CEM, and consists of two sets of models, being the legacy PRICE Estimating Suite (PRICE-H and PRICE-S) and the new generation TruePlanner (True-H and True-S) [137]. Both PRICE models contain hundreds of CERs derived from extensive research and statistical analysis of data from over eleven thousand completed projects with defined product characteristics and known schedules, with most of the data points themselves sanitised. The CERs are proprietary and the database therefore confidential. As such, PRICE-H is what is referred to as a 'data-empty model', also meaning that the model must be calibrated prior to its application for a specific project. The PRICE Estimating Suite is not a dedicated space systems or launcher model, so applications extend across multi-disciplinary estimates. The model is however very frequently applied to the space sector for hardware, software and scheduling estimations and project planning, particularly at the product concept stages [42]. Clients of the PRICE products include organisations like the DLR and NASA, which hold agency wide licenses on the software [135].

Since this Thesis has a hardware focus, only hardware models will be mentioned herein. To complement PRICE-H, the PRICE suite also includes the PRICE-HL (Hardware Lifecycle) and PRICE-M (Electronic Module and Microcircuit) models. PRICE-H has the capability to estimate most manufactured items and assemblies, and requires key inputs such as weight, manufacturing complexity, quantities, schedule information, development costs and production costs [60]. The model must first be calibrated for each individual project by the user, which consequently allows for extraction of benchmark data for future use and reuse. This calibration is achieved through application of multiplication factors including the main Platform and Complexity parameters, the latter are deemed to be the core of the PRICE hardware cost model, being the universal metric for normalised cost density in a hardware item. A basic Platform Value allows for conversion of historical data to more modern applications by transcending different disciplines, and effectively considers different operational environments in terms of commercial, military ground, airborne, manned and unmanned space. Complexity factors must be calibrated respective of product family, with the Engineering Complexity Factor addressing design standard and team experience in combination with a Manufacturing Complexity Factor. While the model facilitates for manual entry of parameter values, default Complexity values are also available.

The complementary PRICE-HL model generates operations and support cost outputs across all phases of hardware life cycle. Additionally, the PRICE-M estimates electronic module and applications specific integrated circuits (ASICs) development and production costs.

4.4.4 *aces* by 4cost

The Advanced Cost Estimating System, *aces*, is a parametrics-based module of the 4cost suite, constituting cost estimating software for gauging plausibility of projects during the early stages. Released by the German company 4cost, this 'most innovative parametric model available' [2] was developed by a group of software, hardware and cost engineers under the leadership of Herbert Spix, and has been on the market since 1992. An annual license fee depending on the license type is applicable.

The 4cost *aces* model is a general all-purpose model applicable to compile cost estimates for mechanical and electronic hardware assemblies and systems as well as software programs [4]. Again, being a data-empty model, 4cost *aces* must be calibrated prior to project application and in line with respective historical company data. A built-in model for life cycle costs allows *aces* to derive costs from acquisition stages, to preliminary design and development through to production and LCC analysis. Optional user calibration allows the model to function like a specific tool. Within the space industry *aces* has been used by companies and research institutions including OHB, DLR and the former EADS Astrium, now known as Airbus Defence and Space.

The model is differentiated by the fact that it does not have an underlying database of past missions. Instead mathematical functions and algorithms (CERs) based on multi-disciplinary data collected and analysed over many years, form the basis of all cost estimates. As a deviation from the traditional processes, inputs like material lists and labour hours are therefore not needed. Instead, inputs pertain to economic conditions, manufacturing processes and development strategies [2], based on which only relevant inputs associated with an appropriate mode are highlighted for the user. Programmed using Visual Studio and C++, *aces* facilitates for common import and export interfaces in various formats including, amongst others, Excel© as well as text files [3].

The resulting output estimate provides an initial 'feasibility check' for a preliminary design, and cost information for hardware development, production and LCC trends. The output also reflects costs including those associated with design engineering, drafting, project management, documentation, system engineering, special tooling and test equipment, material, labour and any overheads. The model also provides estimates for subsystem integration and assembly costs and system testing [2].

4.5 TRANSCOST MODEL TESTING, CALIBRATION & VALIDATION

The process of understanding, testing and validation was only possible and therefore only relevant and applicable for the TransCost model. This is the only transparent, and data-open model which facilitates for a testing and calibration regime to be implemented. The 4cost *aces* and the PRICE tools, being commercial tools, are both data-closed and confidential models with non-transparent databases and thus, model mechanics. Both models, however, are widely utilised within the space sector within formulation of cost estimates for a wide range of missions and applications, and also during various program phases.

4.5.1 Understanding TransCost Development Cost Estimation

Prior to the TransCost model being applied for calculating SpaceLiner development costs, it was deemed important to firstly test the model and establish a solid understanding of its mechanics, and the associated complexity factors, as well as the CERs, their derivations and groupings of underlying reference missions. This was achieved by applying TransCost to several, select known missions, which allowed for calibration of complexity factors for future application to SpaceLiner.

During this process, the programmed Excel interface was also consequently tested and debugged. To achieve this, a TransCost testing and calibration regime was developed and defined, during which TransCost was applied to various launcher programs, the resulting cost estimates analysed and conclusions drawn. This process is illustrated graphically at a top level in Figure 21.

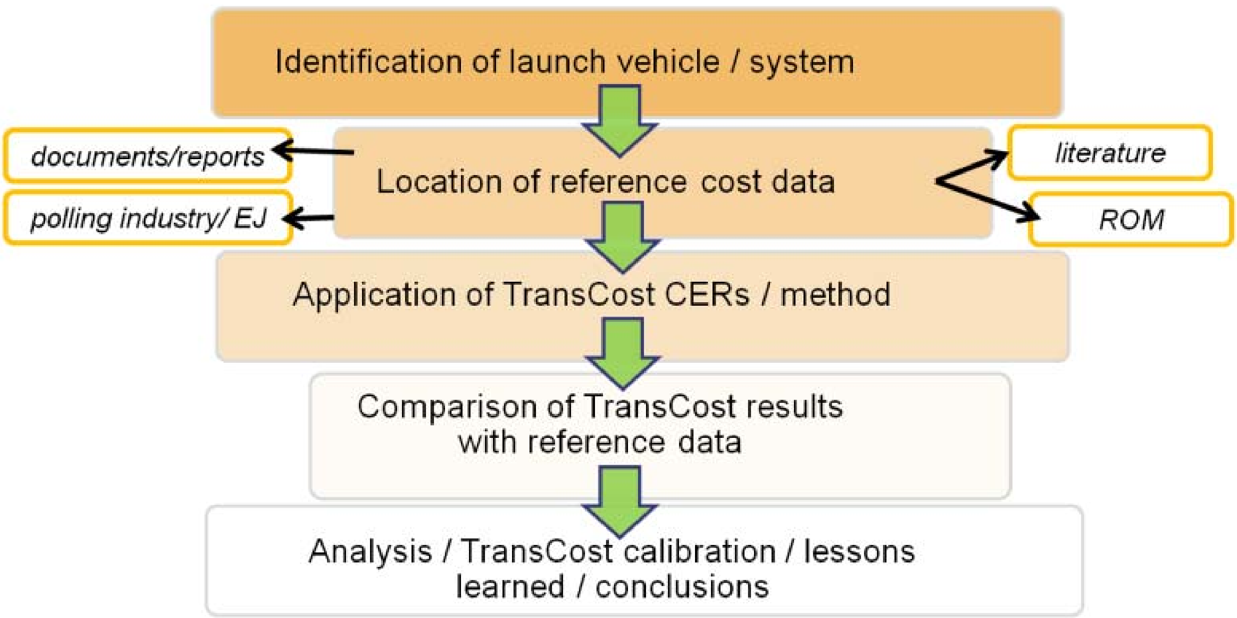


Figure 21: Illustration of TransCost model testing regime

4.5.2 TransCost Development Cost Structure

The TransCost model arrives at its development cost estimates for each individual system component, such as a system stage, booster or propulsion unit, or engine. These are then summed, and complexity factors are applied at a higher level. Here it is important to note that the factors f_6, f_7 and f_8 are collectively known as programmatic factors (PF) since they are associated with program organisation, and are described in the definition of the top level formula:

$$C_D = f_0 (\sum H_E + \sum H_V + \sum H_B)\ f_6 \cdot f_7 \cdot f_8 \ , \qquad (1)$$

where
f_0: systems engineering/integration factor
C_D: total effort (WYr)
H_E: engine CER effort (WYr)
H_V: vehicle/stage CER effort (WYr)
H_B: booster CER effort (WYr)
f_6: scheduling complexity factor
f_7: program organisation factor
f_8: regional productivity factor.

For each category of engine, vehicle and boosters, independent CERs have been derived, taking on the following two forms:

$$H = a \cdot M^x \cdot f_1 \cdot f_3 \ , \qquad (2)$$

$$H = a \cdot M^x \cdot f_1 \cdot f_2 \cdot f_3 \ , \qquad (3)$$

where
H: element CER effort (WYr)
a: derived constant (CER specific)
M^x: mass of component (with derived CER specific exponent, x)
f_1: development standard factor
f2: technical quality factor
f3: team experience factor.

Therefore, each program or vehicle must be segmented into its constituents, which are then costed respectively at a system level. The launcher system elements covered by the TransCost model are split into two categories of *Propulsion/Engine Development CERs* and *Vehicle Systems Development CERs,* the constituent elements of which are shown below.

- **Propulsion/Engine Development CERs**
    - *Solid-Propellant Rocket Motors*
    - *Liquid Propellant Rocket Engines with Turbopumps*
    - *Pressure-fed Rocket Engines*
    - *Air-breathing Turbo- and Ramjet Engines*

- **Vehicle Systems Development CERs**
    - *Solid-Propellant Strap-on Boosters and Stage Systems Rocket Motors*
    - *Liquid Propellant Propulsion Systems/Modules*
    - *Expendable Ballistic Stages and Transfer Vehicles (ELVs)*
    - *Reusable Ballistic Stages and Transfer Vehicles (RLVs)*
    - *Winged Orbital Rocket Vehicles*
    - *HTO First Stage Vehicles, Advanced Aircraft and Aerospace Planes*
    - *VTO First Stage Fly-Back Rocket Vehicles*
    - *Crewed Ballistic Re-Entry Capsules*
    - *Crewed Space Systems*

After this, the appropriate TransCost defined complexity factors are applied, and all individual costs tallied to arrive at a final total system-level cost. The only sub-system information required by TransCost is that for engines (namely the mass and a technology factor, f_2, which is specific on a case to case basis). Inherently, the TransCost model does not adequately facilitate for a reduction in costs due to existing heritage from previous, similar programs. A team experience factor addresses the familiarity of a team with a proposed project. A technology specific factor, f_2, is then applied based on each specific system or element type.

Furthermore, it is important to note and highlight the specific 'development costs' definition which TransCost adopts. Five types of development costs can be identified and classified. These are:

1) Effective Cost to Completion (CTC) – Total cost after completion of the program, including inflation

2) Most Probable / Realistic Development Cost – Including a margin for unforeseen technical problems and delays which cannot be established at commencement of a program

3) Ideal / Theoretical Development Cost – assumes everything goes according to plan with no technical or schedule problems (this is the standard industrial proposal basis)

4) Minimum Credible Development Cost – unrealistic cost estimate under competitive situation in order to win a bid or contract (some cost items neglected)

5) Unrealistic Development Cost – Cost figures based on "believing" with no cost studies nor analyses and a lack of experience in order to sell a concept

Here, the development cost type which is calculated by the TransCost CER algorithms is Type 2 - *Most probable / Realistic Development Cost* since the underlying CERs are based on actual post-program completion system development costs. To put this in a rough numerical context, such a 'most probable' cost is a ROM 15-20% higher than the 'ideal cost' shown above in example 3, and also calculated using the EBU CEM which tallies independent cost estimates at a micro, sub-systems. Here, since TransCost CERs are based on actual costs, including therefore the costs for unforeseen technical problems and delays, TransCost therefore claims to "represent the 'most probable' or 'realistic cost'"[102].

4.5.3 TransCost Production Cost Structure

Similarly to the development costs, TransCost arrives at its production cost estimates for each individual system component, such as a system stage, booster or propulsion unit, or engine. Furthermore, the cost for production of *n* number of units can be calculated, as well as for the n^{th} number of units. The top level formula is described in in *Eq. 4* below:

$$C_F = f_0 \left(\sum_1^n F_E + \sum_1^n F_V \right) \cdot f_8 \ , \qquad (4)$$

where
f_0: systems management/vehicle integration & checkout factor
C_F: total effort (WYr)
n: number of units to be produced
F_E: engine CER effort (WYr)
F_V: vehicle/stage CER effort (WYr)
f_8: regional productivity factor.

If we assume that *n*=1, then we can calculate the production cost for the theoretical first unit (TFU), which is always the most expensive unit of the production chain, since afterwards the learning effect is observed.

Going one level deeper, for each category of engines and vehicles, independent CERs have been derived for production costs, which take on the following form:

$$F = n \cdot a \cdot M^x \cdot f_4 \ , \qquad (5)$$

where
F: element CER effort (WYr)
n: number of units to be built
a: derived constant (CER specific)
Mx: mass of component (with derived CER specific exponent, x)
f4: learning factor.

Once again each program or vehicle must be segmented into its constituents, for which production costs are then calculated. For production, again, the components are split into two categories of *Engine Production CERs* and *Launch Vehicle Systems Production CERs,* as shown below.

- **Engine Production CERs (First Unit Cost)**
    - *Solid-Propellant Rocket Motor, Strap-on Boosters and Stage Systems*
    - *Liquid Propellant Rocket Engines*
    - *Air-breathing Turbojet Engines*

- **Launch Vehicle Systems' Development CERs**
    - *Propulsion Modules*
    - *Ballistic Vehicles/Stages (Expendable and Reusable)*
    - *High Speed Aircraft / Winged First Stage Vehicles*
    - *Winged Orbital Rocket Vehicles*
    - *Crewed Space Systems*

A key consideration within the TransCost production cost category is the learning factor calculation. This hinges on empirical charts featured in the handbook, for engines and stages respectively, and is underpinned by the unit mass (per engine/stage) and the expected annual production rate. In fact, the number of units to be produced plays an important role, since the production cost can be expressed as a sum of a batch of *n* units, or alternatively, as the cost to produce the n^{th} unit in a batch.

As in any industry, consecutive units manufactured in succession to the TFU will be subject to the learning effects of production. Consequently, associated costs are expected to fall. This process can be described mathematically, with various learning effects mathematically noted across different industries. The TransCost model addresses the issue of the learning effect through a production cost reduction factor, f_4 on a component level, as seen in *Eq. 5.* This f_4 factor is based on the learning factor, p. Originally proposed by Theodore Paul Wright in the traditional average unit value approach denotes that a learning factor of 0.8 results in a cost reduction of 80% through the doubling of production for a single unit [100-102].

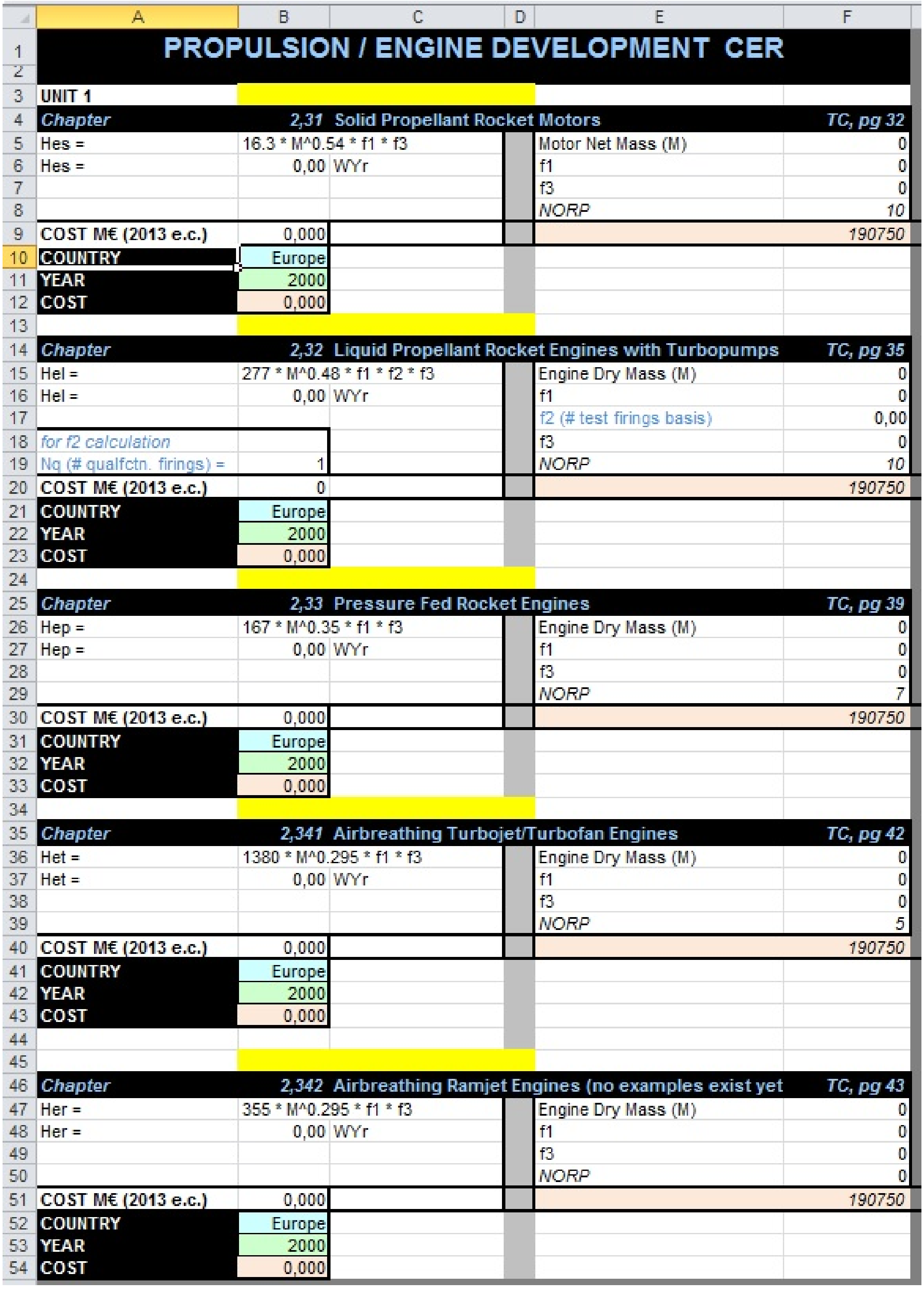
For space systems, the learning curve value has been found to lie generally between 0.80 and 1.0. Concurrently, for the aerospace industry, NASA has established this learning factor to be 0.85 [136, 137]. The specific value, of course, is quite logically dependent on unit size (mass) and the frequency of production (i.e. annual production rate). The basic underlying presumption is that the higher the production rate, the more pronounced the learning phenomenon, and hence the lower the overall production costs.

The number of parallel contractors, or in other words, a collaborative multi-organisational effort for production, also incurs a significant cost increase. For example, in the case of the Concorde, it was rumoured that the development cost increased by 30% due to the collaborative nature of the project, with two production lines required, one in Bristol, and one in Toulouse [145].

While this is an interesting production cost-driver to identify, as the production framework for the SpaceLiner case-study remains to be defined at this early phase, this factor is not incorporated into the calculations. As this becomes known, the cost estimate should be amended and revised, in line with cost engineering principles.

4.5.4 TransCost Model Excel Tool

The TransCost 7.3 model was taken as the baseline and programmed into a dedicated in-house Excel® spread-sheet interface and this tool was used to arrive at development and production cost estimate ranges using information. A screenshot of a development cost spreadsheet is shown in Figure 22 below.



	A	B	C	D	E	F
1	PROPULSION / ENGINE DEVELOPMENT CER					
2						
3	UNIT 1					
4	*Chapter*	*2,31*	Solid Propellant Rocket Motors			*TC, pg 32*
5	Hes =	16.3 * M^0.54 * f1 * f3			Motor Net Mass (M)	0
6	Hes =	0,00	WYr		f1	0
7					f3	0
8					*NORP*	*10*
9	COST M€ (2013 e.c.)	0,000				*190750*
10	COUNTRY	Europe				
11	YEAR	2000				
12	COST	0,000				
13						
14	*Chapter*	*2,32*	Liquid Propellant Rocket Engines with Turbopumps			*TC, pg 35*
15	Hel =	277 * M^0.48 * f1 * f2 * f3			Engine Dry Mass (M)	0
16	Hel =	0,00	WYr		f1	0
17					f2 (# test firings basis)	0,00
18	*for f2 calculation*				f3	0
19	Nq (# qualfctn. firings) =	1			*NORP*	*10*
20	COST M€ (2013 e.c.)	0				*190750*
21	COUNTRY	Europe				
22	YEAR	2000				
23	COST	0,000				
24						
25	*Chapter*	*2,33*	Pressure Fed Rocket Engines			*TC, pg 39*
26	Hep =	167 * M^0.35 * f1 * f3			Engine Dry Mass (M)	0
27	Hep =	0,00	WYr		f1	0
28					f3	0
29					*NORP*	*7*
30	COST M€ (2013 e.c.)	0,000				*190750*
31	COUNTRY	Europe				
32	YEAR	2000				
33	COST	0,000				
34						
35	*Chapter*	*2,341*	Airbreathing Turbojet/Turbofan Engines			*TC, pg 42*
36	Het =	1380 * M^0.295 * f1 * f3			Engine Dry Mass (M)	0
37	Het =	0,00	WYr		f1	0
38					f3	0
39					*NORP*	*5*
40	COST M€ (2013 e.c.)	0,000				*190750*
41	COUNTRY	Europe				
42	YEAR	2000				
43	COST	0,000				
44						
45						
46	*Chapter*	*2,342*	Airbreathing Ramjet Engines (no examples exist yet			*TC, pg 43*
47	Her =	355 * M^0.295 * f1 * f3			Engine Dry Mass (M)	0
48	Her =	0,00	WYr		f1	0
49					f3	0
50					*NORP*	0
51	COST M€ (2013 e.c.)	0,000				*190750*
52	COUNTRY	Europe				
53	YEAR	2000				
54	COST	0,000				

Figure 22: Screenshot of programmed TransCost tool in Excel showing the development cost interface

The initial TransCost 7.3 cost estimation model and the associated CERs and complexity factors were programmed in Microsoft Excel in three dedicated spreadsheets for Development, Production and Operations. Supporting worksheets were also made for key complexity factors, including f4, learning factor, f8, country productivity, as well as the vital TransCost WYr model. This spreadsheet tool was used as the basis for conducting cost estimation calculations for existing programs, and therefore analyses of the TransCost model and its mechanics.

More recently, the latest versions of TransCost 8.1 and 8.2 were obtained and studied closely to identify the changes which have been implemented since the previous TransCost 7.3 version. The existing Excel spreadsheets were consequently reprogrammed to implement TransCost 8.2 and new results calculated and compared to existing cost estimation results. The outcome of this exercise was to ascertain whether the new version was more representative of actual costs. The main changes observed were small variations in factor-defined value ranges, and are shown comparatively in Table 9 from Chapter 4.4.1 above.

A key difference with TransCost 8.1 and 8.2 is that the f_8 country productivity factor is applied on an individual CER basis internally within each of the development, production and operation (DP&O) sub-groups. Previously, however, f_8 was applied to the sum of the latter, at a higher level, when the sum of each CER was individually tallied. From a logic perspective, f_8 represents country productivity. In this sense, it is logical for this factor to apply at a lower level, since within a single project, difference components are frequently manufactured in various countries and are subject to different productivity conditions, which also influences costs. For most of the above development programs, work was performed in Europe and the European productivity factor (0.86) was therefore overall applied to the sum of the development, production and operations rather than on an overall $\sum C_D$ basis. In any case, this minor difference has no significant effect on costs calculated within this Thesis. Nevertheless, a future work to this existing TransCost validation regime could be a re-calculation using the updated and latest TransCost version, which ever this may be at the time of this proposed future re-work.

4.5.5 TransCost Development Cost Test & Calibration

The focal cost category for this Thesis is development cost. A range of launch vehicles of interest and their development programs were identified, being both ELVs and RLVs. TransCost was then extensively tested against existing cost data to obtain a solid feel for model dynamics, cost driving parameters and the complexity factors and their sensitivities. Here, only the development program phase (Phase C) was considered since the TransCost production cost was not ideally suitable for the SpaceLiner case-study example, something for which AA is ideally suited for, as is explained later in the Thesis.

The launcher programs assessed include both realised programs, as well as concept studies, like the ASTRA Hopper vehicle. The programs to which the TransCost model was applied, are listed in Table 10.

Table 10: Space programs used as inputs for extensive TransCost testing process

ELVs	**RLVs**
Ariane 5G	Space Shuttle
Ariane 5ECA	Buran-Energia System
VEGA & VENUS	LFBB
VLM	ASTRA Hopper

The RLV testing process for the LFBB concept is presented in detail within the main body of this Thesis, as this is particularly relevant to the selected SpaceLiner case-study. TransCost applications for RLV vehicles as shown in Table 10, are to be found fully for completeness sake in Appendix E, while all ELV analyses can be found in ref. [207].

The biggest challenge of this testing process and regime was data acquisition and ensuring its validity in terms of availability, sufficiency, representativeness and completeness of information. Sources of data and figures included text books, official documents (program reports, official industry presentations and meeting proceedings), internal sources like documents and technical notes, and complimented by information obtained from the polling of experts. In particular, vehicle program cost data was required, as well as background information and technical parameters, including masses. In many cases, existing data had to be carefully analysed, disseminated and processed to identify respective development and production costs proportion of overall stated program costs which were often expressed as bulk, combined figures.

In addition to the baseline parametric TransCost model and Excel tool, other CEMs which were used concurrently and include the analogy, EJ and the ROM approach. These were necessary and applied during selection of the TransCost complexity factors (f_x), as well as for 'sanity checks' to the resulting costs calculated.

4.6 TRANSCOST TESTING, CALIBRATION & VALIDATION FOR RLVS

Extensive work and analyses were conducted for the purpose of applying and therefore testing, calibrating and validating the TransCost model. Such a strenuous testing regime also allowed to ascertain whether the programmed TransCost model Excel tool (see Chapter 4.5.4) was representative, facilitating for the debugging of any potential programming errors. The created Excel Tool was therefore used to perform all the cost estimations for validation purposes. In addition, in order to be able to calibrate the model in the future for application to other purposes, such as the SpaceLiner case-study, different exampled had to be taken where some available cost data could be found, so as to compare, be it only loosely, the results TransCost costs with some existing stated cost data.

TransCost was applied to the Russian Energia-Buran launcher system, as well as the American Space Shuttle to determine the program development costs (see Appendices 0 and 0). These two programs are of distinct interest since they are the only existing space systems which can be considered as "reusable" (although technically, only partly so) which have flown to date. Due to numerous similarities between the Buran and Shuttle programs, a direct comparison between the two systems and their costs, which firstly need to be identified from literature, was also of interest within the scope of this study. Furthermore, two additional RLVs – the Liquid Fly-back Booster (LFBB), described in the following chapter, and the ASTRA Hopper vehicle (see Appendix E), were also assessed with regards to their program costs.

4.6.1 Liquid Fly-back Booster

There are various LFBB vehicles which have been proposed and consequent studies which have been conducted and documented. There are, however, no realised projects for this category of vehicles. Within context of this particular study and report, the important requirement was to identify some existing data which presented some reflective cost figures for a given project. This way, this data and figures would provide a basis against which a TransCost formulated estimate could be benchmarked and compared with.

Internal documents for the ASSC2-Y9 LFBB were identified [50] which presented cost estimations and a detailed LCC breakdown for this particular LFBB. Therefore the relevant data was also extracted and used for input into the TransCost spreadsheet.

Figure 23: ASSC2-Y9 concept of a semi-reusable launch vehicle with A5 core stage and two attached, reusable fly-back boosters [46]

4.6.1.1 LFBB Configuration

The LFBB (ASSC2-Y9) launch vehicle comprises of the following elements, for which the development costs are applicable:

- Main cryogenic stage EPC-H185 (expendable)
- Vulcain 3 main engine (reusable)
- LFBB (reusable)

Here, the focal element for cost estimation is of course the reusable LFBB stage. Of course this has no bearing on the effort amount, since this is merely a measure of effort, and as such is irrelevant for which year this work effort is converted into a monetary amount. The final costs, however, are all given in 2011 e.c. values to assist for a relevant comparison to be made.

4.6.1.2 LFBB Excel Component Break-down Structure

The component breakdown structure and the Excel TransCost spreadsheet screenshots with all relevant inputs and complexity factors for ASSC2-Y9 are presented in Table 11 through to Table 13 below.

4.6.1.3 LFBB Calculation Assumptions

Some key assumptions also had to be made within the scope of the LFBB cost estimation with regards to numerous inputs and some complexity factors. The key assumptions are outlined below, and are also annotated in **red** with association to the fields which the assumptions affect in the tables above.

Furthermore, for the LFBB, significant heritage exists for various components, and therefore, the newly developed and introduced TransCost f_{12} factor for delta developments, is applied. This is found in Appendix E, where the derivation process is also fully described.

Table 11: TransCost CER for Vulcain 3 engine

TC 7.3, Chapter 2.32		Liquid Propellant Rocket Engines		*pg. 49*
CER	**=**	**277*M^0.48 * f1 * f2 * f3* f5**	Engine Dry Mass (M)	2370
	=	3302.89 WYr	f1	0.70
			f2 (# test firings basis)	0.73
for f2 calculation			f3	0.80
Nq (# qualification firings) =		200	f12 **A1.**	0.70
COST M€ (2011 e.c.)		**922.2**	*NORP*	*10*

Table 12: TransCost CER for main cryogenic stage EPC-H185

TC 7.3, Chapter 2.43		Expendable Ballistic Stages & Transfer Vehicles		*pg. 49*
CER	**=**	**100 * M^(0.555) * f1 * f2 * f3 * f5**	Vehicle DRY Mass w/o Engines (M)	16851
	=	647.66 WYr	f1	0.40
for f2 calculation			f2	1.04
M_NET		204767	f3	0.70
M_engine		2840 **A3.**	f12 **A2.**	0.10
M_propellant		187915		
% Res. Gas at c/o		3		
Res. Gas at c/o		1200		
Usable Prop Mass		186715		
M_dry		15212		
NMF specific		0.08		
NMF average		0.085		
COST M€ (2011 e.c.)		**180.8**	*NORP*	*12*

Table 13: TransCost CER for LFBB

TC Chapter 2.47		VTO First Stage-Fly-Back Rocket Vehicles (no realised projects)			*pg. 74*
CER	**=**	**1462 * M^(0.325)*f1 *f3 *f5**		Vehicle DRY Mass w/o Engines (M) ***A4.***	39090
	=	42479.59 WYr		f1	1.1
				f3	1.0
COST M€ (2011 e.c.)	**11860.4**			*NORP*	*4*

Table 14: Updated CER for LFBB development cost (described later in Chapter 4.7)

Chapter 2.47 (est.) *A5.*		VTO First Stage-Fly-Back Rocket Vehicles (no realised projects)			*TC, pg. 74*
CER	**=**	**493.27 * M^(0.3746) * f1 * f3 * f5**		Vehicle DRY Mass w/o Engines (M)	39090
	=	28488.21 WYr		f1	1.1
				f3	1.0
COST M€ (2011 e.c.)	**7953.9**			*NORP*	*4*

A1. The Vulcain 3R engine and the associated technology already exist. However for the ASSC2-Y9 vehicle, the engine must be reusable. To factor in for this, the f_{12} factor is taken to be 0.7.

A2. For the main EPC stage development, the newly developed f_{12} delta development factor was applied. Based on calibration performed for ELVs (ref. [207]). the value was assumed to be 0.1 since the stage already exists, and only minor delta developments are necessary.

A3. The mass for the engine was extracted from documents pertaining to a previously conducted ASTRA study [199], and was taken to be 2840kg. This mass is seemingly different to the mass entry for actual development of the Vulcain 3R in Table 11. This is explained by the fact that the mass difference between the two is due to a nozzle-extension used for the EPC than for the boosters, despite an identical engine. For the Vulcain 3R engine calculation, this is taken to be the lighter mass, since mechanical tests are independent of the nozzle configuration. For the f_2 calculation of the EPC, the heavier engine/nozzle mass is taken, representative of the actual stage configuration.

A4. The LFBB dry mass w/o engines was calculated using data from [181] with the three Vulcain 3R engines (3 x 2370kg) subtracted from the LFBB gross weight of 46200kg.

A5. A new, modified CER was established (est.) to rectify a shortcoming of the TransCost model. This process is described in a dedicated Chapter 4.7 to be found later on in this Thesis. The new CER applies directly to the LFBB category of vehicles, and is essentially an augmented and modified version of CER 2.47. Here, it is interesting to apply this new, more representative and justifiable CER to the ASSC2-Y9, for the LFBB stage. This recalculation and the new results are shown in Table 14 above.

After calculating all independent components which needed to be developed within the scope of the program, the usual top-level TransCost formula stated in *Eq. 4* is applied.

Here, it is important to note that results incorporate the WYr value calculated by the updated and new CER derived for LFBBs (which is shown above in Table 13 and is outlined in assumption on the previous page A5), and whose development is fully explained in Chapter 4.7.

In this case, the additional TransCost factors which are then imposed on the sum of the constituent elements for ASSC2-Y9 system, are all outlined below, and their chosen values stated:

- $f_0 = 1.08$

(f_0 = 1.04 number of stages, in the case of the ASSC2-Y9, 2)

- $f_6 = 1.0$

(here, assume no deviation from optimum schedule)

- $f_7 = 1.00$

(f_7 = n 0.2; with n being the number of parallel contractor organisations, in this case assumed to be 1)

- $f_8 = 0.86$

(TransCost stated country productivity factor for ESA)

The final development effort of the ASSC2-Y9 system, as calculated using the TransCost 7.3 model, was found to be a little over 30,000 WYr (30,174 WYr), equating to 8.6 B€ at 2013 economic conditions.

4.6.1.4 TransCost LFBB Result and Literature Comparison

Several key internal documents [48-50, 158] were identified to be representative values for a comparison with the TransCost derived calculation. With the LFBB being only a concept, the documents were independent, overall LCC calculations made for the industry using the parametric PRICE-H software [152, 153, 209].

Key data extracted from the ASTRA report [158] for the comparison with TransCost values is shown in Table 15 where it can be seen that the reusable Vulcain 3R engine is not explicitly stated as an independent component in the DDT&E. However this cost is included in the overall 2820 M€ stated for the LFBB. The exact cost of the Vulcain 3R is included in the industry-developed cost estimation spreadsheet [50] and estimates the total development cost of the Vulcain 3R engine as being 758 M€ at 2002 economic conditions.

Table 15: Industry estimated total LFBB development costs [158]

	M€	Remarks
Project Office		
Vehicle System	222	
Mgmt & Ownership	443	
DDT&E		
LFBB	2821	
EPCe	26	interface modifications
ESC-B	14	avionics modification
Upper Section	0	remains unchanged
Flight SW	218	200 men x 5 years
Proto-Flight Units		
2 x LFBB	637	later used in the operating fleet
2 x EPCe	80	2 test flights
2 x ESC-B	37	2 test flights
2 x Upper Section	10	2 test flights
Ground Segment	588	
Total Development Phase	**5096**	

Here, it must also be noted that the development cost for the Vulcain 3R engine is different, to the same engine for the ASTRA Hopper concept. For the LFBB (758 M€), it is more expensive than ASTRA Hopper (664 M€) due to six engines in total which are needed for the two prototype LFBBs, as two booster units are always required per flight, as per the LFBB configuration shown previously in Figure 23. And since development includes prototype units, the added complexity of multiple engine integration, materialises itself in the higher development cost.

Extracting relevant information, and including software costs which are also inherently considered by TransCost, a comparative table between TransCost and literary (L) values is shown below in Table 16. By definition, TransCost development cost already includes the first prototype of the vehicle, while in literature, this is stated separately. Therefore, the literary design and development costs as well as the cost of test models and proto-flight units are summed up in the comparison table below, to make the results comparable with the TransCost development cost calculation.

Table 16: Industry LFBB figures (L) compared with TransCost (TC) estimated values

Components	Literary Cost M€ (2002 e.c.)	TransCost Cost M€ (2002 e.c.)	Delta TC/L (%)
Vulcain 3R Engine	758	572	-25
EPC - H185 stage	106	112	6
LFBB*	2700	4929	83
Software	218	*included	n/a
TOTAL	**3782**	**5613**	**48.4**

**here, we assume the re-calculated value using the newly established CER 2.47 as outlined in assumption A5 and fully detailed later in Chapter 4.7.*

From the independent industry cost estimate, the total stated development cost of overall cost components is 3.782 B€. In contrast, the TransCost calculated development cost, expressed in a monetary value at 2002 e.c., is 5.613 B€, as summarised in Table 17.

Table 17: Comparison of LFBB TransCost 7.3 and industry development cost

		Literature	TransCost		Delta TC/L (%)
C_D	=	3.78	5.61	B€ (2002 e.c.)	48.41

As can be seen, the TransCost estimation seems to be almost 50% greater than the complimentary industry-based estimation performed using the PRICE software. The Vulcain 3R engine component, as calculated by TransCost, is lower than the value derived from the industry report. However, here it was noted that the industry reference spreadsheet [50] and the associated industry report [158] incorrectly assume the heavier engine mass of the core stage of the ASSC2-Y9 vehicle (stated as being 2654 kg), rather than the actual, lower booster engine mass (2370 kg), which was used for development calculation cost in TransCost. Taking this fact into account, the TransCost engine calculation seems to be fairly congruent with the PRICE industry cost estimation. The EPC stage is also in strong congruence with industry-derived estimation. The greatest difference in costs is evident for the LFBB stage. Despite applying the modified CER for LFBB vehicles, development of the LFBB component, as estimated by TransCost, is almost double that than the industry estimate.

Here, it may, however, be relevant to note that the industry document used for the comparison was a competitive estimate to secure funding for the future of the program. Such a cost estimate is defined by TransCost as being the minimum credible development cost produced under a competitive situation in order to secure financing or a contract [102], as already introduced in Chapter 4.5.2. Yet, this is an assumption, and in no way intended to qualitatively nor quantitatively address the discrepancy. The other logical alternative is that, despite a modified CER, TransCost still produces an overinflated development cost of LFBB-stages due to a limited number of only four data points, meaning that each additional point significantly alters the curve, and therefore the CER equation. This hypothesis would require further investigation in the future, but for the present time, alerts us to the variable nature of cost estimation for tank-like structures.

4.7 CER DEVELOPMENT FOR REUSABLE BOOSTER STAGES

Throughout the entire process of using the TransCost model to come up with a cost estimate, the utmost care was taken to ensure that every CER and its underlying data have been understood. In fact, this philosophy is what underpins the logic for this part of this very work. So, at every stage of that TransCost application process, wherever possible, own data has been identified and compared with data points that feature in the TransCost model.

In view of this approach, the TransCost model's Chapter 2.47 CER for *VTO First Stage Fly-back Rocket Vehicles*, based on 4 reference points, triggered some doubt for the data point of the ASSC-2, shown circled in red. This doubt arose during comparison of internal SART data obtained from in-house documents, with the data implied by a reference point on the TransCost CER curve. The CER graph in question is shown in Figure 24, as it appears in the TransCost handbook.

Being one of only 4 data points (one of four reference projects) underpinning the CER and thus the resulting development costs estimation, it was decided to establish a new CER using relevant, available data to promote transparency and comprehension of the underlying database and therefore the resulting development cost estimation figure. The data sets used for the CER formulation were extracted directly from internal DLR and other available documents, and included the following vehicles:

- *ASSC2 V-4*
- *Space Shuttle LFBB*
- *ASSC2 Y-9*
- *FSSC-16 SR*

Reliable and transparent data was readily available and therefore facilitated for dissemination and analysis within context of the CER formulation process.

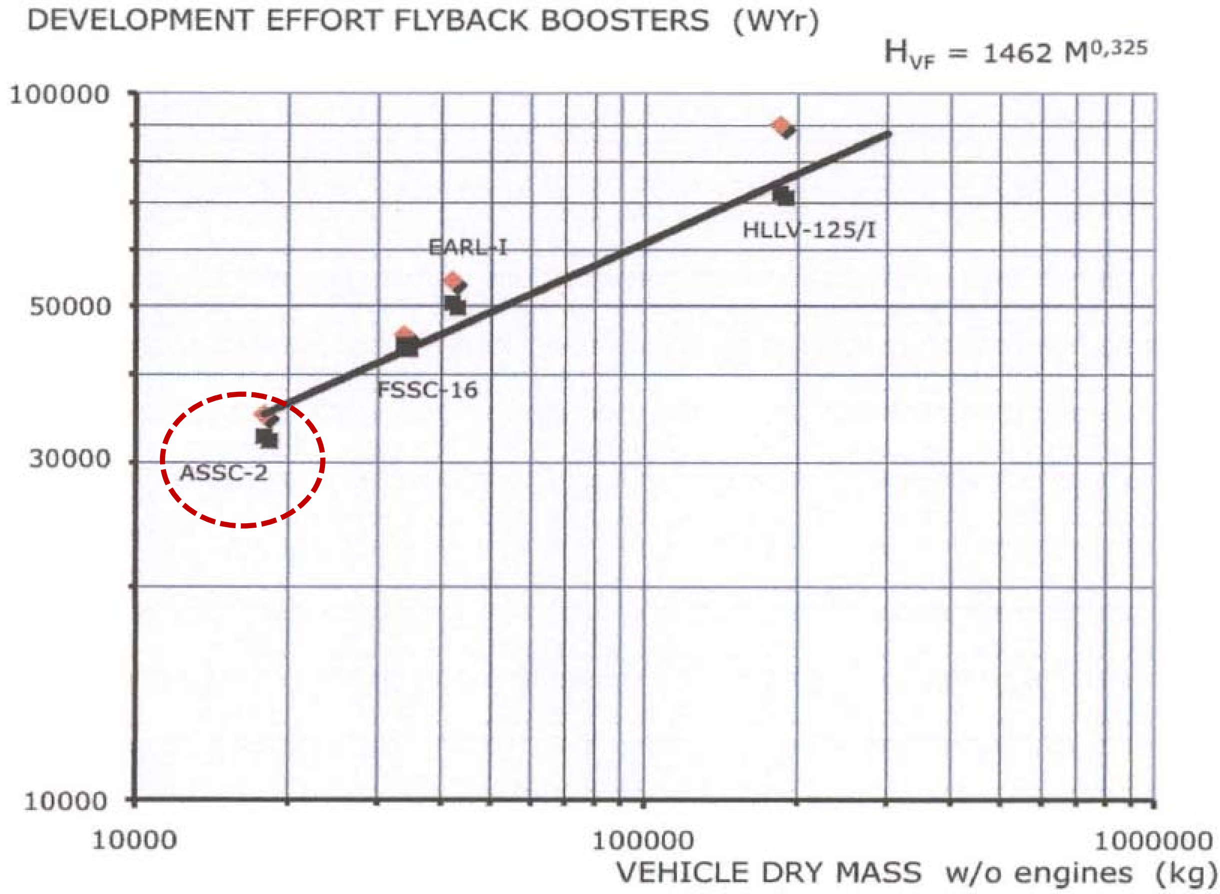


Figure 24: TransCost CER for fly-back boosters based on four reference projects [100]

4.7.1 CER Establishment Process

TransCost represents its CERs graphically with both its x and y axes featuring logarithmic scales, which makes the data easier to see due to its large spread, as shown in Figure 25. The required input data to construct the CER so that it is in a TransCost congruent format is:

- **x-axis:** vehicle dry mass (without engines)
- **y-axis:** development effort (WYr)

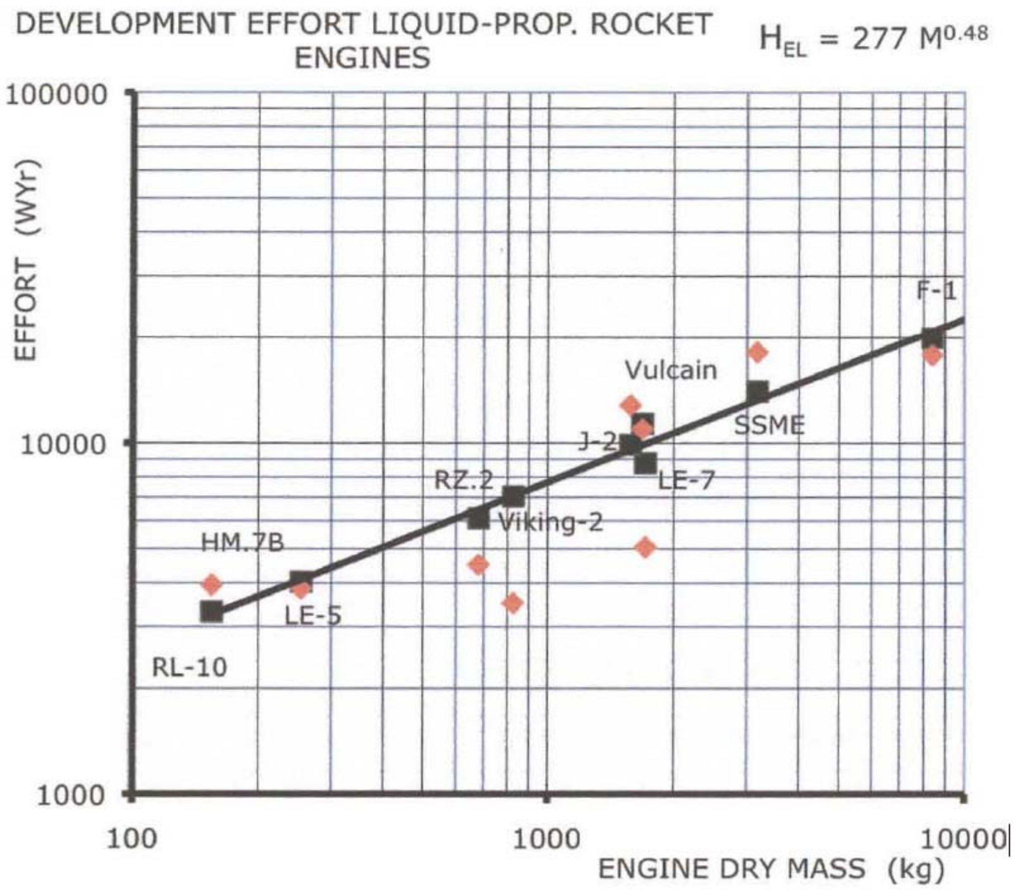


Figure 25: An example of a basic TransCost graph and associated CER with numerous reference data points for rocket engines [100]

The TransCost model measures the development effort in the Work Year (WYr) unit. However WYr figures are not always explicitly available within the literary data that, which presented pure monetary currency costs. Therefore some basic reverse calculations were required to arrive at an effort figure. This was done by identifying the relevant cost figure for each program, as well as the associated year for economic conditions (e.c.). The TransCost Work Year cost history table was then used to divide the total cost by the cost of one Work Year for the particular, respective country, for that particular, respective currency. The result then yielded the Work Year figure. For example:

- *Literary stated cost of Space Shuttle LFBB development: $5 B USD 1999 e.c.*
- *TransCost WYr value for the US in 1999: $203,000*
- *WYr value for Space Shuttle LFBB: $5,000,000,000 / $203,000 = 24,631 WYr*

When a concrete WYr value had been established per program, additional complexity factors, f_1, f_3 and f_{12} were furthermore applied to the final WYr amounts for most of the 4 reference projects. This was done to adjust for differences and complexities between each program, and to bring the figures to a common baseline so that they could be directly compared. To remind the reader about the exact definitions of each complexity factor:

- f_1: development standard factor
- f_3: technical quality factor
- f_{12}: a newly established delta development factor which has been additionally implemented (based on extensive TransCost model application and analysis process, see Appendix E) within the existing TransCost framework to address cases where development of a technology/stage/component has considerable heritage which other existing TransCost factors (such as f_1, f_2 and f_3) do not fully reflect nor encompass.

A summary of the four reference projects, the resulting development WYr figures as well as the associated complexity factors which were assumed, are shown below in Table 18. Reasons, justifications and assumptions are then consequently provided for each program, explaining the complexity factors which have been applied and their values to facilitate for data normalisation.

Table 18: CER complexity factor values assigned to stated cost data for normalisation

Program/ Vehicle	Vehicle Dry Mass (kg)	Development Effort (WYr)	f_1	f_3	f_5	Adjusted Development Effort (WYr)
ASSC-2 Y-9	39090	14656	0.9	0.9	0.9	20104
Shuttle LFBB	64039.6	24631	0.9	0.9	0.9	33787
ASSC-2 V-4	17839.9	17811	1.0	0.9	1.0	19790
FSSC-16 SR	34000	34417	1.1	1.1	1.0	28444

ASSC2 Y-9:

- f_1 = 0.9: considered as a fundamentally EPC-derived standard project
- f_3 = 0.9: similar project to the Ariane 5 EPC stage, and some experience from hypersonic test airplanes
- f_{12} = 0.9: subsystems, like the landing gear (Embraer EMB195), and actuators are reused from existing flight vehicles

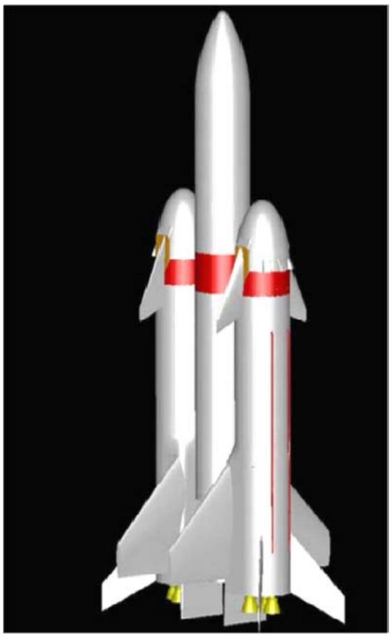


Figure 26: ASSC-2 Y-9 [46]

Shuttle LFBB:

- f_1 = 0.9: based on Atlas V and Space Shuttle Orbiter technology
- f_3 = 0.9: similar project to the Space Shuttle and Atlas V
- f_{12} = 0.9: Atlas V main tank is partially reused

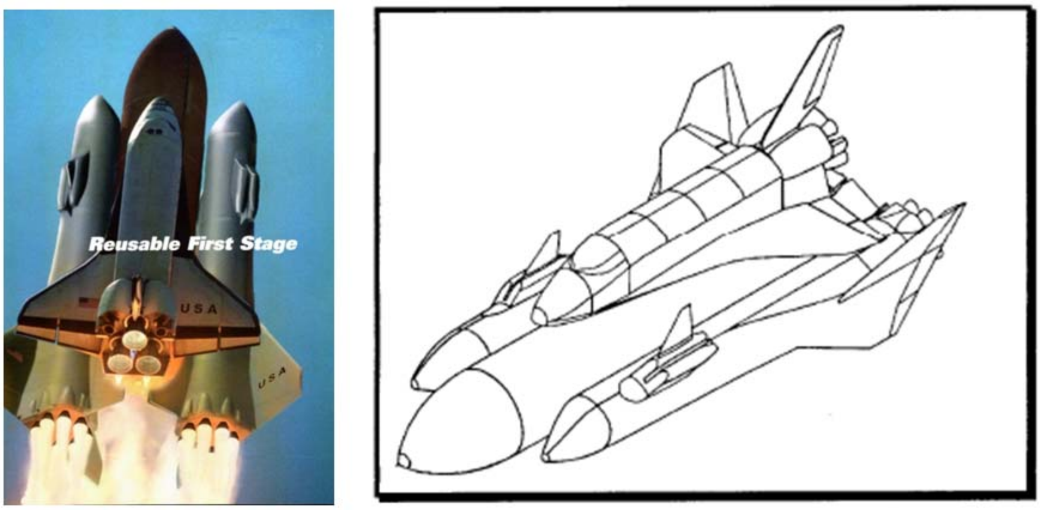


Figure 27: STS configuration (left) and schematic (right) showing Orbiter, External Tank and dual LFBBs in its ascent configuration [26]

ASSC-2 V-4:

- f_1 = 1.0: smaller tank, but novelty in technology (the tanks are separate, which is different to Ariane 5 technology), challenging bulkhead
- f_3 = 0.9: similar project, Ariane 5 EPC, hypersonic test airplanes
- f_{12} = 1.0: no delta development considerations, all new components

FSSC-16 SR:

- f_1 = 1.1: standard project, but more advanced technology than ASSC-2 (the tanks are separate, which is different to Ariane 5 technology)
- f_3 = 1.1: partially new project due to new advanced technology
- f_{12} = 1.0: no delta development considerations, all new components

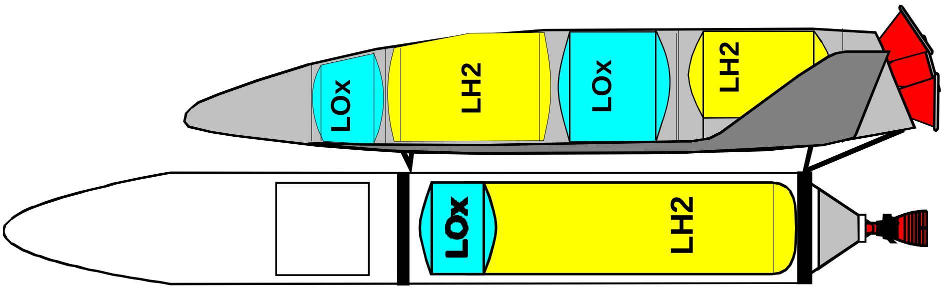


Figure 28: FESTIP FSS-16SR (top) [108]

Ultimately, after being adjusted and standardised, the four reference data points were plotted on axes with logarithmic scales, and the associated power equation deduced, exactly congruent with the TransCost CERs derivation method. The own CER which was consequently derived from, and is shown in Figure 29 below, is:

$$CER = 493.27\ M^{0.3746}. \tag{6}$$

The other points, as seen on the graph with the same x-axis (vehicle dry mass) values, are the values which have been further adjusted through application of complexity factors, f_1, f_3 and f_5, to ensure that four reference projects and data-points are standardised and are in fact comparable, so that a CER can be justifiably established.

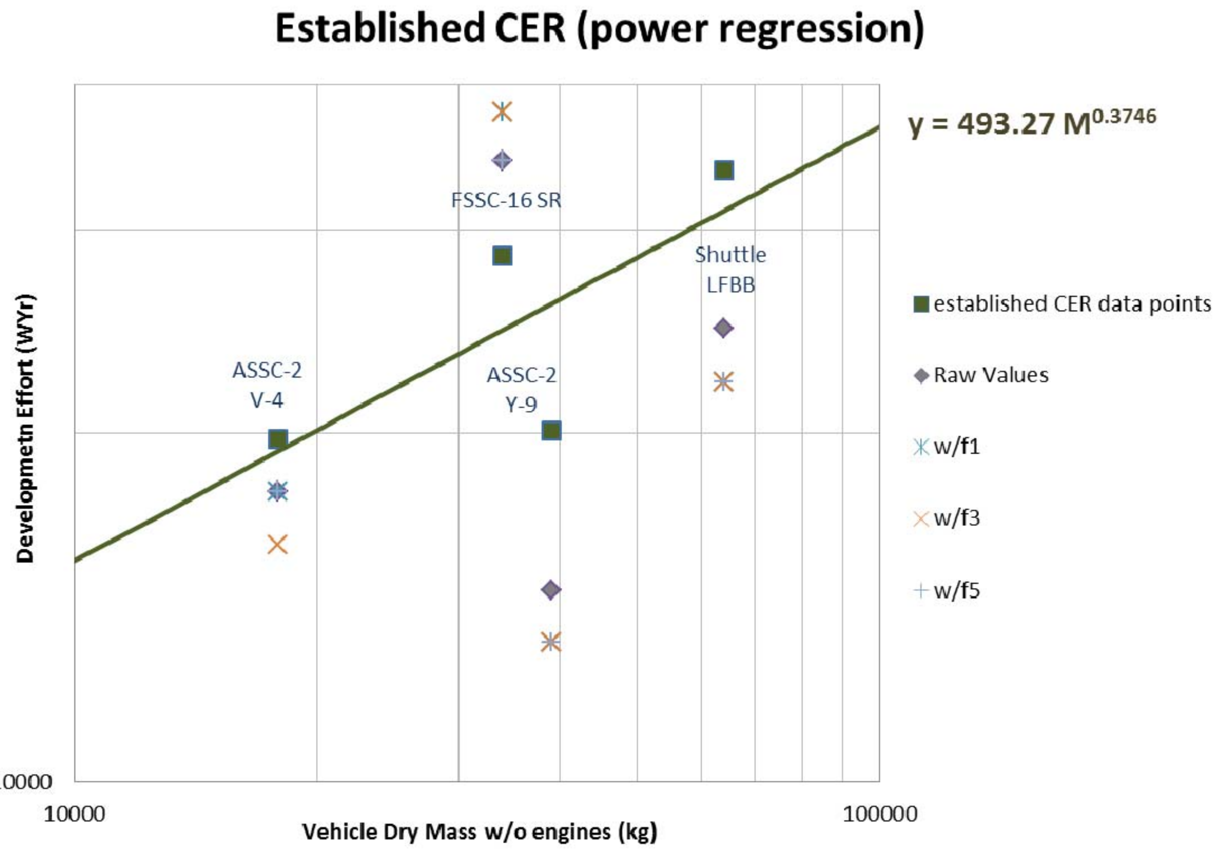


Figure 29: Newly established CER for reusable LFBBs

With a new CER established based on modification of the existing one, it was then most interesting and indeed a logical step to compare the visual representation of this CER with the original TransCost CER version. This comparison is shown in Figure 30.

It can be clearly seen that while the gradient of the two CER curves are similar, the modified, established CER nevertheless has a greater gradient than that of the TransCost curve. This means that based on the underlying CER data, the development effort, and therefore cost, is effectively more sensitive to an increase in vehicle dry mass than the TransCost CER implies. Additionally, due to a lower positioning of the new curve with respect to the y-axis, it can be seen that the absolute WYr effort is roughly a factor of 2 lower than for the original curve. Overall, it is considered that with this modification, a more accurate representative CER has been established for reusable stages.

In addition, and given the newly established LFBB CER, the calculation already conducted for the Liquid Fly-back Booster earlier in Chapter 4.6.1 was also revisited, and a revised development cost for the LFBB stage, calculated. This is outlined in Assumption 5 (***A5***) of Chapter 4.6.1.3 on page 119 of this Thesis, with final results shown in the previous Table 14. As expected, a significant cost reduction of over 30% in this instance is observed between the original TransCost LFBB CER result, and the result of the newly established CER shown in *Eq. 6* above and visually contrasted with the TransCost CER below in Figure 30.

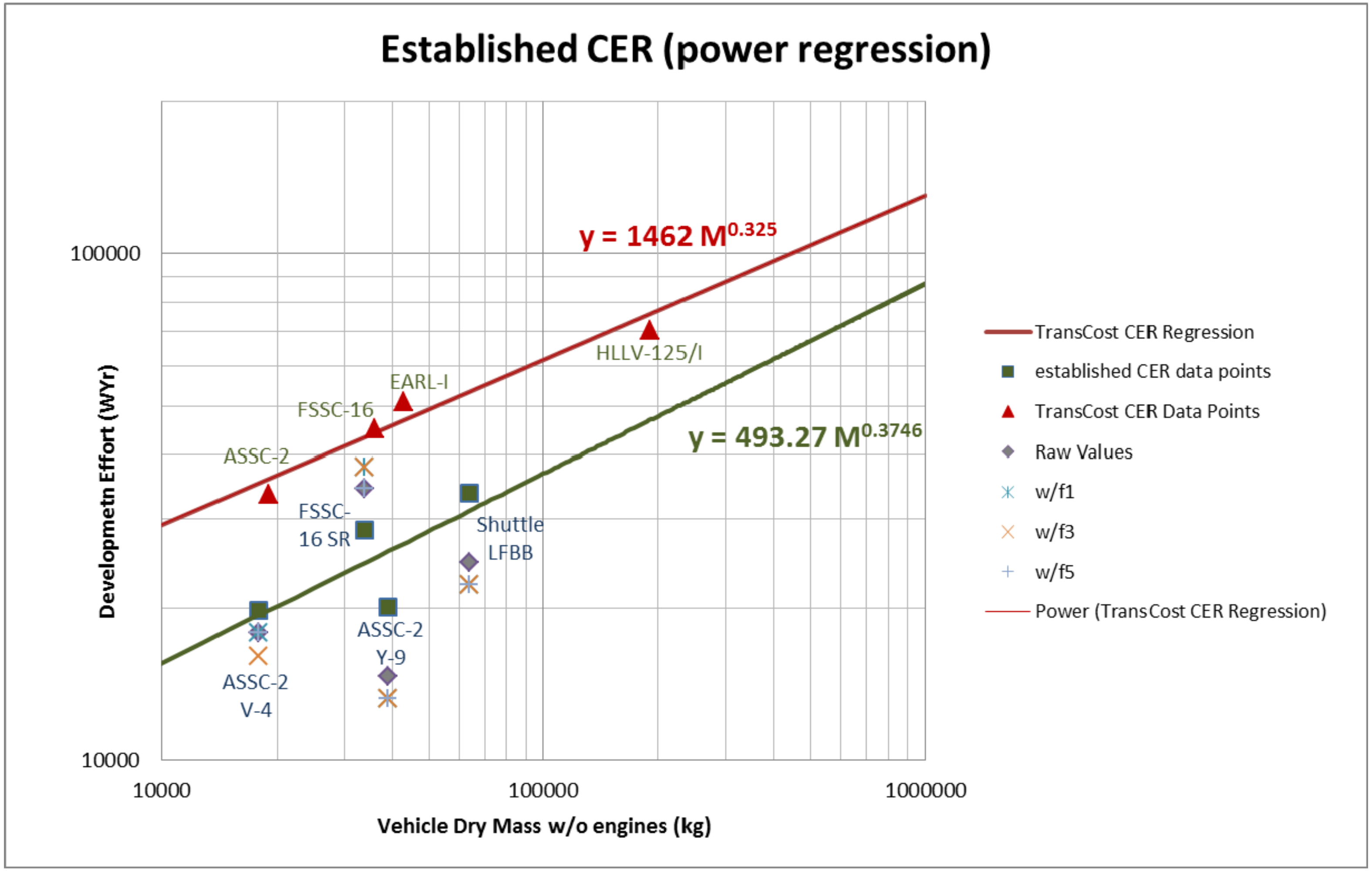


Figure 30: Comparison of newly established LFBB CER (power regression) with the existing TransCost CER

4.8 COSTING THE SPACELINER CASE-STUDY

4.8.1 Methodology

Early phase cost estimation poses a significant challenge given still evolving, limited program information. CEMs, models and tools do exist to deal with very top-level estimates even during early phases. However, most are parametric, meaning historical references are used to model and predict future costs, adjusting for any minor modifications with complexity factors. Yet if the program to be costed is significantly new or state-of-the-art compared with historical projects which form the basis of a CER, then results of a single parametric model may provide a non-indicative result of realistic costs. SpaceLiner is both in the early development phase, and also a largely unprecedented vehicle, so both challenges hold true. As such, the associated risk and uncertainty of the cost estimate, while already being inherently high during early program phase (see Figure 4) is furthermore compounded.

At the top WBS level, as already presented in Chapter 4.1.1, the four key SpaceLiner components of SLB, SLO, SLME and SPC are foreseen to incur non-recurring development costs. Their masses for the SpaceLiner version 7.2 were obtained (see Appendix F) and used as inputs for all models and tools.

The SLO, SLB and SPC form the top hardware categories of the overall developed WBS for the SpaceLiner concept, from WBS element 2000 through to 4000. In the WBS the main engine, SLME, is a subset of level two SLO and SLB elements found under 2200 and 3200 for Propulsion. Here, it should be reminded that only one development cost for the two SLO and SLB engines is incurred, since both engines are mechanically identical, with the only difference being the nozzle extension. Here, to attribute specific percentiles of novelty to two separate engines of the same technology, but of different scaling, would also be unreasonably precise at this early stage. Therefore, with the inherent margin for technology heritage of the engines in mind, it was assumed and deemed sufficient that development cost of one 100% new engine (taken to be the larger mass and dimension) would be calculated, and would adequate to address the engine development effort and cost for both SLO and SLB, as has been discussed in Chapter 4.1.

All cost estimates resulting from multiple modes were entered into the specially developed AA Excel spreadsheet, AAInT, which is specifically designed and developed to ideally support the AA function, as already introduced in Chapter 2.6.2.2. AAInT was then adapted for the unique nature and particular WBS of the chosen case-study. The key objective and function of AAInT is to contain all WBS as well as multi-modal cost data in one spreadsheet. As such, the main summary AAInT cost sheet derives its values directly from the source cost files, thus eliminating the chance of transcription errors and minimising the potential for human error. The summary sheet, as tailored to the SpaceLiner case-study, a snapshot of which is shown below in Figure 31, then allows for direct comparison of costs at WBS level 2 ($L2_{WBS}$) and $L3_{WBS}$ between the different costing modes. Functionally, AAInT is designed to display up to as many levels of a WBS. Each of the WBS elements are categorically listed on the left, with their associated WBS index, and various columns allow for direct entry of resulting costs per WBS element in a common row, facilitating for easy contrast and comparison, as well as efficient analysis across the various levels. Lower-level costs are also tallied and shown in higher level WBS figures. Both a development and production spreadsheet was programmed.

At the end of the cost estimation per SpaceLiner system element, a cost estimation using the analog and EJ CEMs was also performed for the Project Management Office (PMO) component. This critical management function is an essential one, and should not be omitted in the cost estimation.

The WBS level 3 can be further expanded to show the lower SpaceLiner case-study constituent level 4 components also. Such an expansion is shown for the SpaceLiner case-study AAInT tool below in Figure 32. Due to the relatively early program phase and therefore inherent cost uncertainty incurred by still evolving technical input parameters, all cost analyses were performed at $L3_{WBS}$ and $L2_{WBS}$, and as such, the level 4 expansion seen in Figure 32 shows no cost values. While the commercial PRICE and 4cost *aces* tools provided all costs at a constant $L3_{WBS}$, the high level TransCost model (in accordance with its definition) produced only costs at $L2_{WBS}$, except for the engine, SLME, which was calculated at $L3_{WBS}$.

	A	B	C	D	E	F	I
1	DEVELOPMENT						
2	all costs are at 2013 e.c. in EUROS (€)						
3					(baseline case assumed)		DEVELOPMENT
4	WBS Element						2.0 PLTFM
5	C - 1000		SpaceLiner OVERALL SYSTEM		TransCost	4cost	PRICE
6	PM	1100	Overall Project Management Office (PMO)			0,105	0,105
16	Other	1200	Total Project Travel inc. all sub-systems			0,024	* included in calcs.
17			TOTAL (B€)		0,000	0,128	0,105
18	C - 2000		SpaceLiner ORBITER (SLO)		TransCost	4cost (5 protos)	PRICE
19	PM	2100	SLO Project Manegement Office			*included in calcs.	*included in calcs.
26	HW	2200	Propulsion (SLME)		3,815	1,050	2,152
30	HW	2300	Structures & Mechanics			5,390	5,737
37	HW	2400	TPS/TC			1,168	1,117
40	SW	2500	Flight Control System			0,000	0,000
44	HW	2600	Avionics			*combined in WP 3600	*combined in WP 3600
48	HW	2700	Power & Housekeeping			0,490	0,273
53	AIT	2800	SLO AI&T			0,738	0,269
60			CALCULATED TOTAL (B€)		8,489	8,836	9,547
61			STATED TOTAL (if applicable)			8,836	9,547
62	C - 3000		SpaceLiner BOOSTER (SLB)		TransCost	4cost	PRICE
63	PM	3100	SLB Project Management Office			*included in calcs.	*included in calcs.
70	HW	3200	Propulsion			0,714	0,850
74	HW	3300	Structures & Mechanics			6,612	7,267
80	HW	3400	TPS/TC			1,496	1,212
83	SW	3500	Flight Control System			0,000	0,000
87	HW	3600	Avionics			0,348	0,145
91	HW	3700	Power & Housekeeping			0,903	0,576
96	AIT	3800	SLB AI&T			0,955	0,417
103			CALCULATED TOTAL (B€)		10,008	11,029	10,467
104			STATED TOTAL (if applicable)			11,028	10,467
105	C - 4000		SpaceLiner PASSENGER CABIN / RESCUE CAPSULE (SPC)		TransCost	4cost	PRICE
106	PM	4100	SPC Project Management Office			*included in calcs	*included in calcs.
113	HW	4200	Propulsion (CSM capsule solid motors)			0,051	0,086
116	HW	4300	Structures & Mechanics			0,351	0,364
120	HW	4400	TPS/TC			0,257	0,380
123	SW	4500	Flight Control System			0,000	0,000
127	HW	4600	Avionics			0,186	0,072
131	HW	4700	Power & Housekeeping			0,209	0,106
136	HW	4800	Life / Passenger Support Systems			1,200	0,902
142	AIT	4900	SPC AI&T			0,217	0,067
149			CALCULATED TOTAL (B€)		5,664	2,471	1,977
150			STATED TOTAL (if applicable)			2,471	1,977
151							
152			OTHER	f0	1,971		
153			OTHER 2	f6, f7	0,000	0,909	0,185
154			TOTAL		26,132	23,374	22,282

Figure 31: Screenshot of developed AA_{MAC} Excel AAInT tool adjusted for application to the SpaceLiner case-study, shown for development costs

18	C - 2000		SpaceLiner ORBITER (SLO)	TransCost	*4cost (5 protos)*	PRICE
19	*PM*	*2100*	***SLO Project Manegement Office***		**included in calcs.*	**included in calcs.*
20		*2110*	*Project Management (PM)*			
21		*2120*	*Project Control Management (PCM)*			
22		*2130*	*Systems Engineering & Design Management (SEDM)*			
23		*2140*	*Product Assurance Management (PAM)*			
24		*2150*	*Documentation & Configuration Management (DCM)*			
25		*2160*	*Project Risk Management (PRM)*			
26	HW	**2200**	**Propulsion (SLME)**	3,815	1,050	2,152
27		*2210*	*Engine Assembly*			
28		*2220*	*Engine Support Structure*			
29		*2230*	*Feed System*			
30	HW	**2300**	**Structures & Mechanics**		5,390	5,737
31		*2310*	*Main Tanks Assembly*			
32		*2320*	*Upper I/F Adaptor*			
33		*2330*	*Lower I/F Adaptor*			
34		*2340*	*SLO Equipment Bay*			
35		*2350*	*Body Flaps & Actuators*			
36		*2360*	*Landing Gear*			
37	HW	**2400**	**TPS/TC**		1,168	1,117
38		*2410*	*Thermal Protection*			
39		*2420*	*Active Thermal Elements*			
40	SW	***2500***	***Flight Control System***		*0,000*	*0,000*
41		*2510*	*ADCS*			
42		*2520*	*RCS*			
43		*2530*	*Flight Control Software*			
44	HW	**2600**	**Avionics**		**combined in WP 3600*	**combined in WP 3600*
45		*2610*	*On-board Computer (OBC)*			
46		*2620*	*Communications Equipment*			
47		*2630*	*Health Monitoring*			
48	HW	**2700**	**Power & Housekeeping**		0,490	0,273
49		*2710*	*Batteries*			
50		*2720*	*Converters*			
51		*2730*	*Cabling & Connectors*			
52		*2740*	*Sensors*			
53	AIT	**2800**	**SLO AI&T**		0,738	0,269
54		*2810*	*AIT Planning & Management*			
55		*2820*	*MU/BMM*			
56		*2830*	*STM*			
57		*2840*	*EQM*			
58		*2850*	*PFM 1*			
59		*2860*	*PFM2*			
60			**CALCULATED TOTAL (B€)**	8,489	8,836	9,547
61			***STATED TOTAL (if applicable)***		*8,836*	*9,547*

Figure 32: Developed AA_{MAC} Excel AAInT tool screenshot with expanded $L3_{WBS}$ elements to show a further SpaceLiner $L4_{WBS}$ level of detail

As can be seen, the specially designed AAInT spreadsheet facilitates for work and analyses to be performed at an even lower level, if such precision is warranted. This possibility ideally lends itself for a logical transition from the parametric CEMs to the engineering bottom-up (EBU) CEM later on during a program as it develops, and as CEM applicability transitions from the initial higher-level parametric methods to lower WBS-level approaches.

4.8.2 Amalgamation Approach to SpaceLiner

The SpaceLiner program is both in the very early development phase, and also a largely unprecedented vehicle. To address this and the associated challenges this poses to derivation of a representative cost estimate range, the amalgamation approach (AA) proposed in ref. [209] and also introduced in Chapter 2.6, is assumed. AA employs multiple selected, relevant models or tools to obtain several cost estimates of the same program, independently. The results for each model or tool are then analysed individually, before being compared and analysed in reference to each other. During this process, several iterations might be necessary to eliminate discrepancies. Ultimately, the multiple cost values are then synthesised to obtain a representative cost range given certain assumptions and justifications based on analogy or expert judgement. While being more resource intensive to application of a single tool and CEM, when applied at early program phase where uncertainty of the cost estimate is already high, the benefits are significant. AA approach provides an added level of redundancy for an otherwise single cost estimate, which is considered to raise the confidence and representativeness of the single range or figure obtained from application of one method and model alone. In addition, attention is focused on elements where cost discrepancies between multiple modes of cost estimation might arise, indicating variances in cost uncertainty. For the SpaceLiner case-study application, the AA_{MAC} mode (Chapter 2.6.2.2) is assumed and used.

4.9 DEVELOPMENT COST ANALYSIS

"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."

-Dr. Dietrich E. Koelle [102]

The first classical category of program costs are the non-recurring development costs. Basic SpaceLiner information and technical data was assembled and provided for input into the three AA_{MAC} models of 4cost *aces*, the PRICE-H model from PRICE Systems, and the TransCost model. Close attention was paid to ensuring that input data was kept as consistent as possible between all three models to allow for maximally comparable results.

For TransCost, only basic, top-level mass and complexity factor information was needed. For both commercial tools, a higher degree of information was required and included details like masses and complexities for mechanical and electronic components, team experiences, and technical complexities. These latter values were either extracted from existing SpaceLiner data files, or were estimated based on close consultation with relevant experts and professional users for each tool. The resulting costs are all expressed with an economic base of 2013 and in a Euro currency. Basic schedule information for inputs such as the anticipated start of the development Phase C is derived from the overall program schedule introduced in Chapter 4.1.2 and shown in Figure 13.

4.9.1 TransCost SpaceLiner Development Costs

Having analysed and tested the TransCost model to identify its validity, relevance, applicability, and indeed its shortcomings and drawbacks, and after its calibration, it was now suitable to apply the model and its CERs to the SpaceLiner concept to calculate a development effort and cost. The most recently available TransCost 8.2 version was taken.

For the TransCost model structure and for CER application, the top-level SpaceLiner stages, as already presented in Chapters 4.1.1 and 4.8.1, were taken. These are the SLO, SLME, SLB and SPC components. Relevant complexity factors, based on the TransCost model testing and calibration procedure described in Chapter 4.5, also had to be determined and defined. These are summarised in Table 19 below.

Table 19: SpaceLiner complexity factors for each component

Element	f_1	f_2	f_3	f_8
SLO	1.1	0.44	1.0	0.86
SLME	1.1	1.31	0.8	0.86
SLB	1.1	n/a	0.9	0.86
SPC	1.3	1.19	1.0	0.86

For this calculation, it was assumed that there was no deviation from the optimum schedule (f_6=1.0), that cost increase due to multiple parallel contractor organisations is ignored (f_7=1.0) and that the country productivity factor (f_8) is assumed to be that for ESA, defined in TransCost as being 0.86. In additional, for calculation of the SLB, the modified TransCost CER, as described in Chapter 4.7, was applied to determine the development cost.

All inputs were entered into the programmed TransCost interface described in Chapter 4.5.4, with all relevant inputs and complexity factors for the SpaceLiner case-study. All inputs and complexity factors and resulting effort amounts and costs and are shown in detail below, with respective assumptions shown in the tables in **red**, justified.

4.9.1.1 TransCost SpaceLiner Development Assumptions

Key assumptions had to be made for the SpaceLiner cost estimation addressing complexity factors, since physical data about mass was taken directly from latest sources. The assumptions for complexity factor value selection are summarised below and their choice, justified. All assumptions made for each calculation are also annotated in **red** next to the relevant fields in Table 20 to Table 23, are outlined below:

A1. A complexity of 1.1 was chosen for the SLO development standard factor, f_1. The SLO is the SpaceLiner stage into which the passenger stage is integrated into. Due to this proposed integration, the stage is largely unprecedented in nature, structure and application. To address this, the development standard factor is set to indicate a new design with some new technical and/or operational features, as per the TransCost definition of values.

A2. A complexity of 1.0 was chosen for the SLO team experience factor, f_3. Here, while the technical complexity is already addressed with a high f_1 factor (1.1) for the element, the industry team for the SLO development has been assumed to be one which has some related experience to the nature of the project.

A3. For all elements throughout the entirety of the SpaceLiner case-study, the TransCost defined value of 0.86 was assumed for the f_8 country productivity factor. This complexity factor seeks to describe the ESA productivity level with comparison to the baseline value of 1.0 for the US. This assumption is in line with the anticipation that the SpaceLiner program would be led by the European companies, making the current ESA productivity factor the most appropriate value available.

A4. A complexity of 1.1 was chosen for the SLME development standard factor, f_1. The SpaceLiner engine employs standard, heritage cryogenic propulsion and as such, uses no novel technologies. However, a main difference is engine reusability (25 times), which is challenging and unprecedented in the rocket propulsion domain of today. This point is already in part addressed by the increased number of test firings which influence the complexity factor f_2.

However, the development standard factor f_1 is selected to be higher than the norm, indicating a new design with some new technical and operational features. Here, it is also assumed that the development cost of the SLME here also covers the development cost of the engine for the booster, which is mechanically identical, although it has a different nozzle extension.

A5. The number of qualification firings for development of an engine is a key cost driving parameter. For the development of the SLME, 1200 test firings were assumed. This number is extrapolated from a known reference number of 730 test firings for the similarly manned Space Shuttle main engine, or the 800 test firings conducted for the RD-0120 rocket, both of which also have a similar engine mass (3200 kg and 3180 kg for the RD-0120 and SSME respectively). Since the SpaceLiner will be a manned system, although for civilian passengers, carrying a significantly higher number of people on board, the safety and reliability requirements are much higher. As such, the engine would require more test firings than that conducted for the Space Shuttle. The assumed 1200 test firings roughly constitute a 165% increase on both the SSME and the RD-0120.

A6. A complexity of 0.0 was chosen for the SLME team experience factor, f_3. Here, it is assumed that due to significant heritage of the classical liquid propulsion engines in Europe, the development team would have performed development of similar projects (i.e. the ESA Vinci engine).

A7. A complexity of 1.1 was chosen for the SLB development standard factor, f_1. The SpaceLiner booster element is somewhat new in its reusability functionality. In addition, the fly-back capability is also unprecedented by today's space industry standards. As such, the f_1 factor represents this novelty of new design with some new technical and operational features.

Table 20: TransCost CER for SpaceLiner Orbiter (SLO) development

TC 8.2, Chapter 2.45	Winged Orbital Rocket Vehicles			pg. 66
CER	= **1420 * M^(0.35) * f1 * f2 * f3 * f8**		Vehicle DRY Mass w/o Engines (M)	103879
	= 33465.14 WYr		f1 **A1.**	1.1
			f2	0.437
for f2 calculation			f3 **A2.**	1.0
M NET (w/engines)	371000		f8 **A3.**	0.86
M propellant	229600			
M payload	37520.82			
NMF *e**	0.389			
e (TC 8.2, pg. 66)	0.17			
COST M€ (2013 e.c.)	**9537.56**		*NORP*	*8*

Table 21: TransCost CER for SpaceLiner Main Engine (SLME) development

TC 8.2, Chapter 2.32	Liquid Propellant Rocket Engines with Turbopumps			pg. 39
			Engine Dry Mass	
CER	= **277 * M^(0.48) * f1 * f2 * f3 * f8**		(M)	3300
	= 13385.14 WYr		f1 **A4.**	1.1
			f2	1.31
for f2 calculation			f3 **A6.**	0.8
Nq (# qualification firings) =	1200	**A5.**	f8 **A3.**	0.86
COST M$ (2013 e.c.)	**3814.764**		*NORP*	*10*

Table 22: Newly established CER for SpaceLiner Booster (SLB) development

New CER		VTO First Stage-Fly-Back Rocket Vehicles			new CER
CER	=	**493.27 * M^(0.3746) * f1 * f3 * f8**		Vehicle DRY Mass w/o Engines (M)	135379
	=	16416.44 WYr		f1 **A7.**	1.1
				f3 **A8.**	0.9
				f8 **A3.**	0.86
COST M€ (2013 e.c.)		**10007.885**		*NORP*	*4*

Table 23: TransCost CER for SpaceLiner Cabin/Capsule (SPC) development

TC 8.2, Chapter 2.48		Crewed Ballistic Re-entry Capsules			*pg. 76*
CER	**=**	**436 * M^(0.408) * f1 * f2 * f3 * f8**		Reference Mass (M)	37520
	=	42506.85 WYr		f1 **A9.**	1.3
				f2	1.186
for f2 calculation				f3 **A11.**	1.0
N (*crew number*) =		50		f8 **A3.**	0.86
T_M (*max. mission life**) =		0.0625	**A10.**		
COST M€ (2013 e.c.)		**12114.452**	**A12.**	*NORP*	*4*

* *maximum mission design life in days*

A8. A complexity of 0.9 was chosen for the SLB team experience factor, f_3 to signify an experienced team which has performed similar projects in the past, to reflect knowledge and experience gained from manufacture of the Space Shuttle external tank.

A9. A complexity of 1.3 was chosen for the SPC development standard factor, f_1. Although this is the smallest element of the overall SpaceLiner vehicle, the function duality of the passenger cabin which also doubles up as a rescue capsule capable of safely returning all passengers to Earth in case of an emergency, presents an increased technical complexity. As such, the high f_1 factor is chosen to reflect a first generation system and new concept approach involving new techniques and new technologies.

A10. To calculate the f_2 factor for the SPC, the TransCost formula requires input of the number of crew (50, for the SpaceLiner baseline case) and the nominal mission time in days (being 0.0625 for a 90 minute SpaceLiner flight).

A11 A complexity of 1.0 was chosen for the SPC team experience factor, f_3. Although the SPC is a challenging technical element, the team is selected to have some related experience, since the cabin would take significant heritage from the aviation sector. In addition, for such a life-critical system, the team members would have to be selected with significant experience to address the task at hand.

A12. It can be seen that based on the final results, the SPC is by far the most expensive component of the four SpaceLiner elements, at over 12 B€. Here, it must also be noted that the data underlying the CER is considerably old data based on only four data points. These are the Gemini and Apollo capsules from the mid-1960s, as well as the Mercury program, and the more recent Orion capsule proposal values for 2006 [102]. As such, it can be argued that for a passenger capsule to be constructed given today's European experience with manned capsules (for example the Autonomous Transfer Vehicle, ATV), the CER might not be representative of current advances in technology and lessons learned. Furthermore, to acknowledge this fact, the latest TransCost Model 8.2 has introduced two new factors applicable also to the category of Crewed Ballistic Reentry Capsules. These two factors, f_{10} and f_{11} (ref. [102] pgs. 93-95) address the cost reductions seen from past lessons learned, as well as for cost reductions stemming from a commercial application, respectively. Each factor brings down the development cost. It is therefore assumed to apply the each of those factors, using their values which have the smallest cost reduction. The revised calculation is shown below in Table 24. The result is consequently used as the final result, and for comparison within the Amalgamation Approach framework.

Table 24: Revised TransCost CER for SPC with f_{10} and f_{11} complexity factors

TC 8.2, Chapter 2.48				*Crewed Ballistic Re-entry Capsules*	*pg. 76*
CER	**=**	**436*M(0.408)*f1*f2*f3*f8*f10*f11**		Reference Mass (M)	37520
	=	19871.95 WYr		f1 ***A9.***	1.3
				f2	1.186
for f2 calculation				f3 ***A11.***	1.0
N =		50		f8 ***A3.***	0.86
T_M =		0.0625	***A10.***	f10	0.85
				f11	0.55
COST M€ (2013 e.c.)		**5663.506**	***A12.***	*NORP*	*4*

4.9.1.2 TransCost Development Results

Consequently, the TransCost obtained development costs per SpaceLiner element, with the systems engineering factor f_0, but before additional top level programmatic complexity factors are applied, are shown below in Table 25. The f_0 factor addresses the stage integration of a system. For a two stage vehicle (*N=2*) like SpaceLiner, TransCost defines this value as being calculated in accordance with the formula:

$$f_0(DEV) = 1.04^N \text{ .} \qquad (7)$$

When all individual SpaceLiner element costs from Table 25 are tallied, a total of 91,691 WYr is obtained, equivalent to 26.132 B€ at 2013 economic conditions. Here, while two other complexity factors (programmatic complexities) must be applied at a top SpaceLiner system level by definition, they are taken to each be a factor of 1.0. The schedule delay factor f_6 is set at 1.0 implying a rather theoretical ideal case scenario of an optimal schedule, since in reality schedule delays are always incurred. The program organisation is also assumed to feature a single major contractor who would be in charge of the SpaceLiner program, and the factor is also has a value of 1.0. As little is yet known about the SpaceLiner case-study contractor structure, and the schedule, both factors can be reconsidered at a later stage as more specific information becomes available. As such, the total development cost for the SpaceLiner case-study, as calculated by TransCost 8.2, is 91,691 WYr, equating to 26.132 B€ at 2013 economic conditions.

4.9.1.3 TransCost Sensitivities & Development Cost Range

At this early stage of the program, a point value estimate was deemed to be too precise and thus inappropriate for the preliminary and high-level nature of the estimate. As such, a cost estimate range was established. A lower and upper range of values were calculated through

Table 25: TransCost SpaceLiner development costs without programmatic factors

Element	WYr	Cost B€ (2013 e.c.)
SLO	33,465	9.538
SLME	13,385	3.815
SLB	35,115	10.008
SPC	19,872	5.664
Other (f_0)	8,310	2.368
TOTAL	***110,147***	***31.392***

varying three sensitive and arguably subjective TransCost complexity factors for the development standard (f_1), the technical quality (f_2), as well as the team experience factor (f_3). Theoretically, underestimating technical complexity has been quoted as being a major challenge to achieving cost and schedule goals within NASA [138]. Since is both f_1 and f_2 describe technical complexity, they have been chosen to be incremented, to represent an increased technical scenario to the initial baseline. A similarly logic underpins incrementing the team experience f_3 factor so that it describes a less experienced team, thus resulting in a worst case scenario.

The technical quality factor for the SLME hinges on the number of test firings, a value which was altered between 1200 and 2500. For the SLO, SPC and SLB, the team experience factor was also altered to reflect a less experienced team to model and reflect the novel nature of the SpaceLiner case-study. Finally, the development standard factor was also increased to reflect a more novel system. All augmented inputs are shown below in italics, with the subscript *S* to indicate that they are the factors subject to sensitivity analyses. The initial baseline values, as have already been introduced in Table 19, are also displayed in their original form to facilitate for a direct comparison. Table 27 then shows the summarised results of the lower and upper limits in WYr values, as well as their cost equivalents, thus presenting the TransCost development cost range.

Table 26: TransCost complexities sensitivity variations ($_S$) for development cost range

Element	f_1	f_{1S}	f_2	f_{2S}	f_3	f_{3S}
SLO	1.1	*1.2*	0.44	*n/a*	1.0	*1.1*
SLME	1.1	*1.2*	1.31	*1.59*	0.8	*0.9*
SLB	1.1	*1.2*	n/a	*n/a*	0.9	*1.0*
SPC	1.3	*1.4*	1.19	*n/a*	1.0	*1.1*

Table 27: SpaceLiner development costs for lower and upper limits

Element	Lower Limit (WYr)	Higher Limit (WYr)	Lower Limit Cost (B€, 2013 e.c.)	Higher Limit Cost (B€, 2013 e.c.)
SLO	33,465	*40,158*	9.538	*11.445*
SLME	13,385	*20,004*	3.815	*5.701*
SLB	35,115	*42,564*	10.008	*12.131*
SPC	19,872	*23,541*	5.664	*6.709*
Other (f_0)	8,310	*10,303*	2.368	*2.936*
TOTAL	**110,148**	***136,571***	**31.392**	**38.923**

It is seen that through a higher development standard factor (f_1), a lower level of team experience (f_3), and through an increased number of engine test firings to influence the technical quality factor (f_2), very logically increases the cost of the development effort, in this instance, by almost 25% to the original amount. The final development cost range for the SpaceLiner derived through application of TransCost 8.2 and appropriate sensitivity analyses is therefore calculated to be roughly between 31 B€ and 39 B€ for 2013 economic conditions.

4.9.2 Commercial Cost Models & Development Costs

Basic SpaceLiner information and technical data was assembled and provided for input into three selected models and tools, being aces by 4cost, the PRICE-H model from PRICE Systems, and the TransCost model. Close attention was paid to making sure that between all three models, input data was kept as consistent as possible to allow for maximally comparable results. For TransCost, only basic mass and complexity factor information was required. While for the commercial tools, a higher degree of information was required and included details like masses and complexities for mechanical and electronic components, team experiences, and technical complexities. These latter values were either extracted from existing SpaceLiner data files, or were estimated based on consultation with relevant experts for each tool. The resulting costs are all expressed with an economic base of 2013 and in a Euro currency.

The process of compiling a cost estimate using the 4cost *aces* commercial tool was done in parallel with the cost estimate using the PRICE model. Calculations using each model were made with the assistance of trained, highly qualified experts for each tool. The numerical cost estimation results were then entered directly into the specially designed and programmed AA Excel tool, alongside the TransCost values, allowing for the critical analysis step. In line with the AA, several iterations had to be made, with re-calculations of costs from all models, based on analysis of results after they had been committed to the AAInT spreadsheet. The final AA results are therefore shown in this Thesis work as ultimate result from the AA cost estimation process.

Close attention was directed to ensuring inputs were as congruent and comparative between the two models and tools used, to ensure maximum and unilateral comparability of end results. Here, it must be noted that regardless of the fact that an identical data set was provided for input into both software packages. Ultimately, *aces* and PRICE are very different models with different mathematics behind them. Thus, typically, and not surprisingly, same input values will result in different numbers. Variations can be attributed to inherent program algorithms and internally generated factors and complexities for elements, as well as interpretations and assumptions made by the expert cost estimators themselves while entering the data.

While calibration is normally performed for each model in view of the program to be estimated, for the early stage of the SpaceLiner program, and thus the high level overview of sub-systems, this step was unnecessary.

In both cases, the closest of attention was paid to ensure that inputs provided for both models were reflective of the current status of the SpaceLiner technical specifications at the time of model utility. Certain assumptions also had to be made to adjust for the various input formats (i.e. complexity values and their classifications) between each model. Once again, some were dependent on expert and program user interpretation. Additionally, a fixed SpaceLiner "baseline" case had to be established in terms of not only technical data, but also programmatic information. This was provided in a fixed format to both experts. Key criteria and assumptions for the

SpaceLiner "baseline" case have been carefully kept in line with the detailed SpaceLiner philosophy outlined previously in Chapter 4.1.

After all individual results were obtained from the three cost estimation tools and models, in line with the Amalgamation Approach, these were entered into the specially designed AA Excel interface, to allow for the final and most critical step of the process – the result analysis, dissemination and appraisal.

The only cost element missing, as seen on the SpaceLiner case-study developed WBS, is therefore the overall Project Management Office component described by WBS element 1100. An additional element 1200 for travel costs is also considered, since by definition of the 4cost model, travel costs for a program, which are in fact not entirely insignificant, are not calculated by the model in the cost estimate, and need to be added additionally.

4.9.3 *aces* by 4cost

The parametric *aces* tool from 4cost GmbH was input with SpaceLiner data and necessary additional factors which were derived upon consultation with an aces software expert. SpaceLiner data was input, with the following *aces* parameters of focus:

- *Structure and Electronics Element Mass* (W_E/W_M)
- *Development Environment (ENVIRD)*
- *Engineering Difficulty (ENGDIF)*
- *Technology Electronics/Mechanical Index (INDEXE/M)*
- *Amount of New Design (NEWREPE/M)*
- *Year of Technology (TECHYEAR)*
- *Number of Prototypes (PROTO)*
- *Economic Currency Base (ECBASE)*
- *Development phase commencement*

Based on these inputs, an optimal development time was then synthesised by the *aces* software, as well as the associated development and production costs. A basic outline of the key *aces* parameters and defined parameters, and the associated justifications of values, are listed and explained below:

• **W_M /W_E**

The element masses for SpaceLiner were entered from DLR internal documents and calculations, into the WBS structure established in the 4cost *aces* interface. The W_M entry refers to the weight of mechanical items, while W_E refers to electronic item weight.

• **ENVIRD**

The ENVIR value addresses the environment, with ENVIRD describing the environment for the development effort. Four categories of defined complexities are defined classed into the stationary, mobile, aircraft and space environment categories. ENVIRD describes criteria for environmental conditions, manufacturing formalities, deployment conditions and quality assurances. For the SpaceLiner case-study, the categories of aircraft (ENVIRD values 1.9 – 2.1) and space (ENVIRD values 1.9 – 2.2) are relevant. An ENVIRD value of 2.0 was consequently chosen, which encompasses both the higher bracket of the *aircraft* category for military projects, and the lower bracket of the *space* segment for unmanned typical satellite missions. The 4cost table is shown in Figure 33, with the selected values, highlighted in green. Selecting a value which overlaps both domains is representative of the SpaceLiner concept and the associated philosophy of the hybrid nature of the vehicle. Despite being a new vehicle in context, the lower end of the space segment classification is considered to reflect the significant amount of heritage technology of the concept and, although manned, in effect, constitutes an advanced airplane concept.

Quality requirements / to Deploy	ENVIR D / P
Stationary	
"own use / commercial	0,3 - 0,6
Mass Production no support	0,6 - 0,7
commercial / Telecommunication	0,8 - 1,2
typical Software Quality requirements	1,0 - 1,4
military / good industrial Quality	1,0 - 1,4
Mobil	
commercial / Telecommunication	0,9 - 1,2
Car Manufacturing / good industrial Quality	0,8 - 1,3
Ships / Submarine	1,4 - 1,6
military Systems	1,3 - 1,7
typical Software requirements	1,4 - 1,7
Aircraft	
commercial (FAA)	1,7 - 1,8
military Planes	1,9 - 2,0
Software requirements	1,9 - 2,1
Space	
unmanned (typical) e.g. Satellites	1,9 - 2,2
manned Space	2,5
/ Deep Spacemanned Space	2,5 - 3,0
High Software quality requirements	2,5 - 4,2

Figure 33: Typical 4cost ENVIRD/ENVIRP factor values for various applications [1]

• **ENGDIF**

This engineering difficulty factor is a two-dimensional variable represented in a matrix form as an interrelated trade-off between the two aspects of Team and TASK (see Appendix G). The TASK descriptor addresses the scope of the development task (*very simple project – new development*) and the TEAM descriptor reflective of personnel experience (*expert team – new team*). In accordance with EJ, the TEAM factor was selected to describe an experienced team (*aces* table value of 7), being a nominal table value in comparison to the table value of 10, which describes the ‘ideal’ and therefore unachievable team status. The 7 table value is entered into the software as a ‘0’ numerical input. An experienced team is a reasonable assumption to make, since for a project such as the manned SpaceLiner based on largely existing technology, an experienced team would be required for component and hardware realisation. And for a program as expansive, complex and international as the SpaceLiner, an inexperienced, a new, inexperienced team would be inadequate and insufficient.

The TASK parameter was then automatically generated by an assistant function based on other inputs including ENVIRD, TECHYEAR (described below) and mass.

• INDEXE/M

The INDEXE/M is the technology index for electronics (INDEXE) and mechanics (INDEXM). Both are usually empirically derived values representing product producibility while also qualifying the development effort. The numerical input values are available from dedicated INDEX tables incorporated within the 4cost software, and for the SpaceLiner case-study were determined automatically.

INDEXM is a function of physical characteristics, such as material type, finished product density and fabrication method. INDEXE is a function of componentry, packaging density, easy of manufacture, degree of testing and power dissipation. Both parameters depend, in this instance, on the ENVIRD (development environment) inputs, always increasing alongside an increase in ENVIRD. These inputs are also required for the production effort.

• Amount of New Design (NEWREPE/M)

The NEWREPE/M variables are used to quantify the amount of new design and drafting effort required to manufacture electronic and mechanical hardware for non-repetitive assemblies. All NEWREPE/M values to quantify the amount of new design and drafting effort required to manufacture mechanical and electronic hardware were generated either through EJ based on an existing table of value ranges, shown in Table 28 below, or through using the 4cost *aces* NEWREPE/M Assistant function integrated in the software. The NEWREPM value was also manipulated to reflect a 100% new effort for development of the SLO engine, as well as a token 1% new effort for the SLB engine (since a non-zero input in the field is required) in accordance with the SpaceLiner engine philosophy presented in Chapter 4.1.5.

Table 28: 4cost aces table for the scope of mechanical and electronic design novelty [1]

Scope / Task	NEWREPE/M
Preliminary Design	0,65 - 0,75
Layout / Drawings	0,50 - 0,60
Full Design / Detail Drawings	0,40 - 0,30
Assembly Drawings (done)	0,20 - 0,15
Quality Control	0,05 - 0,02

• TECHYEAR

This technical improvement factor, influenced also by the ENVIRD parameter, is applied to account for advances in technology as time progresses. For the calculation of SpaceLiner, to reflect the present level of technology, the TECHYEAR parameter was set at the year 2025 (input as 125), which is when the development phase, in terms of prototyping construction and consequent testing activities of the program is scheduled to begin.

• PROTO

This variable defines the number of prototype units which need to be built as part of the development program phase. For the 4cost *aces* calculation, the number of full SpaceLiner prototype vehicles was taken to be 5, in line with the SpaceLiner philosophy previously outlined in Chapter 4.1.

• ECBASE

The economic base (ECBASE), as the name implies, defines the economic base of the output costs, and was set to the year 2013.

• Development ECBASE

The development commencement was also entered as being the year 2025, which is in line with the proposed SpaceLiner schedule presented in Chapter 4.1.1.

A full list of the relevant, key 4cost *aces* software inputs as well as the resulting outputs can be found in Appendix H.

4.9.4 PRICE

PRICE-H Suite was used as the interface for this calculation. The model facilitates for a large number of control parameters used for primary calibration of the model to a specific environment. However, in view of the preliminary nature of the SpaceLiner program, given the top-level nature of the estimate and the high-level inputs, for this exercise, the model was used in its un-calibrated mode, meaning all control parameters and PRICE-H Global values and multipliers were set at their nominal, unadjusted values. Required complexities were then either generated from look-up tables, or were entered manually by an experienced and expert tool user, to translate technical requirements into representative model parameters. Key model *inputs* included:

- *Individual element mass* (W_S/W_T)
- *Platform value (PLTFM)*
- *Engineering complexity (ECMPLX)*
- *Manufacturing complexity (MCPLXS/E)*

- *Number of prototypes (PROTOS)*
- *Design heritage (NEWST/NEWEL)*
- *Year of technology (YRTECH)*
- *Development start date (DSTART)*
- *Economic conditions (YECON)*

While all detailed definitions can be found in the official PRICE manual [154], a basic outline of the key parameters listed above, their selected values for the SpaceLiner case-study, and the respective justifications for each decision are provided below.

• W_S/W_T

The element masses were entered into the WBS established in the PRICE-H software. The W_S entry refers to structure weight, while W_T refers to total weight per element. As such, the electronic weight is never input directly, but is derived by calculating the difference between the total and structural weights (W_T – W_S). Because of this, the two values are very commonly identical if there are no electronic parts present. Differences do exist between the two values for electronic components in the WBS elements such as *Power and ECS* (WBS elements 2400, 3400 and 4400) or *Cabin Avionics* (element 4600) for example.

• PLTFM

The empirically derived platform (PLTFM) value influences development engineering costs, and addresses the specification and testing level, the operating environment and reliability requirements associated with the element to be designed. Very loosely (but not identically) comparable to the ENVIRD value featured in the 4cost *aces* tool, the PLTFM value is also divided into the four categories of ground, mobile, airborne and space. For the SpaceLiner case-study calculation, a value of 2.0 was selected, being reflective of the quality assurance level for parts and inspections for a typical unmanned space mission. This may seem to be contradictive to the manned nature of the SpaceLiner vehicle by its definition. However, if the PLTFM value of 2.5 for traditional, heritage manned space applications was taken, this would result in an over-inflated cost for the program, as it would not take into account the existing significant heritage for the SpaceLiner technology, nor the commercial nature and context of the program. Since SpaceLiner aims to exploit lessons learned from advanced aviation products, economies of scale, and more mature processes, a lower PLTFM value to strictly and purely space technologies is reflective and representative of this.

- **ECMPLX**

The engineering complexity (ECMPLX) value is a measure of the complicating factors of the design effort as they relate to the level of technology, and the skills of the development team. More specifically, this factor addresses the influence and experience of the design team within the scope of the development effort, with respect to the TRL of the technology. A typical value of 1.0 describes a new design, within state of the art, and performed by an experienced team familiar with similar work. For the SpaceLiner, based on extensive PRICE expert user consultation, the ECMPLX value was set to be 1.5 to reflect a team experienced with similar familiar, but not identical technology, with the scope of the design effort having a new design, with unfamiliar technology. The value is highlighted in **green** in Table 29. Although the SpaceLiner case-study project would be based on significant technical heritage, the context of elements within a new application imposes an added level of complexity, especially given the manned nature of the system. The value of 1.5 therefore takes a more cautious approach, with the aim of not being too optimistic, and to avoid resulting in understatement of development effort and costs. This ECMPLX factor is only relevant to the development effort as it describes the design phase, addressing drawing complexity which is then translated into an effort mount, and therefore does **not** influence production.

Table 29: PRICE engineering complexity (ECMPLX) values matrix [53, 154]

Scope of Design Effort	Experience of Personnel			
	Extensive Experience, Familiar Product	Normal Experience, Familiar Product	Mixed Experience, Some Product Familiarity	Limited Experience, Unfamiliar Product
Simple Modification, Existing Design	0.2	0.3	0.4	0.5
Extensive Modification, Existing Design	0.6	0.7	0.8	0.9
New Design, Existing Technology	0.9	1.0	1.1	1.2
New Design, New Product Line	1.0	1.2	1.4	1.6
New Design, Unfamiliar Technology	1.3 **1.5**	1.6	1.9	2.2
New Design, State of the Art Technology	1.9	2.3	2.7	3.1

• **MCPLXS/E**

The manufacturing complexity values refer to the manufacturing complexity of structure (MCPLXS) and electronics (MCPLXSE). These technology indices describe the structural/electronics portion of the item under development, measuring its technology and producibility, as well as the labour and material required to make the item component. As such, these factors are applicable to both development and production costs. MCPLXS/E are both considerable cost drivers, the values for which can be derived through calibration, from dedicated internal PRICE generators, as well as from reference tables of values extracted from a detailed database of past historical missions and programs.

• **PROTOS**

The number of prototypes entered was 5 units in line with the SpaceLiner case-study prototype philosophy definition outlined in Chapter 4.1.3. For items with multiple articles per

SpaceLiner unit (i.e. engines, with 9 SLB and 2 SLO engines per vehicle), the number of prototypes was increased to provide a complete set of hardware for each higher level assembly. As such, the cost for 45 SLB and 10 SLO engines were calculated within framework of the prototype units for the SpaceLiner development phase. For development of the SLME component (element 2200), the PRICE model does not take into account the test firings for the development effort. As such, a global multiplier was imposed to factor in for the stipulated number of 1200 of test firings, which, at this early stage, was deemed by PRICE experts as a representative amendment to address the qualitatively known cost gap. At a later program phase, however, it would be appropriate to address this model shortcoming by conducting an independent bottom-up analysis of the expected test-firing campaign costs. These should then be added on as a separate element to the PRICE cost estimation structure. Here, it would be necessary to consider the non-recursive costs for test-rig procurement and installation, and then the recursive fixed direct operating costs (DOC) for the test facility as well as staff required for the campaign.

- **NEWST/NEWEL**

The new structure (NEWST) and new electronics (NEWEL) inputs define the amount of the new structure/design effort required, where 100% equates to an input of 1.0. This was only deviated from a 1.0 input to 0.01 for the propulsion component of the booster engine in WBS element 3200, since development of this was assumed to be fully covered in the development of the SLME for element 2200 (see Chapter 4.1.5).

- **YRTECH**

The year of technology defines the technological state for the development phase timeframe. In case of the SpaceLiner program, YRTECH was set to the commencement of the Design and Development (Phase C) of the program identified already in the program schedule described in Chapter 4.1.2, and is determined as 2025, also in line with the 4cost *aces* tool input.

• **DSTART**

The date of production start (PSTART) is given to be January, 2025 (input as 125), in line with the YRTECH input shown above, and also reflective of the SpaceLiner baseline program schedule introduced in Chapter 4.1.2.

• **YECON**

The year of economics (YECON) defines the economic base of the output costs, and was set to 2013.

Based on all above key inputs, development costs per element were calculated. In addition, an optimal development time was also synthesised by the PRICE software assuming an ideal scenario with no schedule delays. A list of key PRICE software inputs which are discussed above, as well as resulting outputs can be found in Appendix I.

4.9.5 Optimal Development Timeframe

The TransCost model is not dedicated to generating scheduling information, although both the commercial software models, 4cost *aces* and PRICE generated baseline development timeframes given an internal synthesis of all available inputs. Both tools rely on internal algorithms to propose an **optimal** development phase which results in no cost penalties under ideal, optimised scheduling conditions.

Duration of the development phase is a parameter which is automatically calculated by the PRICE-H model. This is influenced by other model inputs and factors, including equipment complexity, PLTFM and ECMPLX values, and results in an optimised cost, thus avoiding penalties by enforcing an artificial timeframe. For the SpaceLiner case-study, this was found to be 81 months, commencing in January, 2025 and continuing through until the end of September, 2031. The 4cost *aces* software similarly relies on inputs such as the environment descriptor

ENVIRD, the engineering difficulty ENGDIF and the mechanical index INDEXM as key inputs, and resulted in a development timeframe of 59 months, from January, 2025, until November, 2029.

It must be noted that both software tools produce idyllic and rather uncertain scenarios of a development phase assuming no scheduling delays and no unexpected events. In reality, for a program as large and complex as the SpaceLiner case-study would be, the timeframe is dictated not only by technical capabilities, but also by a myriad of other aspects including politics, economics, financing, as well as unforeseen occurrences. Here, the risk and uncertainty assessment outlined qualitatively in Chapter 4.1.11 would constitute an essential input. As such, taking the longer PRICE tool optimal development phase of 83 months, it can be almost certainly assumed that the development phase would take longer than this.

The baseline results obtained from both commercial tools can be used to build upon as more SpaceLiner program information comes to light. And with an initial program schedule having already and freshly been established translating the still evolving technical details into a timeframe, it is not too unreasonable to assume a simplified and optimised schedule at this stage. Certainly, however, a greater level of scheduling risk analysis will also need to be integrated into the cost estimate at a later program stage alongside revision of the currently proposed program schedule as more precise information becomes available.

4.9.6 Development Project Management Office Cost Estimation

In this section, in accordance with the distinction made between the terms of ‘price’ and ‘cost’ in Chapter 2.1, ultimately the overall figures estimated in for the PMO function are in fact prices, since the profit margin is always incorporated. Nevertheless, to comply with the cost estimation goal of this Thesis, and to avoid confusion, while recognising the difference between ‘cost’ and ‘price’, the term ‘cost’ is nevertheless adhered to.

The PMO functions at the total, top system level ($L1_{WBS}$) and at a major program element level ($L2_{WBS}$), are represented in WBS elements 1000 as well as 2100, 3100, 4100, 5100, 6100 and 7100, respectively. While the independent component PMO function costs for development of the SpaceLiner SLO, SLB and SPC (elements 2100, 3100, 4100 respectively) are already inherently included in all three models used for the AA, the overall, top-level PMO function of WBS element 1000 needs to be estimated. Here, EJ is once again employed to determine a representative and defensible figure.

In addition, and as previously defined, elements 6000 (Ground) is only qualitatively considered within this Thesis, and for the PMO function, it is possible to do a ROM cost estimate using EJ in close consultation with experienced project management experts. For element 7000 (Operations), PMO costs are not considered since, being a recurring cost, they do not apply for the non-recursive elements of the development phase.

For this section of calculations, both literature [114, 147] and high-level space industry management and programmatic experts and professionals were consulted with respect to their knowledge of the project office costs [118, 119], since here, real-industry practical experience is essential for application due to the unique and unprecedented nature of the SpaceLiner case-study. Expert judgement was also relied upon to assist in formulation of the PMO function component breakdown, as well as to estimate preliminary numbers of staff and consequently the costs for this vital function within the overall program framework.

Overall program costs vary significantly during a project as a whole, and more specifically, within each program phase, as illustrated in Figure 34 below. PMO effort and costs are not linear or proportionate with these movements, although it has been observed that the highest levels of PMO and program management activities occur during the early program phases, in the lead-up to production [223]. Such a trend is logically attributed to significant time investment and initiatives for establishing and developing a project plan, which sees an effort increase and therefore a higher utility, need, application and consequently cost of the PMO function in the initial concept and development and implementation phases [79]. Then, as the program matures through development and into the operation, the PMO burden is reduced and re-allocated to task managers.

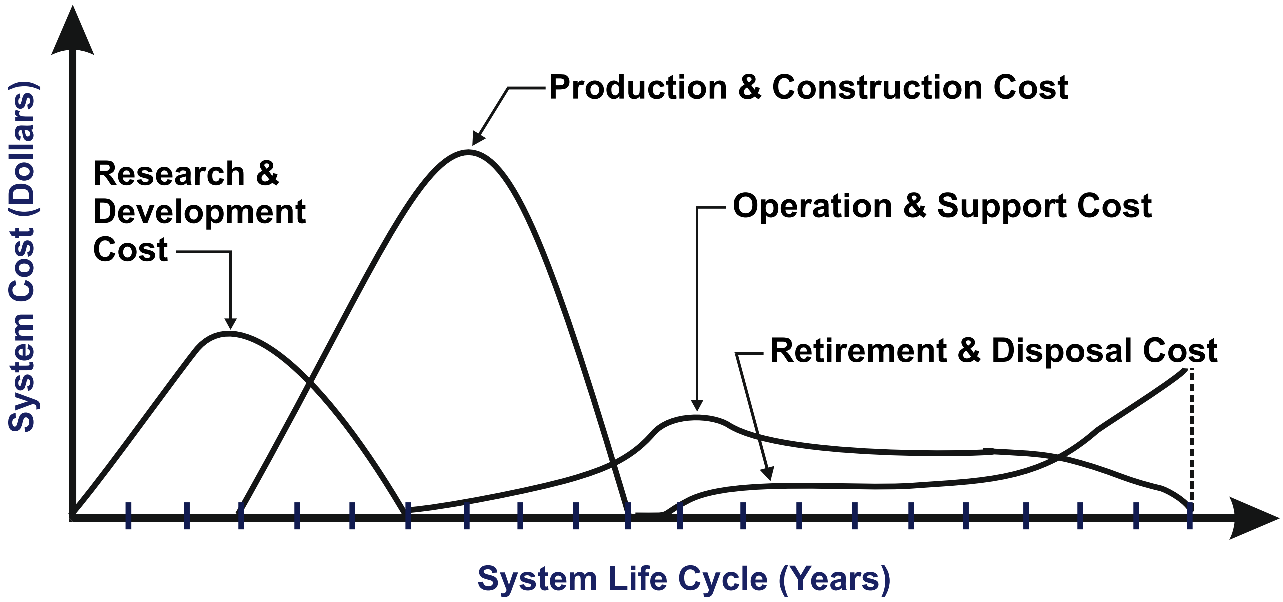


Figure 34: The constituent costs and their typical qualitative variations incurred by each program phase [25, 118]

To determine the top-level PMO effort expected for the SpaceLiner case-study, the task is segmented into its constituent components, for which a total staff requirement is estimated and converted to a cost. The breakdown of PMO functions and component as well as its structure within the SpaceLiner WBS context was compiled through combination of project management theory discussed in this chapter, alongside EJ derived from close consultation with ISU experts with decades of diverse project management experience, including for large, international, complex programs [118, 119]. The derived PMO effort and the constituent functions for WBS element 1000 are shown below in Table 30.

It is estimated that a total of 50 staff-members are required throughout the duration of the development phase to perform for the PMO function of WBS element 1100. This derived figure represents an **average** value of the overall typical work-effort curve, since the project manager's level of effort tends to significantly vary to the overall program effort curve.

To convert the staff numbers to a monetary amount, a relevant cost per annum for the particular nature of the PMO management function had to be determined. The TransCost average WYr Euro value for the 2013 economic year within the space industry is given to be €285,000. However, arguably, since the management function can be classified as a rather specific activity, more in-depth research was conducted into this aspect.

Further analysis of the WYr cost for the PMO elements was undertaken and a bottom-up approach assumed to determine the required effort, and therefore the associated total cost for the program management of the SpaceLiner case-study. Industrial hourly rates are usually highly confidential. For example, within the context of actual ESA projects, the rates are audited directly by ESA, and are therefore not disclosed externally. Nevertheless, a basic and representative cost figure needed to be justifiably determined.

Looking into the commercial tools available, the European 4cost *aces* tool, for example, uses an average hourly rate of €100 for calculation of the average development cost. Here it must emphasised again that 4cost *aces* is a general industry model and the base rate is not specific to the space industry, which, on average tends to be higher than the cross-sectional industry average. However, for high-level management skills, as would be required for PMO of the SpaceLiner case-study, this average should be higher to compensate for the specialised skills required to perform the managerial function. Upon consultation with experts in the project management field for large-scale programs [117], a current management hourly rate of €156 was therefore derived, resulting in a monthly work effort cost per person of roughly €25,000 (€24,960) per annum. The associated assumptions and breakdowns of constituent cost elements of this total annual PMO cost figure are shown below in detail.

Table 30: Qualitative break-down into constituents of the PMO function with an EJ estimate for average number of personnel required per function [119, 147]

1100 PMO Cost Breakdown			
	PMO Functions		Estimate of Personnel
1	**Program management (Deputy & Secretariat)**		**Total: 3**
2	**Systems Engineering**		**Total: 15**
a.	*Engineering Management & Secretariat*	*2*	
b.	*Overall system & interfaces control*	*4*	
c.	*SLO supervision & monitoring*	*2*	
d.	*SLB supervision & monitoring*	*2*	
e.	*SPC supervision & monitoring*	*2*	
f.	*AIT supervision & monitoring*	*1*	
g.	*ground supervision & monitoring*	*2*	
3	**Product Assurance (PA)**		**Total: 8**
a.	*PA management & Secretariat*	*2*	
b.	*reliability*	*2*	
c.	*quality*	*1*	
d.	*maintainability*	*1*	
e.	*safety*	*1*	
f.	*central parts procurement*	*1*	
4	**Project Control - schedule & cost control**		**Total: 7**
a.	*PC management & Secretariat*	*2*	
b.	*schedule control*	*2*	
c.	*cost/finance control*	*3*	
5	**Documentation & Configuration management**		**Total: 5**
a.	*documentation control*	*2*	
b.	*archiving*	*1*	
c.	*configuration/change control*	*2*	
6	**Risk Management**		**Total: 2**
a.	*risk monitoring & analysis*	*1*	
b.	*risk mitigation*	*1*	
7	**Logistics & Transportation management**		**Total: 1**
8	**Communication & Reporting**		**Total: 2**
9	**External support**		**Total: 7**
	TOTAL AVERAGE STAFF AT SYSTEM LEVEL / p.a.		**50**

4.9.6.1 PMO Cost Assumptions

- ***€120/hour base:*** average hourly industrial gross rate for PMO functions, catering for management, highly qualified engineering personnel and necessary support staff.

- ***<u>plus</u> 20% other direct costs (€24/hour):*** allowance and provision for extra costs such as for transportation, travel and lodging, communication, rental of special purpose equipment, small value item purchases, social events etc. ***(updated total €144/hr)***

- ***<u>plus</u> 8% profit (€12/hour):*** the standard industry ESA profit margin ***(updated total €156/hr)***

- ***140 hours per month:*** hours required per management function based on the following assumptions:
    - 4 weeks per month
    - 5 work days per week
    - 7 hours per day

The German office of Statistics [68] stipulates that on average, in 2012, individuals in Europe worked 37.5 hours per week, which is roughly 156 hours per month. In addition, TransCost states that in Europe (ESA) an average of 1583 effective hours are worked per year, translating to an equivalent of 132 hours per month and 33 hours per week. Therefore, the value of 160 hours per month, as estimated for the SpaceLiner PMO function, is well in line with both the general and the industry-specific averages. The slightly higher 160 hour per month estimate is revised up from both averages to correspond with a schedule of respectively higher intensity in line with the large scope and very complex nature of the SpaceLiner program, requiring increased management efforts. Combining and summarising the analyses, the resulting figure for the estimated PMO function is therefore €156 per hour, with 160 accountable hours per month.

Here, by definition, the calculated monthly total WYr amount represents the effort quantity required to adequately address the PMO function. Consequently, using the derived figures, at a total of €156 per hour, with 160 hours of effort per month, per employee, we have a monthly cost of €24,960 (rounding up to $25,000) and an annual cost of €300,000 per employee. This is reflected in the Table 30 above. Furthermore, from a ROM perspective, the figure is very well aligned with the TransCost 2013 e.c. cost of €285,000 in terms of order of magnitude, as well as underlying logic.

A summary of the total PMO costs within the derived WBS is consequently calculated and is shown in Table 31 below, where the calculated annual WYr cost of €300,000 for the PMO function is assumed. The optimal development phase period, as extracted from both the 4cost *aces* (63 months) and the PRICE (80 months) software calculations for the optimal baseline development case including the five-model prototype philosophy, was assumed to be ideal, with no time delays incurred. Given these PRICE and 4cost development schedule averages, a 7 year development timeframe (84 months) is assumed. This is also independently and consistently reflected in the preliminary program schedule introduced in Chapter 4.1.2. WBS element 7100 is obviously omitted since the operations are recurring, and as such, do not apply to development.

Table 31: Estimated PMO costs for 7 year development phase

WBS Element		Personnel Qty.	Cost (M€) Per Annum	Cost / Optimal Development Time
1100	SpaceLiner System PMO	50	14.98	104,83

In reality, it is important to concede that for an international program as complex and expansive as the SpaceLiner case-study would be, schedule delays would be highly likely. Scheduling delays are always inherent due to various external factors, often beyond the control of management. Risk analysis is therefore essential to address and potentially mitigate the latter.

Any schedule delays would consequently incur time and therefore cost penalties. For the PMO category, any penalty costs can be simply derived from the calculated figures presented in Table 31 above. For every month of delay to the development phase, global program PMO costs for all WBS elements incurred would have to cover employment of the full program PMO staff, being 250 personnel, and costing 6.24 M€.

Another factor to consider here is that due to the magnitude and scope of the program, the size of the teams to be managed by one manager, might be comparatively large. Management studies have shown that the span of control of a supervisor over a complex activity should not exceed 12 workers. For simple activities, the ratio of supervisors to employees can go down. But the 1:12 ratio (8.3%) will usually yield best results. Project Management for a complex project can add an additional 10 to 14% [202]. This fact should also be considered within context of any further and more in-depth studies of the PMO function and cost within such a large, complex, international program as the SpaceLiner case-study.

4.9.7 Development Amalgamation Approach Results

With all cost element fields being complete, results amongst the three AA_{MAC} models could be analysed. Before the final development costs can be presented, however, a cheeky sub-chapter is absolutely essential to visually show and practically explain the intensively iterative nature of the AA_{MAC} process. Such an example of just one iteration of many which happen prior to the final cost-range figures being achieved, shows both the power and effectiveness of the AA_{MAC} method, especially when applied in conjunction with the specifically designed and developed AAInT.

4.9.7.1 An AA_{MAC} Iteration Example

Before AA_{MAC} final results are achieved, which will be presented shortly, the AA_{MAC} can lend itself to many numerous iterations for each model if this is necessary before the final cost range is reached. The aim of these iterations is to identify potential inaccuracies in results whether due to model input, because of human error or incorrect logic, or perhaps translation of technical data into model inputs. It can also be that sometimes a particular model is not capable to effectively estimate the cost of a particular element, and may thus be inappropriate for the application. Whatever the reason, the logical structure of the AA_{MAC} maximally ensures that any inconsistencies can be identified.

Thus, upon completion of a cost-estimate run for each of the three respective models and tools and entry of all into AAInT, a critical analysis must then made between the estimates. As shown previously in Figure 7, if significant differences are identified in costs for a common element between models, this is immediately an indication to the cost estimator that further analyses should be performed to determine the reason and justify the significant delta. The conclusion of these analyses could yield explanations such as the non-applicability of a particular tool or model to the current element (or even project) being costed, an inaccurate translation of a variable could be discovered, or even human error could be noted, amongst others. Identification of any issues or problems allows for them to be corrected before the next cost iteration is made. As such, every single iteration serves to eliminate error in the final result, thus also reducing the uncertainty through a staunch and justifiable result. An example of one such iteration is outlined briefly here.

Upon completion of an almost-final development cost run across all three models, the following results were observed of the SLO component, per model, as shown in the simplified table extracted from the AAInT tool below in Table 32.

Table 32: Example of an essential iteration in the AA_{MAC} process

Element	TransCost	4cost	PRICE-H
SLO (B€, 2013 e.c.)	4.67	8.84	9.55

Firstly, and immediately, a significant deviation can be seen between the 4cost and PRICE results, compared with the significantly lower TransCost figure. Furthermore, building on previous experience established from extensive TransCost model testing (see Appendix E and ref. [207]), the fact that the TransCost result is so much lower compared with the other two models is a very surprising and unexpected one. TransCost is a dedicated launch vehicle model and as such, is based on data for orbital vehicles, which, depending of course on the mission, may have different characteristics. Generally, through the model testing regime, the TransCost model has shown to result in either equal or higher results compared with at least literary figures, as the model also is defined is presenting the "real project cost" inclusive of a margin.

In identifying a suspiciously high cost deviation, in line with AA_{MAC} principles, the cost delta needed to be analysed further and justified. Going back to the TransCost interface inputs, and upon further investigation of the mass data and complexity factors, the Technical Quality Factor f_2 was noted to be particularly and illogically low.

Upon further investigation, a critical inconsistency was discovered. It was seen that a calculation for the Net Mass Fraction (NMF) required by the TransCost manual to determine f_2 was assumed from an incorrect TransCost model graph which was dedicated for ELVs rather than the relevant RLV category of vehicles. After a quick consultation of NMF values for the correct graph, the modified results, as shown in Table 33, were thus obtained and updated in AAInT. It can be seen that all three AA_{MAC} cost estimation results lie within an excellent common range.

Table 33: Example of an essential iteration in the AA_{MAC} process

Element	TransCost	4cost	PRICE-H
SLO (B€, 2013 e.c.)	9.54	8.84	9.55

The AA_{MAC} technique supported the identification of an input inconsistency shows. Here, the cost estimator's experience with the AA_{MAC} models being applied, and in this particular instance, specifically with the TransCost model dynamics, was essential to detect an unusual and unexpected trend between multiple AA_{MAC} results as an alert and indication of an underlying error. As previously mentioned in Chapter 2.2.1, cost estimator experience and competency is one of the three key elements required for obtaining a high-confidence estimate. And it is exactly in this way, through numerous, consecutive iterations, and through repeated analyses at the conclusion of each iteration for any inconsistencies, that the AA_{MAC} maximally and effectively assists in the elimination of various factors which could otherwise contribute to a non-representative end cost estimation result. With correct application of AA_{MAC} uncertainty is reduced with each iteration and the most optimal early program phase cost result is honed in upon.

4.9.7.2 AA_{MAC} Final Development Results

The finalised AA_{MAC} results are presented in Table 34 to Table 38 which are extracted directly from the AAInT interface. Each of the three tables show the costs for the three SpaceLiner elements being the passenger orbiter stage (SLO), the booster (SLB) and the passenger cabin and rescue capsule (SPC). The original, pre-sensitivity TransCost calculated development costs are assumed from Chapter 4.9.1.2. As can be seen, the TransCost model presents costs at a higher $L2_{WBS}$, while the PRICE and 4cost models also present costs at the lower $L3_{WBS}$. Additionally, Table 37 also contains extra rows for "*Other costs*". The AAInT also allows for any other additional costs generated by AA methods or tools to be incorporated. Here, one field is used to apply the TransCost top level engineering factor, f_0, while top level I&T costs are also listed for the commercial models. For both commercial models and TransCost, too, the cost of money is not considered in any of the calculated results.

A comparative summary of the initial set of costs from all three models within context of the AA_{MAC}, is then shown in Figure 35. While the qualitative nature of the ROM figures is representative, it must be noted that the segmentation of costs between TransCost, 4cost and PRICE varies. Namely, that the TransCost model imposes complexities for programmatic factors, at a later stage, after the costs of all individual elements are already determined. Both PRICE and 4cost *aces* impose PFs internally to each element. In addition, TransCost considers SW costs as being embedded in the development effort, although their specific proportion is undefined. The 4cost *aces* model does generate basic SW development costs based on physical electronics hardware specifications. The PRICE-H model relies on its PRICE-S partition which is specifically designed for SW cost calculations, which can then be incorporated into overall hardware cost structure. However, as very little information is available pertaining SpaceLiner case-study SW requirements, SW cost is treated outside the scope of this Thesis work. The results of both commercial tools thus exclude SW, while TransCost includes it in the design effort. A detailed discussion on SW costs and the philosophy adopted for this Thesis can be found previously in Chapter 4.1.6, as well as below in Chapter 4.9.8.5.

Table 34: AAInT spreadsheet for SpaceLiner PMO development costs

C – 1000		SpaceLiner OVERALL SYSTEM	TransCost	*4cost*	PRICE
PM	1100	Overall Project Management Office (PMO)*		*0.105*	*0.105*
Other	1200	Total Project Travel inc. all sub-systems°		*0.024*	*included in calcs.*
		TOTAL B€ (2013 e.c.)	0.000	0.128	0.105

** EJ determined overall top PMO costs (4cost and PRICE models* ***only****, see Chapter 4.9.6.1), ** with EJ derived cost for travel.*
° travel costs already addressed by PRICE tool in PMO calculations global to each element.

Table 35: AAInT spreadsheet for SLO case-study development costs

C - 2000		SpaceLiner ORBITER (SLO)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	*2100*	*SLO PMO**		*included in calcs.*	*included in calcs*
HW	2200	Propulsion (SLME)~	*3.815*	1.050	2.152
HW	2300	Structures & Mechanics		5.390	5.737
HW	2400	TPS/TC		1.168	1.117
SW	*2500*	*Flight Control System°*		*0.000*	*0.000*
HW	2600	Avionics^		*incl. in 3600_{WBS}*	*incl. in 3600_{WBS}*
HW	2700	Power & Housekeeping		0.490	0.273
AIT	2800	SLO AI&T		0.738	0.269
		TOTAL B€ (2013 e.c.)	13.352	8.836	9.547

** Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLO.*
~ This amount is **included** *in the 8.480 B€ total calculated below, and is therefore shown in italics*
° SW costs not included
^ Avionics costs were calculated for both SLO/SLB, and shown as a single amount in the SLB element 3600, as shown below in Table 36

Table 36: AAInT spreadsheet for SLB case-study development costs

C - 3000		SpaceLiner BOOSTER (SLB)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	***3100***	***SLB PMO****		*included in calcs.*	*Included in calcs.*
HW	**3200**	**Propulsion**		0.714	0.850
HW	**3300**	**Structures & Mechanics**		6.612	7.267
HW	**3400**	**TPS/TC**		1.496	1.212
SW	*3500*	*Flight Control System°*		*0.000*	*0.000*
HW	**3600**	**Avionics^**		0.348	0.145
HW	**3700**	**Power & Housekeeping**		0.903	0.576
AIT	**3800**	**SLB AI&T**		0.955	0.417
		TOTAL (B€, 2013 e.c.)	**10.008**	**11.029**	**10.467**

**Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLB.*
° SW costs not included
^ Costs shown here represent avionics costs for both SLO/SLB.

Table 37: AAInT spreadsheet for SPC case-study development costs

C - 4000		SpaceLiner PASSENGER CABIN / RESCUE CAPSULE (SPC)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	***4100***	***SPC PMO****		*included in calc.*	*included in calc.*
HW	**4200**	**Propulsion (CSM capsule solid motors)**		0.051	0.086
HW	**4300**	**Structures & Mechanics**		0.351	0.364
HW	**4400**	**TPS/TC**		0.257	0.380
SW	*4500*	*Flight Control System°*		*0.000*	*0.000*
HW	**4600**	**Avionics**		0.186	0.072

HW	**4700**	**Power & Housekeeping**		0.209	0.106
HW	**4800**	**Life / Passenger Support Systems**		1.209	0.902
AIT	**4900**	**SPC AI&T**		0.217	0.067
		TOTAL (B€, 2013 e.c.)	**5.664**	**2.471**	**1.977**
		Other costs	(f_0) 2.368	*(overall I&T) 0.909*	*(overall I&T) .185*
		Other costs			

**Both 4cost aces and PRICE already factor in for PMO costs relevant to SPC.*
° SW costs not included

Table 38: Total SpaceLiner case-study development program costs, with margin

SpaceLiner CASE-STUDY	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
TOTAL PROGRAM DEVELOPMENT COST	31.39	23.37	22.28
MARGIN (20%)	*already included*	*4.67*	*4.46*
GROSS PROGRAM DEVELOPMENT COST	**31.39**	**28.05**	**26.74**

4.9.8 Discussion of AA_{MAC} Development Costs

A comparative summary of AA_{MAC} derived costs at a high level only (excluding for example, the overall top-level PMO function) is shown below in Figure 35 and Table 39. While TransCost already incorporates an inherent 20% margin in all calculated costs by its definition, a 20% margin also assigned for the PRICE and 4cost *aces* models to address risk in line with the case-study philosophy established in Chapter 4.1.11. However, as shown in Table 38, this margin is applied at a top $L1_{WBS}$ and only at the end of summation of individual results. Therefore to ensure that a representative comparison is made, both Figure 35 and Table 39 compare the results per element, with the 20% margin included for all figures. It is important to note that the end results per model are the same, although an alternative order for the numerical margin and programmatic factor application is simply adopted to facilitate for a meaningful visual comparison to be made.

When considering the calculated and presented final program development costs at an overall system level ($L1_{WBS}$), an excellent congruence can be observed between the costs for all three AA tools (TransCost, 31.4 B€; 4cost *aces* 28.0 B€; PRICE 26.7 B€). Respective deltas are 1.31 B€ between the lowest PRICE result and the 4cost *aces* estimate. Between the 4cost *aces* and PRICE results, a cost delta of 3.34 B€ is observed, while the range of all three AA_{MAC} estimates can be described by a humble 4.65 B€ delta. However, and as seen in Figure 35 and Table 39, looking deeper at $L2_{WBS}$ values for the four key elements to be developed, slightly more pronounced cost variations are evident. Figure 35 shows an outstanding development cost estimation congruence for the SLO element (range of 8.8 - 9.5 B€) as calculated by all three models. For the SLME component, however, the cost expands over a 1.2 – 3.9 B€ broad range. The SLB element then again has a strong correlation of development costs calculated across all three models, being consistently in the 10 - 13 B€ range. Here, it must be recalled that the TransCost CER applied for the SLB was the modified and newly developed CER (see Chapter 4.7) developed as a direct outcome of the intensive TransCost model testing process conducted within this Thesis and, in part, presented in Appendix E as well as in ref. [207]. The firm congruency of the new SLB TransCost CER with both results of the PRICE and 4cost *aces* models presents a solid confirmation of its representativeness well in line with the AA_{MAC} theory and context. Finally, for the SPC element, a close correlation is observed between the PRICE (2.37 B€) and 4cost *aces* (roughly 3 B€) models, with a much higher estimate of over 5.6 B€ calculated by TransCost.

Again honing in on development costs observed at an even lower $L3_{WBS}$, as can be seen in Table 35 to Table 37, more pronounced cost variations are evident. The cost deviations and variations between the multiple models are, in fact, not at all surprising, and should be expected when applying the Amalgamation Approach. In line with the AA principle, the greater cost variations across the multiple models serve as an indication that those elements carry a higher cost uncertainty. As such, and depending on the degree of deviations, further work for the cost estimator may entail determining or justifying possible reasons for the differences. Thus, the last and most crucial stage of the AA process is the associated analysis for any significant deviations amongst the multiple results. It is through this process that potential mistakes can be located, or any other inconsistencies, errors or merely model features, identified. In this way the AA_{MAC} resulting cost estimate is maximally justified, which supports a reduction in uncertainty.

The following sub-chapters seek to explain key differences and development cost deviations and deltas identified through application of the AA_{MAC}. Deviations at both the top WBS level as well as lower levels for the SpaceLiner case-study are addressed and discussed in detail through analytical reasoning and theoretical logic and justifications which are directly linked with model mechanics.

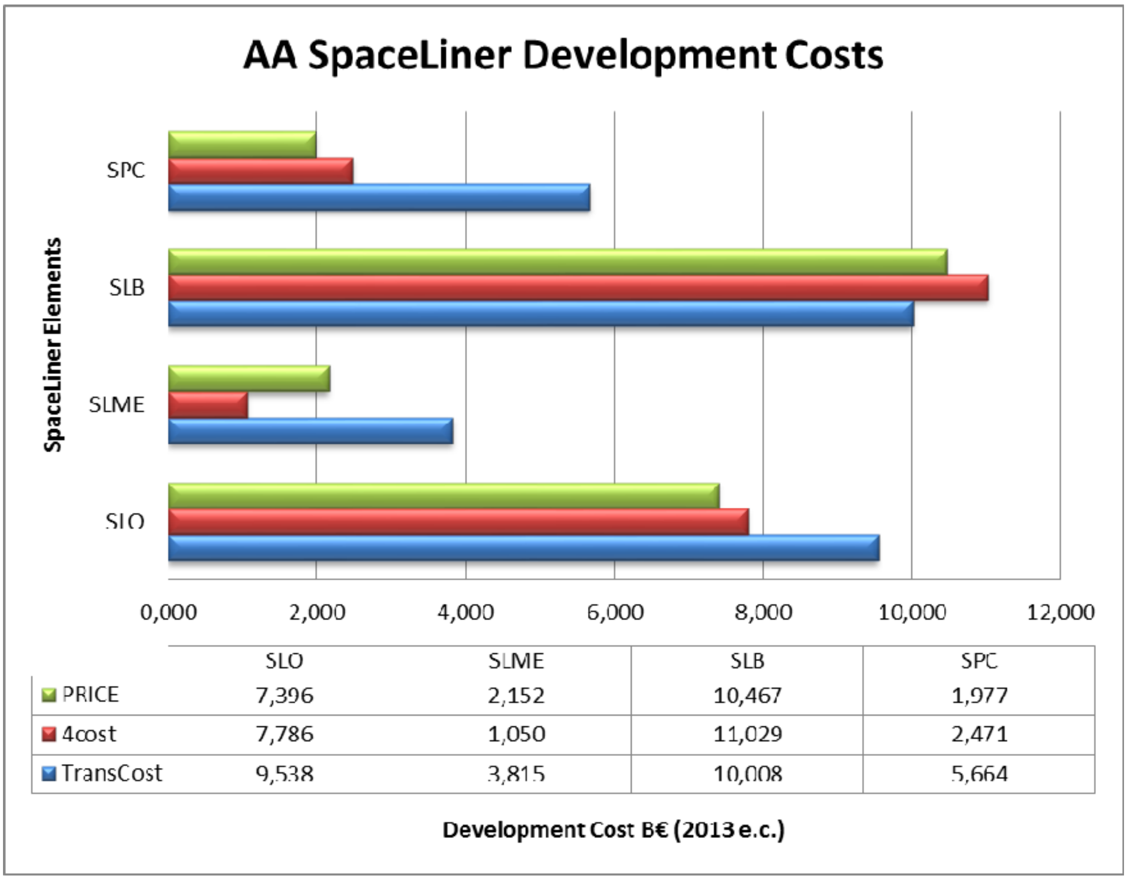


Figure 35: Visual comparative representation of AA_{MAC} development costs per element only, without programmatic factors, but including 20% margin

Table 39: Comparative summary of AA_{MAC} total program development costs per element with 20% margin, including all programmatic factors

Component	TransCost	4cost (incl. 20% margin)	PRICE (incl. 20% margin)
SLO	9.54	9.34	8.88
SLME	3.82	1.26	2.58
SLB	10.01	13.23	12.56
SPC	5.66	2.97	2.37
Other	2.37	1.25	0.35
∑ AA_{MAC} PRODUCTION TOTAL COST B€ (2013 e.c.)	**31.39**	**28.05**	**26.74**
AVE. AA_{MAC} PRODUCTION COST B€ (2013 e.c.)	**28.73**		

4.9.8.1 SLME Development Cost Difference

A key distinction between the 4cost *aces* and PRICE models relevant to development effort of engines was that both commercial tools do not take into account the number of test firings, which is a key cost driver in the simple, top-level TransCost calculation. However, the models deal with this aspect through other factors, like complexity and environmental parameters. As such, a direct comparison of factors and their values is impossible. With the chosen number of test firings entered into the TransCost model (being 1200, based on Space Shuttle main engine firings of 800 times), the f_2 factor is increased to 1.31, resulting in a respective linear increase to the engine development cost by 31%. For the commercial tools, however, the increase in required test firings is reflected through complexity values (PLTFM, MCPLXS and ECMPLX variables for PRICE and ENVIRD, ENGDIF HW and INDEXM for 4cost *aces*).

4.9.8.2 SPC Development Cost Difference

Once again a significant cost difference exists between TransCost and the highly congruent PRICE and 4cost *aces* models for SPC development. This distinction has largely been described in Chapter 4.1.9, in that TransCost CER data-points refer to capsules like Mercury and Gemini, which significantly differ to the SpaceLiner SPC, both in purpose, PAX capacity and lifetime. It is important to note that the TransCost model development cost-driving parameters includes the number of crew, and the mission lifetime, which is given in days (as seen in Table 23). Needless to say cost variances and the dynamics of the development effort would be significantly different for a capsule with a 4-6 PAX capacity over several days, to a 50 PAX cabin over a 90-minute duration. Through extrapolation of a relationship based on description of the latter, it is not surprising that the SpaceLiner case-study SPC is ultimately over-estimated.

4.9.8.3 Variability of Model Mechanics

In addition to specific reasons for cot variation, each cost estimation tool and model has an own unique structure of cost segmentation, as well as internal model mechanics and inputs and outputs structure (also see Chapter 2.6.5.2). As such, variability of model mechanics, in part, would contribute to differences between element costs, especially as observed at the lower WBS levels. The TransCost model, for example, calculates costs using basic element CERs, after which the sum of all individual CERs is calculated, and as a last step, programmatic factors applied. These programmatic complexities address overall system integration, schedule delays, hierarchy of participating companies within a program with respect to the structure of prime and sub-prime contractors, as well as the commercial nature of a program. The other two AA employed tools, PRICE and 4cost, do not necessarily segment their costs in this manner, but incorporate them in other groupings, and with a different roll-up order and structure across cost categories. As such, when comparing costs at a very low level of detail, particularly within an early program phase, variations in costs between different models and tools must always be expected. It is only when these variations are significant (namely a multiple order of magnitude inconsistency) that further work and analyses should be conducted to determine why in line with the AA philosophy introduced previously and outlined in Chapter 2.6.2.

4.9.8.4 Variability in Model Users & EJ Bias

All three 4cost *aces*, PRICE and TransCost models required utility of EJ at various stages of the calculating process to arrive at a cost.

The commercial tools, 4cost *aces* and PRICE, required inputs of various factors and complexities either generated internally by the software, or as deemed appropriate by the expert users. For each decision, EJ is relied upon and employed by the model user. Multiple separate, independent users entered and calibrated data for their respective cost estimation models throughout the course of the calculations described within this Thesis. As such, it cannot be expected that all users consistently generated identical complexity factors, potentially resulting in various degrees of EJ bias already described in Chapter 2.4.4. The subjective nature of the EJ method constitutes a well-known and identified weakness of the EJ approach. In addition, minor errors and/or fluctuations in EJ concerning determination and assignment of complexity factors, coupled with case-study system inputs which are themselves estimates, and not fully crystallised, would also contribute to discrepancies and fluctuations between the two commercial cost models on a micro-, subsystem and component level.

4.9.8.5 Software Considerations

In the calculations for the SpaceLiner case-study, in line with the SpaceLiner philosophy, it was decided to exclude software (SW) costs due to an immature specification status within the program context (see Chapter 4.1.6). This decision, however, has ramifications on the development and in part, later on production costs. In view of the SpaceLiner case-study being in the early program phase and approaching maturity in terms of SW considerations in the future, the SW WBS elements are still included in the WBS to facilitate for future incorporation of costs once these can be calculated. As such, in the AA representation, the largely software element 2500, 3500 and 4500 fields are shown in *italics*, also with a zero cost.

Here, it must also be recalled that SW costs were addressed differently by the two commercial 4cost aces and PRICE tools used for the AA framework. The PRICE-H module of the PES software did not explicitly calculate SpaceLiner case-study SW costs. If software costs are required with the PRICE Estimating Suite, the dedicated PRICE-S module is used. Still, this module requires basic inputs, which, for the SpaceLiner case-study, are unavailable. The 4cost *aces* model, however, does calculate basic, global SW development and production costs based purely on electrical hardware component inputs for the WBS. The *aces* tool then derives a very basic, top level, un-calibrated baseline SW estimate in line with the hardware components which require software. Yet although estimated loosely by the 4cost *aces* tool, the software costs were excluded as they were seen as being extremely preliminary in nature, and therefore potentially misrepresentative of true SW costs, and thus introducing uncertainty.

The top system-level TransCost model inherently does incorporate SW costs in its CERs although at a global level. The segmentation of these SW costs amongst the respective elements, as well as between development and production cost categories, is embedded within total CER results, and could not be determined individually.

In recognising that all three models treat SW costs differently, it was necessary to decide on a logical, defensible and consistent approach to ensure the models were most optimally comparable. Since SW costs could not be generated accurately and justifiably enough due to insufficient specification data, it was decided to eliminate the existing SW costs from the 4cost *aces* calculation. In this way, both commercial models would then **exclude** any SW costs, especially since the resulting numbers would have been speculative and unfounded in any case. Nevertheless, in view of the SpaceLiner case-study coming to a maturity in terms of SW considerations in the future, the software elements of the WBS were still factored in for to facilitate future incorporation of these costs once they can be calculated. As such, in the AA representation shown in Chapter 4.9.7, the software elements 2500, 3500 and 4500 fields are shown in *italics*, and with a zero cost.

Since TransCost SW costs are globally addressed, their segmentation within overall development and production costs, as already mentioned, could not be determined. Therefore, although being impossible to quantify, this important distinction must be identified as a contributing factor to why TransCost may yield higher development (and in fact partially production costs) than the two commercial models, 4cots *aces* and PRICE.

4.9.9 Development Cost Sensitivities

In extension to the AA utility, and in addition to the sensitivity study already presented during the process to ascertain a TransCost range in Chapter 4.9.1.3, it was interesting to perform some sensitivity studies to the baseline case-study configuration. Since the development costs showed a strong congruence between the two commercial tools, the 4cost *aces* tool was chosen as the backbone to initiate some first sensitivity analyses. It was interesting to see overall costs may be affected through changes to select criteria known to influence development. Two such variables are the number of prototypes as well as the level of the development team experience. Both values were augmented to represent a worse-case scenario compared with the baseline, also congruent with a more conservative approach which is prudent during early program cost analyses to assist in factoring in for risk and uncertainty.

4.9.9.1 Prototype Quantity

The baseline 5 prototype-model philosophy (Chapter 4.1.3) was subjected to sensitivity analyses. It is known that during development, one of the most cost-consuming activities is the number of proto-models produced, which also includes the associated testing and validation of technology processes. The proto-model quantity was increased to 8 and 10 models. Within a large, complex aerospace program context, while increasing the number of test model units would increase the development costs, in the long run, the full-scale and high-fidelity prototypes could potentially be sold at a discount rate to interested parties after undergoing and passing necessary certification. So, within a full program LCC context, some monies expended for more prototype units could be recovered through their consequent sales. Results of the sensitivity are shown below in Table 40. Quite clearly, an increase in prototype units results in a noticeable cost increase for the development effort. A 34% increase was observed for a 3-unit increase to the baseline, with a 56% increase on the baseline for a doubling of prototype units. The results firmly prove that the prototype quantity is a strong cost driver for the development phase.

Table 40: 4cost aces prototype quantity sensitivities for development costs

S_D	Sensitivity	Development Cost (B€)	% of BL
S_D0	**Baseline (5 Models)**	**20.35**	100%
S_D1	8 Models	27.24	134%
S_D2	10 Models	31.66	156%

4.9.9.2 Team Experience

The baseline team factor for the SpaceLiner case-study was assumed to represent an experienced team (*aces* table value of 7), as already described in Chapter 4.9.3, and detailed in Appendix G. The first sensitivity analysis was conducted altering this TEAM value to 6, representing a team which knows the task and has done something similar before (-1 *aces* input). A further decrement to a TEAM value of 5 (-2 *aces* input) was also done to represent a standard team. As shown in the Table 41 results, a decrease in team experience results in an increase of roughly 10% for every increment to the 4cost *aces* complexity factor.

Table 41: 4cost aces TEAM complexity sensitivities for development costs

S_D	Sensitivity	Development Cost (B€)	% of BL
S_D0	**Baseline (TEAM 7)**	**20.35**	100%
S_D3	TEAM 6	22.15	109%
S_D4	TEAM 5	24.28	119%

4.9.9.3 Development Sensitivity Discussion & Summary

Basic sensitivities were performed for the baseline development costs calculation, augmenting the prototype quantity and team experience. It was most interesting to note that as expected, and based on past program experience and practice, it has been shown that the prototype quantity constitutes a significant cost driver for the development Phase C. Again quite logically, decreasing the team experience during the development process also increases cost although not as pronouncedly as through a prototype quantity delta.

4.9.10 Development Cost Calculation Conclusions

Through applying AA, development costs at $L1_{WBS}$ calculated by all three tools, *4cost*, PRICE and TransCost, present a very strong congruency. A consistent final development cost range was also identified, converging on a gross program development cost between 26 - 32 B€, with the average range firmly centered on 28 B€. While greater cost fluctuations exist at a lower component and WBS level, in line with AA_{MAC}, this is indicative of a greater margin of uncertainty associated with those costs. As such, as the program matures, the cost estimates should be continually monitored and revised to incorporate any new information and data.

The basic sensitivity analyses performed also showed that the prototype quantity during production has a strong influence on cost, as does the experience and competence of the development team, as was to be well expected.

Overall, it can be seen that through the AA_{MAC}, a highly congruent and comprehensive development cost range is established for the case-study vehicle that is still in the pre-phase A. With such strong congruence between results, the level of uncertainty associated with the cost estimate is low. Cost estimation confidence is also significantly enhanced through solid, documented analysis and justifications, as well as careful analytical explanations of any significant deviations or inconsistencies. Finally, the key framework for the cost estimation process of large, complex, international programs has been determined and logically presented. Numerical data can later be updated, re-entered, and re-calculated at a later stage, and the cost estimate consequently reworked as the SpaceLiner concept and its definition reaches a more mature phase.

4.10 PRODUCTION COST ANALYSIS

The process to ascertain the recurring production costs for the SpaceLiner case-study, featured a similar conformity to the process for development costs. In line with the AA approach, multiple models were used, being the same three models as for development. Here, the SpaceLiner philosophy about the qualitative development schedule (see Chapter 4.1.2), the prototype model logic (Chapter 4.1.3) and the element reusability philosophy (Chapter 4.1.8) were drawn upon and integrated into the calculations in a practical, consistent, numeric and logical manner.

For the program production Phase D, the cost figure of interest is the cost of the theoretical first unit (TFU). Furthermore to the TFU cost, it is also interesting to know the total cost of the overall production batch which, for the SpaceLiner concept was chosen to be a baseline of 500 units (see Chapter 4.1.7). For such batch production, the learning factor (LC) is a critical value to model and reflect cost reduction observed from learning in application of processes during production, as described and quantified in Chapter 4.10.1 below.

4.10.1 Learning Curve Determination

The concept of LCs is applied for uninterrupted manufacturing and assembly tasks to describe learning for highly repetitive and labour intensive processes [137]. LCs seek to describe and quantify the typical phenomenon of human performance improvement when activities are done on a repetitive basis. Here, the time required to perform a task is seen to decrease with increasing repetitions [201, 202]. From an organisational perspective in particular, and irrespective of industry, determining the predictability of the learning effect is essential to underpin estimation of costs during the production phase. Some examples of various LCs in the engineering industry are shown in Figure 36. If such a learning relationship is identified and plotted on a log-log scale, the result is a straight line reflective of a certain learning percentage, thus forming the basis of LC estimates, as furthermore shown in Figure 37 [201].

As previously mentioned, in line with the SpaceLiner case-study philosophy established in Chapter 4.1.2, the production scheme of the SpaceLiner has been assumed to bear a close resemblance to the aviation sector. As such it is essential to study the production practices of this particular industry and determine how this correlates with commonly accepted and frequently assumed space sector LC values.

In literature, it has been proposed that the manufacturer production cost for each series of aircraft depends on several key considerations including production quantities and the technology risk [217], with the learning effect of production also being crucial to the recursive production costs.

Aircraft production size of a fleet has been shown to be directly linked to market research which determines the break-even point to ensure financial gain for the aircraft or vehicle from a particular fleet [217]. Here, the assumption of a total production of 500 SpaceLiner units is a baseline albeit preliminary one, and prone to change in the future as a clearer operational scenario is established. However, the initial TFU cost range calculated at this stage through application of AA can be considered to constitute a solid baseline for future incorporation of new information to reflect program modifications.

The technology risk refers to a cost increase observed at higher Mach numbers [102]. As such, more expensive materials are required, with the known result that more expensive systems constitute a larger fraction of empty weight, and consequently increase the airframe cost per unit weight [217].

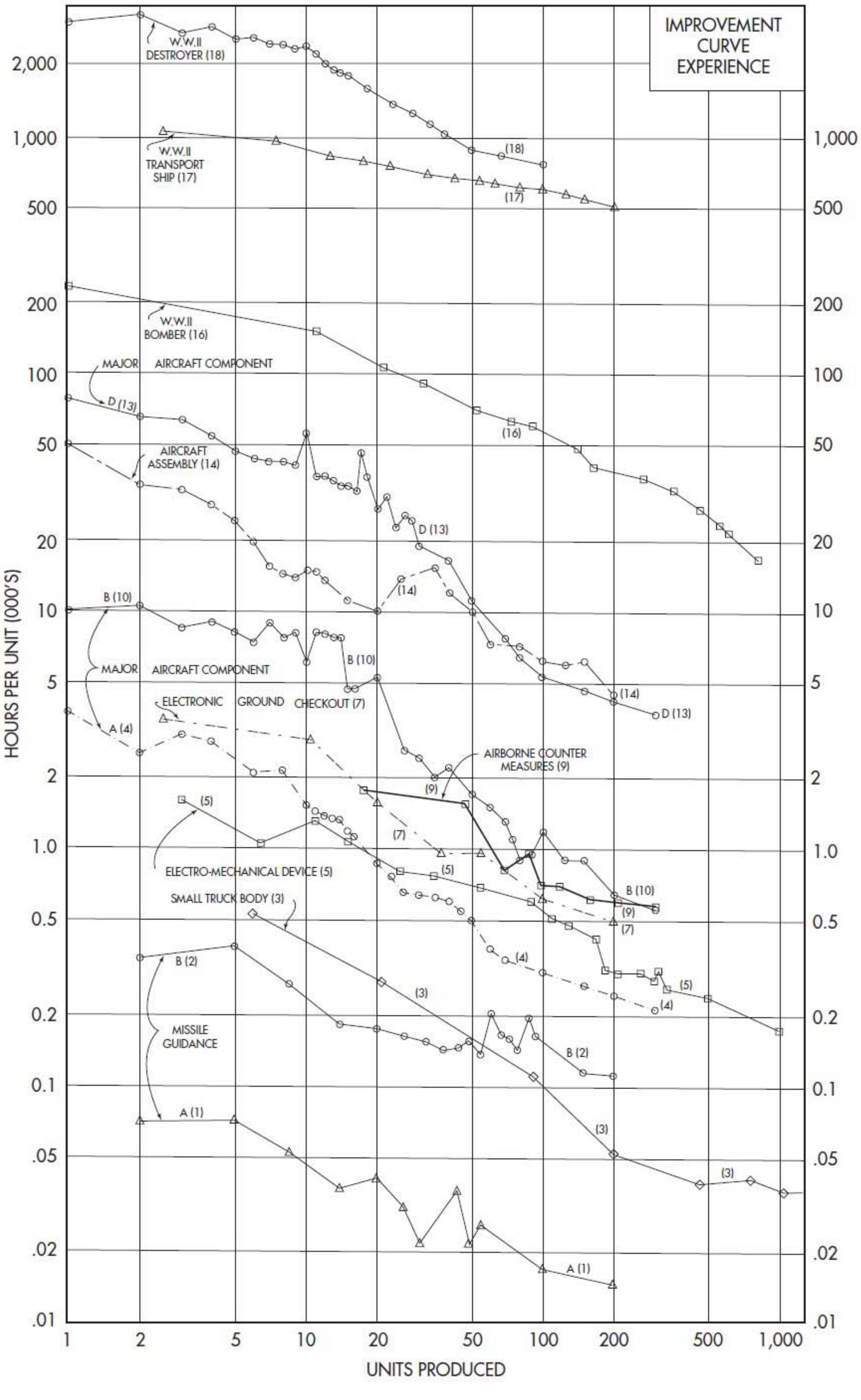


Figure 36: Some examples of learning curves across various industries [201]

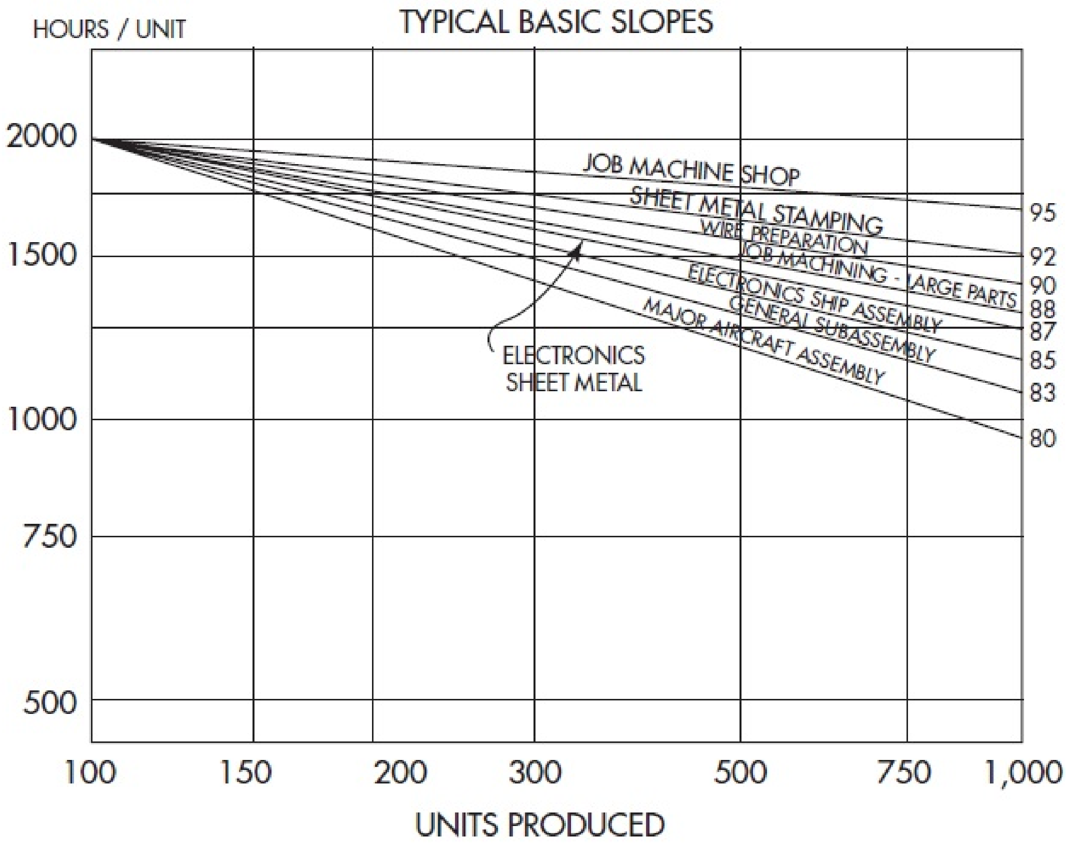


Figure 37: LC slopes of typical activities at a higher overall-industry level [201]

For the critical LC consideration, this refers to the learning effect which occurs with multiple-item production of a vehicle. From polling literature about the aerospace and aviation industries as a whole, the LC for particular aviation and space is defined by TransCost to lie within a broad range of 1.0 to 0.70 [102]. The NASA Cost Estimating Handbooks [135-137] then states a more specific average LC value of 85% for the aerospace domain, which is then confirmed, accepted and consistently utilised in wider scientific and academic literature [78, 201, 224].

To nevertheless independently confirm the general industry figure for the aerospace sector, the aviation industry was furthermore polled to identify production LCs of military fighter jets and large commercial aircraft. A summary of the sourced production programs and their respective, reported and documented production LCs are shown below in Table 42. An average LC figure is consequently deduced to be around 0.82.

Table 42: Summary of learning curves for high-speed and large aviation programs polled from various literature sources

SOURCE	PROGRAM	REPORTED LC (*p*)
[126]	Boeing 787	0.84
[127]	Boeing 777	0.84
[224]	Concorde (*target only*)	0.75
[220]	F-35	0.89
[24]	Lockheed-1011	0.75
[129]	Blackbird	0.86
	AVERAGE	**0.82**

With the calculated average of 82% lying perfectly within the TransCost stipulated LC range of 1.0 – 0.70, and also being highly congruent with the NASA value of 0.85 across both aviation and aerospace industries, the 0.85 learning factor was consequently and justifiably adopted for all calculations of production costs within this Thesis using the three tools and models for the SpaceLiner case-study AA. A crucial and simplified academic assumption here was that the same and constant 85% learning curve would be applied across all SpaceLiner case-study system elements, and this, throughout the entire production lifetime of the program. In reality, this would not be the case. From practice, such a large-scale and extremely complex program would commence gradually, with perhaps initially only a small amount of vehicles gradually entering the market. As such, at the beginning, it should be anticipated that only a few vehicles would be produced, with again more time before a full-fledged serial production process could be achieved. This would of course consequently have time implications on the production schedule which, in this Thesis, has been assumed to be optimal.

Returning back to the LC value, this is indeed a dynamic figure and, as already seen from Figure 36 and Figure 37, would vary not only depending on production quantity, but also on the component or element being produced.

While at this early stage a common and consistent LC of 85% is a sufficient albeit simplified, academic assumption for the respective level of detail, at a later stage, this would have to be reassessed and honed in for different elements at lower levels.

4.10.2 TransCost Production Cost Calculation

For the TransCost model structure and for CER application, the top-level SpaceLiner components, as already presented in Chapter 4.1.1, and as assumed also for production cost calculation, were taken, being the SLO, SLME, SLB and SPC. Yet, a critical difference between the development costs and the production costs lies in the fact that while the TransCost model was an ideal tool suitable for calculating the development costs of the SpaceLiner, for the production cost group of calculations, no TransCost CERs exist to ideally address all four SpaceLiner system elements. While suitable CERs exist for the SLME (*Liquid Propellant Rocket Engines* CER_{Space}) and SPC (*Crewed Space Systems* CER_{Space}), no dedicated CERs could be identified for the SLO nor the SLB system elements. The two most relevant CERs were for these elements were the *Winged Orbital Rocket Vehicles* and *High Speed Aircraft / Winged First Stage Vehicles* CER ($CERs_{Avio}$), which are clearly more relevant to the aviation segment. An indirect approach to determine the TFU production cost range was therefore undertaken in order to arrive at a preliminary yet justifiable cost figure.

The preliminary approach which was undertaken fairly firmly ensures that the resulting production cost of the SpaceLiner case-study would be within the range of combining a 'worst-case' TransCost scenario which assumes the space-applicable TransCost CERs, as well as a 'best-case' scenario, which takes the aviation TransCost CERs. Given the hybrid nature of the

SpaceLiner vehicle, the fleet would operate in a regime more congruent with the airline industry due to the high production quantities and high expected frequency of flights, albeit through utility of space standard technologies, therefore reducing cost for space access. So given a lack of direct CERs to describe production for the SLO and SLB, it was rationalised that if both the space and aviation CERs were applied to SpaceLiner data, the range of values would be an indicative ROM indication of the expected SLO and SLB production costs. Then, combining and contrasting this result with the other two results expected from the 4cost *aces* and PRICE models would further allow to verify the validity of the figure, or alternatively challenge it.

It is clear that a lower production cost can be expected from the application of the aircraft CER (CER_{Avio}) while the higher production cost would be derived from the Rocket Vehicle CER (CER_{Space}) due to a difference in technical levels and complexity, as well as echelon of technological standards. The resulting two calculations were taken to be the lower and higher cost limits, accordingly, for production cost scenarios, and to establish a production cost range.

For the SpaceLiner case-study production cost calculation, the required inputs were:

- number of units to be built *(1 for TFU; 500 for total program production)*
- component mass

The TransCost complexity factors which are then applicable to production cost calculation, included:

- f_4: learning effect factor
- f_8: country productivity
- f_{10}: cost reduction by past experience
- f_{11}: cost reduction through government-free development factor

The TransCost f_4 learning factor is calculated based on the learning rate, *p*. Once again in terms of the SpaceLiner case-study, the two key factors in the production cost area are *p*, as well as consequently the TFU cost.

For the TransCost production costs sub-model, the TFU value is the pivotal value on which consequent series production costs are then based on. For calculation of the all-important TFU production cost, the learning factor, $f_{4,}$ is taken to be 1.0. For a batch of *n* units, the cost reduction factor, f_4, factor is calculated based on the learning rate in line with the Crawford system (see Appendix D for more information about the Crawford system), using the following the formula:

$$f_4 = \frac{1}{n} \sum_{n}^{1} n^{\frac{\ln p}{\ln 2}}. \tag{8}$$

Similarly, to calculate the cost reduction factor f_4^* for the production of the n^{th} unit in a series production, the following formula applies:

$$f_4 * = n^{\frac{\ln p}{\ln 2}}. \tag{9}$$

The country productivity factor (f_8) is assumed to be that for ESA, defined in TransCost as being 0.86 [102].

The f_{10} factor addresses cost reductions resulting from past experience and the "lessons learned" from previous works and program involvement, including utility of modern computing tools and application of systems engineering principles. The attributed cost reduction for this factor lies between 15 to 25%. As such, f_{10} is commonly in the range of 0.85 and 0.75. For the SpaceLiner production process, this was taken to be the minimal 15%, since past experience can be based on the example set from vehicle series production of aircraft from the commercial and military aviation sector.

The f_{11} factor applies only to commercial, non-governmental projects which have no government contracts' requirements and no customer interference, significantly reducing the high costs involved with government requirements, procedures requirements and the associated personnel. TransCost stipulates that without governmental specifications, requirements, procedures and reporting, a significant saving of 45 – 55% is achievable. The resulting commercial development cost correction factor f_{11} is therefore 0.45 – 0.55. For the SpaceLiner case-study production costs calculation, this value was taken to be the minimal 0.55 to reflect that the program would be a commercial initiative, and would, therefore, fully maximise the expected cost benefits associated with such a financing structure.

Here, it must be emphasised, that at this stage, the SpaceLiner case-study is foreseen to be a commercial venture. However, depending on the actual financing scheme, which may change from being purely commercial to perhaps a public-private-partnership (PPP) arrangement if this is more beneficial, the f_{11} factor may be equally subject to change. As such, it should be revised in line with any new programmatic developments.

Again, all inputs were entered into the programmed TransCost interface described in Chapter 4.5.4, with all masses and relevant inputs and complexity factors for the SpaceLiner case-study which have already been outlined. All entries for production cost of the all-important TFU to be produced are shown below in Table 43 - Table 48.

By taking the calculation for the worst-case (CER_{Space}) and best-case (CER_{Avio}) scenarios, it was possible to find an average case of the two. While it may be argued that certain strategic weightings may be applied to each of the high-speed aviation and space CERs, at this stage, since the production CERs are not ideally tailored for the SpaceLiner case-study, the simple, unweighted and equal average of the two values is deemed a sufficient ROM indicator of the expected range of production costs. Here, it must be heavily highlighted that due to the latter assumption, the uncertainty associated with the equal 50/50 average approach for two elements out of four being costed, is therefore transferred into the resulting production cost not only for each element, but also at the highest and top WBS level.

Consequently, Table 49 - Table 51 present a summary of the three resulting TransCost scenarios showing the total cost of the **TFU** for each case, upon which the serial production reflective of the selected learning curve can be further modeled with a TransCost defined Crawford learning curve of 85%.

Table 43: TransCost CER for SpaceLiner main engine (SLME) TFU production

TC 8.2, Chapter 3.42 a)	Liquid Propellant Rocket Engines - SLME	pg. 125	
CER	= 3.15 * n * M ^(0.535) * f4 * f8 *(f10 * f11)	number of units to be built (n)	1.00
	= *96.60*	Motor Net Mass (M)	3300
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	23
TFU COST (M€)	**= 27.53**	*WYr cost (2013 e.c.)*	*285000*

Table 44: TransCost CER for Orbiter (SLO_{Avio}) TFU 'best case' production

TC 8.2, Chapter 3.53	High Speed Aircraft / Winged First Stage Vehicles $–SLO_{Avio}$	pg. 132	
CER	= 0.357 * n * M^(0.762) * f4 *f8 (*f10 * f11)	number of units to be built (n)	1.00
	= 953.99	Motor Net Mass (M)	103879.18
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	16
TFU COST (M€)	**= 271.89**	*WYr cost (2013 e.c.)*	*285000*

Table 45: TransCost CER for Orbiter (SLO_{Space}) TFU 'worst case' production

Winged Orbital Rocket Vehicles – SLO_{Space}			
TC 8.2, Chapter 3.54		*pg. 134*	
CER = 5.83 * n * M^(0.606) * f4 *f8 (*f10 * f11)		number of units to be built (n)	1.00
= 2570.19		Motor Net Mass (M)	103879.18
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	3
TFU COST M€	**= 732.50**	*WYr cost (2013 e.c.)*	*285000*

Table 46: TransCost CER for Booster (SLB_{Avio}) TFU 'best case' production

High Speed Aircraft / Winged First Stage Vehicles - SLB_{Avio}			
TC 8.2, Chapter 3.53		*pg. 132*	
CER = 0.357 * n * M^(0.762) * f4 *f8 (*f10 * f11)		number of units to be built (n)	1.00
= 1167.32		Motor Net Mass (M)	135379
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	16
TFU COST M€	**= 332.687**	*WYr cost (2013 e.c.)*	*285000*

Table 47: TransCost CER for Booster (SLB_{Space}) TFU 'worst case' production

Winged Orbital Rocket Vehicles – SLB_{Space}			
TC 8.2, Chapter 3.54		*pg. 134*	
CER = 5.83 * n * M^(0.606) * f4 *f8 (*f10 * f11)		number of units to be built (n)	1.00
= 3017.65		Motor Net Mass (M)	135379
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	3
f4 COST M€	**= 860.03**	*WYr cost (2013 e.c.)*	285000

Table 48: TransCost CER for Passenger Cabin (SPC) TFU production

Crewed Space Systems (no realised projects yet)			
TC 8.2, Chapter 3.55		*pg. 135*	
CER = 0.16 * n * M^(0.98) * f4 *f8 (*f10 * f11)		number of units to be built (n)	1.00
= 1955.18		Motor Net Mass (M)	37520.82
		f4	1.00
		f4*	1.00
f4 calculation		f8	0.86
Learning Factor ***p*** =	0.85	f10	0.85
n units (f4) =	1.00	f11	0.55
n th unit (f4*) =	1.00	NORP	7
f4 COST M€	**= 557.23**	*WYr cost (2013 e.c.)*	285000

Table 49: TransCost 'worst case' TFU production cost calculation per element using the TransCost 'Space' CER

ELEMENT	WYr	Cost M€ (2013 e.c.)
SLME	97	27.53
SLO_{Space}	2570	732.50
SLB_{Space}	3018	860.03
SPC	1955	557.23
TOTAL	***7640***	***2177.29***
TOTAL (with f_0)	**8105**	**2309.89**

Table 50: TransCost 'best case' TFU production cost calculation per element using the TransCost Aviation 'Avio' CER

ELEMENT	WYr	Cost M€ (2013 e.c.)
SLME	97	27.53
SLO_{Avio}	954	271.89
SLB_{Avio}	1167	332.69
SPC	1955	557.23
TOTAL	***4173***	***1189.33***
TOTAL (with f_0)	**4427**	**1261.76**

Table 51: TransCost 'average case' TFU production cost calculation per element assuming an average of the 'Space' and 'Avio' TransCost CER results

ELEMENT	WYr	Cost M€ (2013 e.c.)
SLME	97	27.53
SLO_{Ave}	1762	502.20
SLB_{Ave}	2092	596.36
SPC	1955	557.23
TOTAL	***5906***	***1683.31***
TOTAL (with f_0)	**6266**	**1785.83**

Here, the additional external TransCost factor for systems engineering, f_0, has been added in the last line of each of the above three table, which, for production of a two-stage vehicle

(N=2) like the SpaceLiner, is calculated by *Eq. 10*. For this SpaceLiner, f_0 is therefore 1.06, as calculated by the formula:

$$f_0(PROD)_{Liquid\ Propulsion} = 1.03^N . \qquad (10)$$

It must be noted that for the above tables, single element value elements **only** are shown. Namely, for a complete SpaceLiner vehicle, eleven engines are required (two for the SLO and nine for the SLB). As such, and using all other figures derived from Table 51 for the 'average' cost case, the following Table 52 for a single, total and complete SpaceLiner vehicle is shown. Since learning occurs even for the production of the eleven engines, the 85% learning curve must also be applied to reflect the cost reduction for production of this engine sequence. While TransCost identifies a specific relationship between the learning factor and the annual quantity produced for classical liquid rocket engines (shown and briefly described with reference to the SpaceLiner application in Appendix □), this only gives a maximum production rate of 100 units produced per annum. To calculate the production cost **of a single TFU SpaceLiner unit**, this graph can, however, be used. Given that a single SpaceLiner vehicle requires a total of 66 engines, and using the LC formula derived in Appendix □, an LC of roughly 82% is derived. This LC value is applied to the first 66 SpaceLiner engines produced, and is shown in Table 52, which shows the learning factor per consecutive unit, with the associated reduced WYr amounts and costs for the production of eleven engines.

Table 52: TransCost 85%LC calculation of production cost for eleven SLME engines

Number of units (n)	LF (p)	WYr	Cost M€ (2013 e.c.)
1	1.00	97	27.53
2	0.85	82	23.40
3	0.77	75	21.28

4	0.72	70	19.89
5	0.69	66	18.88
6	0.66	63	18.09
7	0.63	61	17.45
8	0.61	59	16.91
9	0.60	58	16.45
10	0.58	56	16.05
11	0.57	55	15.69
TOTAL	*N/A*	*742*	*211.61*
TOTAL (with f_0)	**N/A**	**788**	**224.50**

Consequently, substituting the above result for the cost of eleven engines into the existing Table 51 for the first SpaceLiner unit yields the following total TFU cost, shown in Table 53:

Table 53: Calculation of production cost for all components for the SpaceLiner TFU

ELEMENT	WYr	Cost M€ (2013 e.c.)
11 SLMEs	*742*	*211.61*
SLO_{Ave}	1762	502.20
SLB_{Ave}	2092	596.36
SPC	1955	557.23
TOTAL	*6552*	*1867.39*
TOTAL (with f_0)	**6951**	**1981.12**

The significantly higher production quantities of engines foreseen for the SpaceLiner program, however, would imply that using the dedicated rocket engine graph to determine an independent LC value would be non-representative and unjustifiable due to the limited annual production rates. As such, the chosen standard 85% Crawford learning curve selected for overall SpaceLiner case-study production is adhered to for all other overall program production cost calculations.

We can see that using the simplified average method between the TransCost high-speed aviation (*Avio*) and space (*Space*) domain CERs, the TFU production cost for a single, first SpaceLiner unit is roughly 2 B€ at 2013 economic conditions. If we then calculate the production cost of the 500th, by applying the overall program constant and **consistent** 85% cost reduction factor calculated with *Eq. 9* for f_4^*, then we then see that the 500th unit production should cost roughly 460 M€, calculated by:

$$500^{\frac{\ln 0.85}{\ln 2}} \cdot 1981.12 = 461.42 M€,$$

and constituting approximately 23% of the initial approximate 2 B€ production cost due to the learning curve effect.

It is also interesting to calculate the cost of the full estimated 500 SpaceLiner units to obtain the total program cost, which would be a necessary indicator for financial ramifications and requirements concerned with potential investors, thus framing the potential SpaceLiner business case in accordance with the concept's current technological definition and status. Here, the sum of each of the 500 SLOs, SLBs, SPCs and 5,500 SLMEs (at time of manufacture and installation for one initially functional unit) needs to be tallied. Each SpaceLiner then requires a further **five full sets of replacement engines** in addition (55 engine total) to match the higher reusability requirement of the stages. This equates to 33,000 engines. For such a high quantity, production cost reductions are again modeled in accordance with an academic 85% Crawford learning curve. Table 54 shows the resulting WYr and costs for the total production of 500 SpaceLiner units, including the cost for production of 33,000 engines.

Table 54: Total TransCost production costs for a batch of 500 SpaceLiner vehicles with a global 85% production learning curve

ELEMENT	WYr	Cost B€ (2013 e.c.)
33,000 SLMEs	363098	103.48
500 SLO_{Ave}	266869	76.06
500 SLB_{Ave}	316908	90.32
500 SPC	296113	84.39
TOTAL	***1242988***	***354.25***
TOTAL (with f_0)	**1318686**	**375.83**

As can be seen, the total production cost of 500 SpaceLiner, when mass-produced, is a little over 375 B€, with each SpaceLiner vehicle then, on average, costing around 750 M€ to produce. It must be again conceded that this result is given a constant and simplified assumption of an 85% LC throughout the entirety of the production phase, and whole duration of the 500 unit program. It should also be noted that the resulting cost amount does not consider the cost of money (interest) nor inflation rates, but rather presents the basis amount at the 2013 economic conditions. In addition, as is later discussed in Chapter 4.10.8.2, the constant LC for such a large quantity of vehicles, and the even larger order of magnitude quantity of engine production, is a very simplified assumption. However for a baseline scenario, this assumption is a sufficient one at this stage. Any numbers can then be easily revised within the established framework of processes and calculations as soon as more programmatic information becomes available.

4.10.3 4cost *aces* Production Cost Calculation

For the *aces* production cost category, the ass inputs key inputs were predominantly kept the same as already outlined for 4cost *aces* development in Chapter 4.9.3. SpaceLiner data was input, with the following *aces* parameters of focus:

- Mechanical and electronic component mass (WM/WE)
- *Production Environment (ENVIRP)*

- *Electronics/Mechanical index (INDEXE/M)*
- *Production quantity (QTY)*
- *Production Start (STARTPD)*

Inputs which were new or different to those already described for the 4cost *aces* development cost calculations, are shown in *italics*. The *aces* model computes production costs using the INDEXE/M values weight, and the environment (ENVIRP) as main inputs. The INDEXE/M parameters are already introduced in the development Chapter 4.9.3, and their values remain the same, although a reiteration of the input function within context of the production effort is highlighted. Of course other inputs such as production quantity (500 SpaceLiner units, 33,000 SLMEs), and the learning curve value, which was fixed at 0.85 for all AA processes. The ideal production starting date was also an input, although this was generated by the 4cost *aces* software based on the output of the development schedule. The key parameters which are unique or different from inputs already detailed for the development cost calculation, are described and quantified below:

• Production Environment (ENVIRP)

Upon discussion with experts, ENVIRP was chosen to be 1.8 (see Figure 33). This is a lower value than that for development, since production of the SpaceLiner fleet is anticipated to follow an aviation model due to large production quantities. This factor value is therefore exclusive to the "Aircraft" section, under "commercial" projects. A higher sensitivity analyses limit was defined as being 2.5, to see how this would affect the overall calculated cost.

• Electronics/Mechanical Index (INDEXE/M)

As previously introduced for development, INDEXE/M is the technology index for electronics (INDEXE) and mechanics (INDEXM). Both inputs are used to calculate element TFU costs for production, and reflect the cost of more stringent reliability requirements associated with most extreme operating environments. Values were generated from internal INDEXE/M tables.

• Production Quantity (QTY)

The production quantity, in line with the SpaceLiner case-study philosophy outlined in Chapter 4.1.7, was SpaceLiner 500 units, and therefore also 33,000 SLMEs. Production cost was assumed to be for acquisition of a SpaceLiner unit, as well as the required replacement engines to ensure a common life-time for all SpaceLiner vehicle components. Since the lifetime of the engines is expected to be shorter than that for the SpaceLiner stages and passenger cabin/rescue capsule, more engine units are therefore required.

• Start of Production (STARTPD)

This STARTPD input determines when the production effort begins, in months and years. This input can be manually entered, or can be generated by the 4cost *aces* software to formulate an optimal schedule, the latter being the case for the SpaceLiner case-study application, and was given as commencing in December, 2029.

The production costs as calculated by the 4cost *aces* tool (found in the *ModAmuc3* column in Table 126 in Appendix H) represent the basis production cost of the full batch of 500 SpaceLiner vehicles, including 25% for general and administrative (G&A) costs and a further 10% fee and profit allowance. While by definition *ModAmuc3* also contains a SW production component, in line with the SW philosophy adopted for this Thesis and outlined in Chapter 4.1.6, this SW element was subtracted out of the costs. The TFU cost, while not being focal for the purposes of this study, is nevertheless shown in the column *T1ModT1* of Appendix H for data completeness.

4.10.4 PRICE Production Cost Calculation

For the PRICE tool production cost calculation, the required key inputs for production cost calculations are shown below:

- Structural and electronic component mass (WS/WT)
- *Platform Value (PLTFM)*
- *Manufacturing Complexity (MCPLXS/E)*
- *Learning Curve (Materials / Labour)*
- *Year of technology (YRTECH)*
- *Production quantity (QTY)*
- *Production start (PSTART)*

The mass inputs were kept the same as already presented for PRICE development estimation in Chapter 4.9.4, while inputs in *italics* highlight new parameters or information specific to production, and are therefore briefly described below:

• PLTFM

For the SpaceLiner case study, this value was chosen to be 1.8, in line with the philosophy that the SpaceLiner production resembles more that of the aviation industry. The only exception here was made for production of the engines, which are, nevertheless, rocket engines, where, upon extensive consultation with space programmatic experts as well as PRICE user experts, the PLTFM was set at a higher value of 2.0.

• MCPLXS/E

The MCPLXS/E values for all components were adjusted in accordance with Peter Korda's formula for manufacturing complexity, which stipulates that the PLTFM value is a defining parameter [53]. Here, when the PLTFM value is arbitrarily set, then the MCPLX values should also be adjusted accordingly (for the case of the SpaceLiner case-study, the values were lowered). Hence, this was done manually for all elements affected. The engine complexity, however, was kept the same to address the stringent reusability and operational safety requirements, resulting in a higher level of complexity.

• Learning Curve

The learning curve was set at 85%, in line with the LC philosophy developed and described in Chapter 4.10.1.

• Production Start

The PRICE software calculated the optimal starting time for production, based on optimal development timeframe which had already been calculated. The production start date was given as being January, 2032.

The production costs resulting from the PRICE software also show the total production cost for 500 SpaceLiner units (also including similar 25% G&A and 10% additional fees and profit margins, in line with the same values input for the 4cost tool), in the column entitled *MANUFACTURING_PROD_Total* found in Table 130 of Appendix I. The Unit Production Cost (*UPC*) column the shows the calculated average production cost per unit, which can be derived by dividing the total cost by the total number of production units. Consequently, the *AMORTIZED_UNIT_COST* column is then calculated to show the average cost per unit, while also including costs for production engineering, production manufacturing, and production tooling and test for the component being modelled. Another column called *AMORTIZED_UNIT_COST_TOT** has also been included. The definition of the values here are identical to the values of *AMORTIZED_UNIT_COST,* except that a significant cost increase can be seen for WBS elements 2200 and 3200, to account for not only the original eleven engines per vehicle, but also the consequent additional 55 engines to ensure that all SpaceLiner vehicle components have a common 150 times reusability capability.

The TFU costs are then shown in the column *T1_COST,* is influenced by the PRICE Unit Learning Curve (ULC), selected and set to be a fixed 85%, and the Development Cost Multiplier (DMULT) which is used to include markups for G&A, for example. Again, however, unlike for the TransCost calculation, the commercial PRICE model TFU value is not interesting for the purposes of this study, as will be further outlined later in Chapter 4.10.7. The TFU values are nevertheless included rather for the sake of data completeness.

In addition, Table 130 of Appendix I also includes the separate and segmented cost components calculated by the PRICE tool for manufacturing, program management and engineering efforts during the production phase.

4.10.5 Optimal Production Timeframe

For both commercial 4cost *aces* and PRICE software tools, an optimal production timeframe was calculated on the basis that an optimal schedule of activities and task execution were assumed. TransCost yielded no scheduling results as per its definition of a top level cost estimation model only.

The optimal duration of the PRICE tool production phase is a parameter which was automatically calculated by the PRICE-H model. This is influenced by other model inputs and factors, including equipment complexity, PLTFM and ECMPLX values, and results in an optimised cost, thus avoiding penalties by enforcing an artificial timeframe. For the SpaceLiner case-study, this was found to be 127 months, commencing in January, 2032 and continuing through until the end of July, 2042. This logic is repeated in the 4cost *aces* optimal production duration, which his heavily influenced by key factors including the electrical and mechanical complexities (INDEXE/M) and the environment ENVIRP factor, amongst others, and resulted in a production timeframe of 116 months, beginning in December 2029, and finishing in July of 2039. Both software tools are highly congruent in their estimation, of roughly 10 years for production.

For both models, the optimal production timeframe assumes no delays, resulting in a very optimistic and rather idyllic scenario of a development phase with no delays. In reality, for a program as large and complex as the SpaceLiner case-study would be, the timeframe would also be dictated not only by technical capabilities, but also by other aspects including politics, economics and financing not under program management influence, as has already been discussed in Chapter 4.9.6.1 for program development. Similarly for production, program delays would almost certainly be evident during program execution especially for an undertaking of such complexity and expanse as the SpaceLiner. This would be a point for further analysis and dissemination as more program information crystallises and becomes available. However, it can be assumed with a high degree of certainty that the production process, being even longer than the development phase, would also extend well beyond the more extreme 127 months as calculated by the PRICE software. Applying a margin of 50% at this early program stage, and in consultation with project management experts, based on calculation, a baseline preliminary timeframe of 15 years for the production effort was therefore assumed.

4.10.6 Production Project Management Office Cost Estimation

Similarly as for the development cost estimation, while all three AA models already factor in for PMO cost on an element level, the top WBS element 1100 PMO cost for production had to be estimated separately for both the commercial 4cost *aces* and PRICE models as it was not taken into account.

Once again, EJ and professional opinion was extensively discussed, polled and an outcome concluded from top level PM experts from the ISU, resulting in a breakdown and personnel allocation shown in Table 55 below. The starred elements, (*) represent activities which are already addressed in WBS element 1140 for Project Control*.

Here, we are considering the top PMO office for production. At this stage it is unclear how many production sites would be established, but this is certainly an important variable since it would influence the quantity of staff required for PMO functions at the sites, locally. Here, we assume a doubling of the PMO staff shown in Table 55 to represent two production sites, tallying up to a total of 12 full-time staff for the PMO function. Applying the same monetary figures of $300,000 per annum per employee, over the duration of the overall production effort (for 500 SpaceLiner units) based on the previously established assumption that the production duration is 15 years (see Chapter 4.10.5), results in a total production PMO cost of 54 M€ (2013 e.c.).

Table 55: Derived qualitative break-down of the PMO function with an EJ estimate for average number of personnel required per function [119, 147]

1100	Overall Project Management Office (PMO)	Personnel Qty.
1110	Program Management (PM) & Secretariat	2
1120	Systems Engineering & Design Management	2
1130	Product Assurance	1
1140	Project Control*	1
1150	Documentation & Configuration	(*)
1160	Project Risk Management	NA
1170	Logistics & Transportation Management	(*)
1180	Communication& Reporting	(*)
1190	External Support	NA
	TOTAL	**6**

4.10.7 Production Amalgamation Approach Results

With all production cost element fields being complete, the cost results for the overall program costs as well as the average costs per unit value were determined. Once again using the powerful AA interface, the results could be contrasted with each other in line with the AA philosophy. While for TransCost model the TFU value was very important on which to base the cost of all consequent production units from, for both commercial tools, due to the imposed and fixed LC value high production quantities for a complex space sector program, the TFU values, which are highly dependent on both the chosen LC value (which in this instance, was synthetically and externally imposed) were non-focal. For both PRICE and 4cost *aces* advanced internal software mechanics, the TFU (T1) value is treated, quite logically, as a direct function of the manufacturing process, hinging also on the proposed LC and production quantity. The TransCost model assumes a mire simplified approach here, where any differences in the manufacturing process having no influence on the TFU value. Arguably, this may not be representative of reality, as has been demonstrated in learning curve theory and shown in practice [1, 154]. As such, the T1 values were deemed unimportant and largely irrelevant within the context of this cost analyses. Instead, here the two key figures of interest were the total program production cost, as well as the average unit cost for production of 500 SpaceLiner case-study vehicles as calculated by each AA model and tool. Summarised tables of results are directly from the AAInT Excel interface already described in Chapters 2.6.2.2 and 4.8.1. The first PMO Table 56 is applicable to the entire production phase, assumed to be 15 years, as already presented in Chapter 4.10.6. All further tables then show the costs for the three SpaceLiner elements (SLO, SLB, SPC). As previously noted for development costs, once again the top-level TransCost model presents production costs at a top $L2_{WBS}$, while the PRICE and 4cost models present their costs at the lower sub-system and component levels 3 and 4.

Additionally, and similar to the development AAInT spreadsheet, Table 88 contains an extra row for "*Other costs*" used to apply the TransCost top level engineering factor, f_0, previously discussed in Chapter 4.10.2. The AA interface also allows for any other additional costs generated by AA methods or tools to be incorporated at this final stage.

Furthermore, it is then interesting to present the same costs showing production for an average SpaceLiner unit of production, as calculated by each of the three selected AA tools. All results are shown in Table 60 – Table 62 below. For the PRICE tool, the values are extracted from the data column '*AMORTIZED_UNIT_COST_TOT*'* (Appendix I) which shows the calculated production the unit per SpaceLiner including a total of 66 engines per vehicle. Similarly, for the 4cost *aces* software these values are taken from the column '*ModAmuc3 (no SW)',* (Appendix H), which has been calculated to remove any SW costs. Finally, Table 63 shows a summary of AA total program production costs, followed by the average vehicle unit cost.

Table 56: AAInT spreadsheet interface for ***overall*** *SpaceLiner production PMO costs*

D - 1000		SpaceLiner OVERALL SYSTEM	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	1100	Overall Project Management Office (PMO)		*0.054*	*0.054*
Other	1200	Other Costs		*0.000*	*0.000*
		TOTAL (B€, 2013 e.c.)	0,000	0.054	0.054

* *EJ determined overall top PMO costs for the 4cost and PRICE models* ***only*** *(see Chapter 4.10.6)*

Table 57: AAInT spreadsheet interface for SLO ***total*** *case-study production costs*

D- 2000		SpaceLiner ORBITER (SLO)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	*2100*	*SLO PMO**		*included in calcs.*	*included in calcs.*
HW	2200	Propulsion (SLME)~	*103.483*	27.955	22.843
HW	2300	Structures & Mechanics		19.214	24.801
HW	2400	TPS/TC		3.893	4.075
SW	*2500*	*Flight Control System°*		*0.000*	*0.000*
HW	2600	Avionics^		*0.000^*	*0.000^*
HW	2700	Power & Housekeeping		0.785	0.850
AIT	2800	SLO AI&T		0.657	1.289
		TOTAL (B€, 2013 e.c.)	179.541	52.451	53.857

* *Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLO.*
~ *This amount is* ***included*** *in the 179.541 B€ total calculated below, and is therefore shown in italics*
° *SW costs not included*
^ *Avionics costs were calculated for all of SLO/SLB/SPC, and shown as a single amount in the SLB 3600*$_{WBS}$ *shown in Table 58 below*

Table 58: AAInT spreadsheet interface for SLB ***total*** *case-study production costs*

D - 3000		SpaceLiner BOOSTER (SLB)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	***3100***	***SLB PMO****		*included in calcs*	*included in calcs.*
HW	3200	Propulsion		80.970	90.156
HW	3300	Structures & Mechanics		24.367	30.694
HW	3400	TPS/TC		5.381	8.981
SW	*3500*	*Flight Control System°*		*0.000*	*0.000*
HW	3600	Avionics^		0.578	0.573
HW	3700	Power & Housekeeping		1.530	1.910
AIT	3800	SLB AI&T		1.213	2.443
		TOTAL (B€, 2013 e.c.)	**90.319**	**114.04**	**134.757**

**Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLB.*
° SW costs not included
^ Costs shown here represent avionics costs for all three elements of SLO/SLB/SPC.

Table 59: AAInT spreadsheet interface for SPC ***total*** *case-study production costs*

D - 4000		SpaceLiner PASSENGER CABIN / RESCUE CAPSULE (SPC)	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
PM	***4100***	***SPC PMO****		*included in calcs.*	*included in calcs.*
HW	4200	Propulsion (CSM)		0.307	0.209
HW	4300	Structures & Mechanics		1.142	0.960
HW	4400	TPS/TC		0.909	1.015
SW	*4500*	*Flight Control System°*		0.326	0.163
HW	4600	Avionics^		*0.000*	*0.000*

HW	4700	Power & Housekeeping		0.342	0.287
HW	4800	Life / Passenger Support Systems		3.804	4.119
AIT	4900	SPC AI&T		0.174	0.218
		TOTAL (B€, 2013 e.c.)	**84.392**	**7.004**	**6.971**
		Other costs	(f_0) **21.574**	0.481	2.406

**Both 4cost aces and PRICE already factor in for PMO costs relevant to SPC.*
° SW costs not included
^ Avionics costs were calculated for all of SLO/SLB/SPC, and shown as a single amount in the SLB_{WBS} 3600 shown in Table 58 above

Table 60: AAInT spreadsheet for SLO ***average unit*** *case-study production costs*

D- 2000		SpaceLiner ORBITER (SLO)	TransCost M€ (2013 e.c.)	4cost *aces* M€ (2013 e.c.)	PRICE M€ (2013 e.c.)
PM	***2100***	***SLO PMO****		*included in calcs.*	*included in calcs.*
HW	2200	Propulsion (SLME)	3.136	57.853	45.685
HW	2300	Structures & Mechanics		48.625	49.602
HW	2400	TPS/TC		9.942	8.151
SW	*2500*	*Flight Control System°*		*0.000*	*0.000*
HW	2600	Avionics^		*0.000*	*0.000*
HW	2700	Power & Housekeeping		2.530	1.700
AIT	2800	SLO AI&T		1.781	2.578
		TOTAL (B€, 2013 e.c.)	**359.081**	**120.731**	**107.715**

** Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLO.*
° SW costs not included
^ Avionics costs were calculated for all of SLO/SLB/SPC, and shown as a single amount in the SLB 3600_{WBS} shown in Table 61 below

Table 61: AAInT spreadsheet for SLB ***average unit*** *case-study production costs*

D- 3000		SpaceLiner BOOSTER (SLB)	TransCost M€ (2013 e.c.)	4cost *aces* M€ (2013 e.c.)	PRICE M€ (2013 e.c.)
PM	***3100***	***SLB PMO****		*included in calcs**	*included in calcs.**
HW	**3200**	**Propulsion**		163.237	180.313
HW	**3300**	**Structures & Mechanics**		61.282	61.388
HW	**3400**	**TPS/TC**		13.657	17.962
SW	*3500*	*Flight Control System°*		*0.000*	*0.000*
HW	**3600**	**Avionics^**		1.846	1.145
HW	**3700**	**Power & Housekeeping**		4.831	3.820
AIT	**3800**	**SLB AI&T**		2.954	4.886
		TOTAL (B€, 2013 e.c.)	**180.637**	**247.806**	**269.514**

**Both 4cost aces and PRICE already factor in for all PMO costs relevant to SLB.*
° SW costs not included
^ Costs shown here represent avionics costs for all three elements of SLO/SLB/SPC.

Table 62: AAInT spreadsheet for SPC ***average unit*** *case-study production costs*

D - 4000		SpaceLiner PASSENGER CABIN / RESCUE CAPSULE (SPC)	TransCost M€ (2013 e.c.)	4cost *aces* M€ (2013 e.c.)	PRICE M€ (2013 e.c.)
PM	***4100***	***SPC PMO****		*included in calcs.*	*included in calcs.*
HW	**4200**	**Propulsion (CSM)**		0.710	0.418
HW	**4300**	**Structures & Mechanics**		2.957	1.921
HW	**4400**	**TPS/TC**		2.332	2.031
SW	*4500*	*Flight Control System°*		1.018	0.325
HW	**4600**	**Avionics^**		*0.000*	*0.000*

HW	4700	Power & Housekeeping		1.094	0.574
HW	4800	Life / Passenger Support Systems		10.008	8.238
AIT	4900	SPC AI&T		0.569	0.435
		TOTAL (B€, 2013 e.c.)	**168.784**	**18.689**	**13.943**
		Other costs	(f_0) **43.148**	(Total I&T) 1.427	(Total I&T) 4.811

**Both 4cost aces and PRICE already factor in for PMO costs relevant to SPC.*
° SW costs not included
^ Avionics costs were calculated for all of SLO/SLB/SPC, and shown as a single amount in the SLB 3600$_{WBS}$ shown in Table 61 above

Table 63: Total SpaceLiner case-study production program costs, with margin

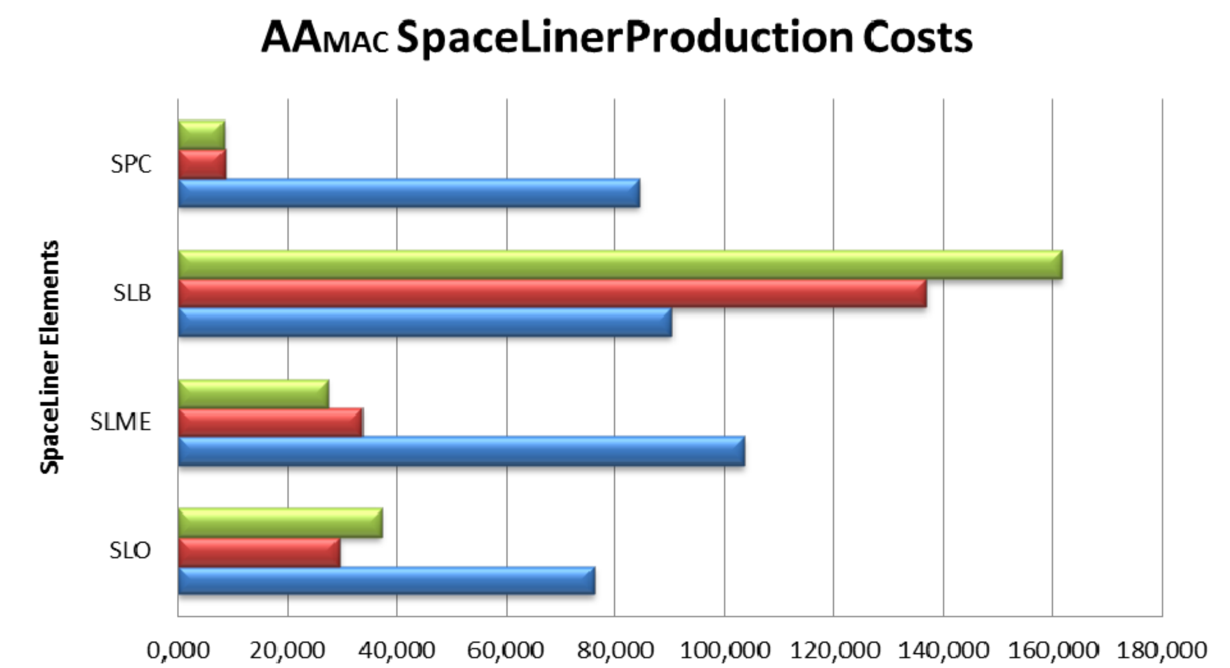
SpaceLiner CASE-STUDY	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
TOTAL PROGRAM PRODUCTION COST	375.83	174.03	198.05
MARGIN (20%)	*already included*	*34.85*	*39.61*
GROSS PROGRAM PRODUCTION COST	**375.83**	**208.09**	**237.66**

Table 64: SpaceLiner case-study average unit production costs, with margin

SpaceLiner CASE-STUDY	TransCost B€ (2013 e.c.)	4cost *aces* B€ (2013 e.c.)	PRICE B€ (2013 e.c.)
AVERAGE UNIT PRODUCTION COST	0.752	0.389	0.396
MARGIN (20%)	*already included*	*0.078*	*0.079*
GROSS AVERAGE UNIT PRODUCTION COST	**0.752**	**0.466**	**0.475**

4.10.8 Discussion of Production Amalgamation Approach Costs

As can be seen from looking at the production cost results presented in the above tables, both for the overall program as well as for the average unit cost, a considerable deviation can be noted between the significantly higher TransCost and the PRICE and 4cost *aces* model results. Figure 38 and Table 65 below provide a visual representation and numerical comparison of the AA_{MAC} results for overall program production costs, with a 20% margin also included on an individual level (imposed on top of figures presented in Table 57 - Table 59) to facilitate for a meaningful inter-tool comparison.



	SLO	SLME	SLB	SPC
PRICE	37,218	27,411	161,708	8,366
4cost	29,395	33,546	136,848	8,405
TransCost	76,058	103,483	90,319	84,392

Total Program Production Cost B€ (2013 e.c.)

Figure 38: Visual comparative representation of total program production costs per case-study vehicle element only using AA_{MAC}

Table 65: Comparative summary of total program production costs per case-study vehicle element using AA_{MAC}

Component	TransCost	4cost (incl. 20% margin)	PRICE (incl. 20% margin)
SLO	76.06	29.40	37.22
SLME	103.48	33.55	27.41
SLB	90.32	136.85	161.71
SPC	84.39	8.41	8.37
Other	21.57	0.64	2.89
∑ AA_{MAC} PRODUCTION TOTAL COST B€ (2013 e.c.)	**375.83**	**208.84**	**237.59**
AVE. AA_{MAC} PRODUCTION COST B€ (2013 e.c.)		**274.09**	

Between the 4cost *aces* and PRICE commercial models, production results demonstrated a very high degree of congruency, extending even to the lower WBS levels. The commercial model results indicated that on average, each of the 500 SpaceLiner case-study units would cost between 466 – 475 M€ each to produce, given the selected LC of 85% and taking into account a 20% additional overall margin to address risk (see Chapter 4.1.11). The TransCost calculation however, indicated that the average production cost per unit would be a little over 750 M€, being approximately 60% greater than that of the two commercial model results. In accordance with AA theory, such a deviation would warrant further investigation to identify reasons for the deviation, and to compile an analytical justification therefore.

Based on the results, while noting the higher cost range of the TransCost model, the significantly higher amount, based on analyses detailed in consequent chapters, the initial production cost range for the SpaceLiner case-study can be established using results from the PRICE and 4cost *aces* results only. For **total program production**, the lowest calculated cost value from PRICE and 4cost *aces* is also assumed as the lowest limit since it is known that program costs usually trend upwards rather than falling during implementation and execution of a program, with cost and schedule growth being pervasive and biased toward underestimation [31].

The cost delta between AA results is then taken between the PRICE result (238 B€) and the 4cost *aces* (210 B€), being approximately 28 B€. This delta is then multiplied by a cost risk factor of 1.5 (42 B€), and added to the higher PRICE cost estimate, to obtain the higher production cost estimate limit of 280 B€.

The same process is applied to the average unit production cost, where the PRICE-4cost aces delta is 9 B€ (475 – 466 M€), is multiplied by the same 1.5 cost risk factor (roughly 15 B€) which, added to the highest PRICE average unit production cost of 475 M€ produces a total of €490 M€, which is assumed to be the highest production range boundary cost.

4.10.8.1 TransCost Production Cost Deviation

As can be seen from AA_{MAC} results, there is a considerable deviation in the TransCost overall program production costs as well as the average unit costs as compared to results from the PRICE and 4cost *aces* models. Looking at the values presented in Table 65 above, for example, not only is the cost delta significant, but also the production cost distribution between elements is also different. TransCost results in highest cost for SLME production, followed by SLB, then SPC with the SLO component being the cheapest to produce. The commercial tools, however, both indicate that by far the most expensive element to produce is the SLB, followed by the SLO, SLME and finally, the cabin/capsule SLB element. In any case, in line with AA_{MAC} theory, it is important to analyse and ascertain where and why such a difference would have arisen. Upon further analysis, three main contributing factors for the incongruence between TransCost and the PRICE and 4cost *aces* models can be identified. These are listed and explained in the following sub-chapters.

4.10.8.1.1 TransCost Non-Applicability to SLO & SLB

As already outlined in Chapter 4.10.2, TransCost does not appear to be an ideally suited model to reflect production costs for a novel vehicle with high production rates and with a passenger transport application such as the SpaceLiner case-study, which is addressed in this Thesis. The existing TransCost CERs could be identified to adequately represent two of the four main components of the SpaceLiner vehicle, being the SLO and SLB components. As such, and to conform to the SpaceLiner philosophy which has been described in Chapter 4.1.4, the production cost estimation conducted using the TransCost model was based on the rather gross assumption that for the SLO and SLB, an average cost was assumed between the aviation and space domain CER groups (also see Chapter 4.10.2). For the SLO, the average result of the two CERs for *Winged Orbital Rocket Vehicles* (space domain), and *High Speed Aircraft / Winged First Stage Vehicles* (aviation domain) were assumed. Similarly, for the SLB, the same two CER results were again averaged to arrive at a production cost range. An equal 50/50 split was taken between each CER, since at this stage to assign particular fractions seeking to represent a different weighting between the space and aviation domains would have been premature, unjustified and thus, non-constructive. A summary table of the TFU results for the SLB and SLO elements is shown below in Table 66. As can be seen, the production cost delta is significant between the space and aviation domain CERs, resulting in a percentile difference of roughly 260 – 270%. Therefore, because of the necessary although highly simplistic assumption to assume an average production cost between the aviation and space representative CERs, it must be conceded that a significant amount of uncertainty, especially pertaining to the SLO and SLB components, is associated with the cost figures. As such, although unlike the development costs discussed in Chapter 4.9.1, the TransCost production costs should be interpreted tentatively.

Table 66: Summary of individual TransCost 'best-case' (aviation) and 'worst-case' (space) assumed CER results prior to obtaining their equal average

TFU	Avio M€ (2013 e.c.)	Space M€ (2013 e.c.)	Space/Avio Delta
SLO	271,89	732,504	269%
SLB	332,69	860,030	259%

4.10.8.1.2 TRANSCOST MODEL 'CLASSICAL SPACE PRODUCTION'

A further point to make is that the TransCost model deals largely with classic space systems, a key feature of which is very low production rates. Looking at the Ariane 5 launchers program, for example, with an average of 5 launches in 2013 and 2014, it can be seen that such a production schedule is significantly lower than the one proposed for the SpaceLiner case-study. While for the aviation CER used to synthesise both SLO_{Avio} and SLB_{Avio} costs, some data-points underpinning the CER did include those of serially-produced subsonic commercial aircraft with production quantities of over 400, the SLO_{Space} and SLB_{Space} TransCost results still represent the classical space sector trend and high costs associated with low production quantities.

Additionally, through its CER formulas, the TransCost model makes a simplistic assumption which implies a fixed and steady-state manufacturing environment, with no adjustments to production processes given various cadences of production quantities. Also, there are no factors which affect the crucial TFU value (which then forms the cost basis for all consequent units produced in series) to reflect the manufacturing environment, including conditions and processes. Such an approach may be representative for low production rates of the previously discussed classical orbital launch vehicles, but is not representative of highly produced vehicles like the SpaceLiner case-study. Not reflecting the varying (usually higher) levels of production automatisation and the economies of scale expected to be invoked by the high production rates associated with 500 SpaceLiner vehicles, it is not surprising that the

TransCost model results in costs double those of the commercial models. The LC distinction is discussed in more depth in the following Chapter 4.10.8.2.

Here, the significant cost deviation seen for the TransCost calculated SPC element compared with PRICE and 4cost *aces* results must also be briefly mentioned. The TransCost CER applied for calculation of SPC production costs was for *Crewed Space Systems* and is based on reference points for a wide range of vehicles, ranging from crewed re-entry capsules, which include the Mercury and Gemini capsules, lunar transfer and landing vehicles (Lunar Lander), and even the Shuttle Orbiter, although without engines. The TransCost manual openly states that this category of vehicles also incurs the highest production cost, due to the need for complex life-support systems, power supply and electronic/communications equipment necessary for crewed space systems [102]. However, the context of the SPC within this selection of vehicles, and also within its SpaceLiner vehicle case-study application, is arguably misplaced, as has already been presented in Chapter 4.1.9 which outlines and establishes details of the baseline SpaceLiner case-study philosophy.

The SPC differs greatly from the function and technical requirements for a lunar-lander, or Space Shuttle Orbiter vehicle. The SPC bears more resembles to a plane cockpit, and in this respect, many COTS elements could easily be used during the production process. While it is true that the cabin must also function as an escape capsule, this is foreseen to be in the unlikely case of an emergency, after which the SPC will not be re-used. As such, the functionality, operational lifetime under space conditions and hence technical requirements of the SPC can be considered to significantly differ to those of, for example, the Space Shuttle. And with the highest costing CER, in this context it is not surprising that the TransCost model results in a production cost of more than 84 B€ for the SPC element compared to the roughly 7 B€ as calculated by both PRICE and 4cost *aces*. Given this analysis within the AA_{MAC} framework, it can be concluded that the TransCost model, in this instance, results in unrepresentatively high production costs of the SPC element, and as such, in line with AA theory, is not considered further.

4.10.8.1.3 TRANSCOST ORBITAL VEHICLE FOCUS

While the TransCost model is a dedicated tool for launch vehicle cost determination, the data points which underpin its CERs mainly consider programs which are orbital missions (i.e. Shuttle Orbiter). And while the case-study vehicle assumed for analysis in this Thesis relies on traditional launch technologies, it is only a sub-orbital vehicle with a significantly shorter overall mission duration, and a sub-orbital trajectory. This of course has an associated bearing on the production costs. It is important to highlight that this distinction between vehicle types would be relatively insignificant and therefore would have little bearing on the development effort, since the development processes, sequence, prototypes, and testing would be similar for orbital and sub-orbital vehicles. The largest influence for development, in fact, would be other aspects such as for example whether a vehicle is designed for manned applications, in which case whether orbital or sub-orbital, testing would be equally as extensive. Such a requirement this would dictate an increased number of prototype models to be built and tested, which, as has already been shown in this Thesis (see Chapter 4.9.9.1), is a key cost driver for the development effort.

During the production effort, however, a much greater cost delta would be evident due to more extreme operating environments, different expected lengths of operation and requirements for a vehicle like the case-study SpaceLiner, and the Space Shuttle Orbiter. This then translates directly into technical and mechanical aspects to reflect the nature of the mission and the different mission lifetime, all of which then transfers into a higher cost for production. This observation and critical distinction for orbital and suborbital vehicles dependent on the nature of the mission has already been made and documented in the ISU study assessing the potential for suborbital transportation [6]. A modified version of the TransCost model is then very briefly mentioned in the ISU report, referred to as '*SUBORB-TransCost*', although its mechanics and what changes have been implemented to the original TransCost, remain undefined and undisclosed. In any case, due to the SpaceLiner case-study being a sub-orbital vehicle, costed using parametrics based on mainly orbital programs underpinning the CER data-points, would be a contributing factor to a higher cost than may be expected for a vehicle such as the SpaceLiner case-study.

4.10.8.2 Learning Curve Assumption

For all three models taken for the Amalgamation Approach, a pure, singular and consistent learning curve of 85% has been assumed for all 500 SpaceLiner units and components. However, studies and literature also show that pure models like Crawford, often do not exactly fit with actual observation [64], since actual learning phenomena are more complex than the pure models describe. For example, as task complexity increases, less learning is to be expected due to different learning types for simple and complex tasks. Also, the more automatisation there is in a task, the less the learning which can be expected. Finally, and more specifically applicable to the SpaceLiner case-study, with a higher production rate, the lower the learning rate can be. In this instance, with no limitation to the learning curve, for very large quantities of production, the unit cost becomes very small – which is actually in contradiction with experience, since learning has hard limits [64]. As a practical and directly relevant example, it can be noted that for larger production quantities within the aircraft industry, the increase in quantity results in a variation of the LC (denoted as Λ_c), which changes for various production quantity ranges (ranks), as shown in Table 67. Furthermore, Table 68 shows another example of in-depth learning curves within the aviation industry as outlined by the Defense Contract Audit Agency (DCAA) [51].

With relevance to the SpaceLiner, a very high production rate of engines is required, which is significantly greater than historical and current space industry programs. Each SpaceLiner vehicle requires 11 engines to be produced, which, at a 25 time reusability would then warrant an additional 55 replacement units per vehicle to service the intended 150 flight lifetime of the SLO, SLB and SPC elements. For a fleet of 500 SpaceLiner vehicles, this equals a considerable total of 33,000 engines to be produced. If engine lifetime is increased to 50 flights, then the number of engines required would be halved to 16,500. Yet still, such a high quantity, which is significantly beyond the scope of the 400 unit maximum shown in Table 67, would definitely have implications on the learning curve, reducing the learning effect as it becomes increasingly more automated, and consequently tapering off the cost decrease. This aspect has been in part considered by the sensitivity analyses presented in this Thesis (see Chapter 4.10.9 below) which augment production quantities as well as the learning curve variables.

Table 67: Crawford learning rates (λ_C) observed in the aircraft industry [64]

	λ_C	From rank to rank
Mechanical parts	0.92	1–6
	0.84	6–60
	0.95	60–130
	0.97	>130
Sheet-iron works and sub-assemblies	0.88	1–6
	0.82	6–60
	0.90	60–150
	0.95	150–200
	1.00	>200
Assembly – fitting out	0.85	1–6
	0.76	6–60
	0.85	60–150
	0.90	150–200
	0.95	200–400
Integration	0.85	1–6
	0.76	6–60
	0.85	60–150
	0.90	150–200
	0.95	200–300
	1.00	>300
Control	0.94	1–6
	0.86	6–60
	0.95	60–150
	1.00	>150
Global	0.88	1–6
	0.80	6–60
	0.92	60–200
	0.99	200–400

While it is true that the Crawford model can be modified to adapt for complexities outside the typical model definition, here it is also interesting to note that other learning laws exist, such as a derivative and complexification of the Crawford law, being the Broken Line Model, or De Jong's law, which could also be applied to the SpaceLiner concept at a more advanced stage. These models, however, are beyond the scope of this Thesis, with much extensive, in-detail literature existing on these topic for the interested reader [42, 64, 201, 202].

Table 68: Summary of typical learning curves within the aviation industry [51]

Items	Database Qty	Average LC	Median LC
End Item Aircraft	29	79.4%	78.7%
Airframe Components, Instruments, Equipment & Accessories	67	88.3%	89.2%
Aircraft Engines & Parts	27	85.7%	88.0%
Communication Equipment	13	84.3%	81.5%
Flight Controls, Fire Control & Navigation	26	83.8%	83.8%

Of course for the purpose of the SpaceLiner case-study, being only at the concept phase, and with no precedent to support formulation of learning trends from observations available, a theoretical and academic approach has been assumed in this Thesis. The consequent assumption of a fixed Crawford learning curve value during production is both unavoidable and sufficiently justifiable at this preliminary stage to establish a baseline scenario from which to build upon. Nevertheless, as the SpaceLiner program matures, the learning curve assumptions and approaches may need to be refined in line with emergence of new program information. The exact and detailed influence of production quantity on the learning curve would need further consideration at a macro level per SpaceLiner case-study element in the future, particularly when required production quantities have been fixed in line with a clear business case and thus routes, and operational scenarios.

4.10.8.3 Other Production Cost Fluctuations

To explain the minor cost fluctuations observed between the two commercial 4cost *aces* and PRICE tools, similar justifications as already discussed within context of development costs, can also be applied here. The variability in internal model mechanics and algorithms already discussed at length in Chapter 4.9.8.3 would contribute to fluctuations. Additionally, any changes of the model user throughout the process and the potential for introduction of personal bias through exercising EJ during translation of caste-study data into model-specific parameters would be another contributing factor to cost deviations and fluctuations, as already outlined in Chapter 4.9.8.4. While human error may also be a contributing factor, the nature of the AA_{MAC} approach, as supported by the AAInT spreadsheet, considerably minimises any significantly influential errors, as has been already explained and detailed in Chapter 4.9.7.1. For production costs, as well, as has already been discussed in Chapter 4.9.8.5, the fact that both PRICE and 4cost *aces* in this instance do not consider software costs, would also, to a very minor extent explain that the TransCost results are higher, since TransCost inherently addresses SW in its CERs.

4.10.9 Production Cost Sensitivities

To complement the sensitivities conducted for the development cost calculations, it was also interesting to perform some basic sensitivity analyses for the baseline case-study production phase. Since the TransCost model yields a greater uncertainty in its production cost results (see Chapter 4.10.8.1), it was logical to use one of the commercial tools. To keep congruent with the development cost sensitivity process, the 4cost *aces* tool was once again applied to implement the chosen sensitivity deltas. Three variables, the influence of whose deltas are interesting to examine with respect to production costs, were identified. These are variations in learning curve (LC), the production quantity, as well as the reusability capability of the engines, resulting in a different quantity of engines to be produced. The variables were not necessarily chosen to reflect a worst-case scenario, but most commonly straddled the baseline value, as will be outlined below, for each sensitivity-case. The 4cost *aces* model data used to extract the three key values of interest from the sensitivities datasets, were total production cost (*PrdTotal*), the 4cost *aces* model calculated average unit cost (*ModAmuc3*), and the cost of the TFU first unit produced (*T1ModT1*), referred to as T1 by 4cost *aces* vocabulary. Here, it is important to note that the 4cost *aces* model calculated output for the average cost per unit produced was **not** the simple total production cost (*PrdTotal*) divided by the production quantity. Through the internal mechanics of the model, the *ModAmuc3* value which represents the average unit cost of production, also includes the overheads and profit margins assigned by the modes, assigned to be 10% (see final paragraph of Chapter 4.10.3), as well as a basic software component, which, although eliminated for the total production case, was left in for the sensitivity analyses. Its impact is almost negligible in the context of costs.

Furthermore, while it was inefficient to include the countless datasheets for each of the nine sensitivities, the baseline datasets of inputs (Table 125) and more particularly the outputs (Table 126) included in Appendix H can be consulted to see the structure and source of the respective 4cost *aces* tool data required and used also for the sensitivities.

4.10.9.1 Learning Curve Variation

The LC for production using the 4cost *aces* tool was varied from 80% (sensitivity study baseline LC value) to 85% and ultimately 90%. Here, it was interesting to see how the LC delta would influence overall production costs given the internal mechanics of the model. The results for total production cost as well as the resulting average unit production costs are shown in Table 69 while Table 70 shows the resulting costs for the TFU (referred to as T1 within 4cost *aces* tool terminology, so to be used interchangeably and synonymously with the term TFU) for every LC variation.

As can be clearly observed upon first glance results of the LC sensitivity analyses costs in Table 69 changing the LC values seems to have a negligible influence on the total production costs (the percentile delta is shown to two decimal places so that the small delta can be identified). A less than 1% total production cost deviation results for both S_P1 and S_P2 despite an LC delta of ±5% compared to the baseline S_P0 LC value of 85%. This is a surprising and seemingly counterintuitive outcome since it might be expected that the chosen LC deltas would have a stronger impact on production costs, and thus yield a more pronounced cost delta. Yet while the total production cost does not seem to change, as can be seen in Table 70, the TFU values fluctuate strongly between the baseline and two sensitivities.

The reason for this, however, can be attributed to the 4cost *aces* model mechanics, and in particular the close and specific interrelation between the LC input, the production quantity and resulting T1 cost given the myriad of other 4cost *aces* inputs.

The 4cost *aces* model applies the LC in close accordance with the cost of the theoretical first unit to be produced (T1). These results are based on the various user-provided inputs such as, for example, weight, technology index, and environment (see Chapter 4.10.3) in combination with other values derived from internal 4cost *aces* generators, tables of values and other internal model algorithms.

Table 69: 4cost aces LC sensitivity summary for average production costs

S_PX	Sensitivity	∑Production Cost (B€)	% of Baseline	Average Production Cost/Unit (B€)	% of Baseline
S_P1	LC 80	173.68	99.72%	0.389	99.72%
S_P0	**LC 85 (Baseline)**	**174.23**	**100.00%**	**0.390**	**100.00%**
S_P2	LC 90	174.71	100.25%	0.391	100.25%

Table 70: 4cost aces LC sensitivity for T1(TFU) production costs

S_pX	Sensitivity	T1 (M€)	% of Baseline
S_p1	LC 80	1128.18	143%
S_p0	**LC 85 (Baseline)**	**787.68**	**100%**
S_p2	LC 90	591.36	75%

The key point to highlight here is that in practice and in reality, and as the 4cost *aces* model seeks to reflect, the first few units to be produced have a very different production cost to units produced in consequent series. To reflect this distinction, and again in practice and in reality, the LC values between the initial units produced, and consequent units, would also vary. For example, it is typical for the first 10-20 units to be modeled reflective of a high manual-input working environment with a representative LC being roughly around 80%. After this, the LC should be adjusted to be typical and representative for a 500 unit production, with representative values being perhaps in the mid-90% range. Additionally, for the higher production rate of the SpaceLiner engines (33,000 baseline quantity) yet again a variation in the LC value being in the very high 90% range (for example, 97-98%) would be appropriate. This fact and logic is furthermore substantiated by data found in Table 67 from Chapter 4.10.8.2. In such a varied and tailored LC instance, the *aces* model would then pick up the last calculated cost of the first 10-20 units and apply its own manufacturing process factor following the digression of that LC.

For the SpaceLiner case-study however, the simplified and academic assumption has been made to impose a theoretic and consistent LC value at this preliminary cost analyses stage as justified and explained in Chapter 4.10.1. The chosen value of 85% implies a manufacturing process with a consistently higher level of manual labour. This also makes the first units, and indeed the T1 unit, very expensive in relation to a learning curve of, for example, 90%. This phenomenon is reflected exactly in Table 70 where a higher LC (i.e. 90%) features an associated lower T1 cost than a lower LC (i.e. 80%) which has a very high TFU, where this cost difference consequently accrue due to the automatisation process of the product line.

Therefore, due to the artificially imposed, academically and theoretically synthetic and simplified constant LC value, the 4cost *aces* model results in the same average production cost for all sensitivities, as seen in Table 69. The very minor variations (-0.28% and +0.25%) simply reflect rounding effects present within the 4cost *aces* model. This is a result of the constant LC input which was chosen.

This particular cost sensitivity highlights the important issue of learning curve consideration and understanding its effect, influence and interrelation on other crucial cost variables –and in this instance, particularly so when a high production quantity under 'space environment' conditions defined by other factors and complexities is imposed. As an extension of this work, future work can be continued to implement unique LC values for the various quantities of production for the SpaceLiner case-study (also see Chapter 5.1.2.2).

4.10.9.2 Production Quantity

For the sensitivity, the production quantity of SpaceLiner units was also both incremented (850 units) and decremented (300 units) with respect to the baseline of 500 units. Through increasing the quantity also increased the total production cost, and given the LC and T1 theory and logic presented in the previous Chapter 4.10.9.1, it was also interesting to see the effect of the sensitivities on the TFU values.

As seen in Table 71, quite logically the total production costs are seen to increase in line with a production quantity increase. Concurrently, the model-calculated average production costs per unit are seen to decrease in line with LC theory.

Table 71: 4cost aces production quantity sensitivity for average production costs

S_PX	Sensitivity	∑Production Cost (B€)	% of Baseline	Average Production Cost/Unit (B€)	% of Baseline
S_P3	Qty 300	95.36	55%	0.410	105%
S_P0	**Qty 500 (Baseline)**	**174.23**	**100%**	**0.390**	**100%**
S_P4	Qty 850	287.55	165%	0.363	93%

Table 72: 4cost aces production quantity sensitivity for T1 (TFU) production costs

S_PX	Sensitivity	T1 (M€)	% of Baseline
S_P3	Qty 300	1047.662	133%
S_P0	**Qty 500 (Baseline)**	**787.676**	**100%**
S_P4	Qty 850	1255.553	159%

Here, again, production quantity has a direct impact on the T1 values. The 4cost *aces* model will use the QTY and MAPROC, the LC value and economic base inputs as well as the ENVIRP (1.8 for SpaceLiner case-study) and technology indexes to calculate the appropriate T1. In addition, T1 is then directly related to the chosen LC (as previously discussed in Chapter 4.10.9.1, an LC of 80% would result in a higher T1 than an LC of 90%, which yields a lower T1), in conjunction with the production quantity. Therefore, as seen in Table 72 the T1 varies in a seemingly inconsistent pattern to the increasing quantity of production. However, for this particular sensitivity example looking at the TFU value is only interesting to demonstrate the multi-faceted nature of the commercial 4cost *aces* tool, as well as highlight the complexity of its input and variable interdependencies. Similarly to the overall production costs, the focal value of interest here remains the average production cost per unit which, given an increased number of units to be produced from 300 through to 500 and 850, is shown to very logically decrease due to the learning effect.

4.10.9.3 *Engine Reusability*

Another interesting variable to consider within context of production was the technical capability of engine reusability. This directly influences the quantity of engines required per SpaceLiner vehicle. Taking the baseline case, with 500 SpaceLiner units and a reusability capability of the SLO, SLB and SPC being 150 times, but with a 25-time reusability for engines, means that a single SpaceLiner vehicle produced requires a total of 66 engines during its lifetime. If the reusability criterion was increased to a 50-time reusability, this halves the number of engines required to just 33 engines per operational vehicle. As such for a program of 500 SpaceLiner vehicles, the total requirement for overall engine production falls from the baseline case of 33,000 to 16,500 units. This would clearly have an influence on production costs, logically reducing them. Results of the sensitivity below in Table 73 show that the total program production costs decrease as do the costs for the average unit production. Table 74 furthermore shows the respective TFU costs.

Table 73: 4cost aces engine reusability sensitivity for average production costs

S_PX	Sensitivity	∑Production Cost (B€)	% of Baseline	Average Production Cost/Unit (B€)	% of Baseline
S_P0	**25 x Engine Re-use (Baseline)**	**174.23**	**100%**	**0.390**	**100%**
S_P5	50 x Engine Re-use	143.47	82%	0.328	84%

Table 74: 4cost aces engine reusability sensitivity for T1 (TFU) production costs

S_PX	Sensitivity	T1 (M€)	% of Baseline
S_P0	**25 x Engine Reuse: 33,000 produced (Baseline)**	**787.676**	**100%**
S_P5	50 x Engine Re-use: 16,500 units produced	990.086	82%

As can be seen, through halving the required number of engines, the total program production cost drops down by 18% compared to the baseline scenario. More importantly for this sensitivity study, it is shown that through enhanced engine reusability, the production of each SpaceLiner vehicle, on average, decreases from 390 M€ to 328 M€, which constitutes a 16% cost drop per unit. This confirms the fact that the engine is a very important cost-driving parameter of the overall SpaceLiner system. Concerning the TFU values which are included for interest only, the smaller quantity of engines produced implies a less significant automatisation process, and as such, in line with previously established theory, increases the TFU, as seen in Table 74.

4.10.9.4 Production Sensitivity Summary

The sensitivity study presented in the latter chapters determined the cost effect for production using the 4cost *aces* tool, through varying three key production process variables; the LC values, the production quantity, and the engine reusability (which reflects on the production quantity of the case-study propulsion unit). Total program production costs and consequent average unit costs were calculated, as well as TFU values shown, with percentile differences between the sensitivities and values of interest also calculated to facilitate of more tangible comprehension of sensitivity impact on costs. While LC sensitivity results were surprising, a deeper analysis into the 4cost *aces* model mechanics revealed the complex albeit very logical interrelations and influence of key quantity, LC and TFU cost parameters on one another. The LC sensitivity analysis also highlighted that LC theory would need to be considered at a deeper level for the SpaceLiner vehicle case-study in the future, considering not only a fixed LC value throughout the production process, but a varying one, depending on production quantities.

Variance of production quantities logically revealed a cost increase to an increased production amount, and a decrease, with a decreased quantity produced. Finally, enhanced engine reusability also impacted the total program costs in a positive way, as was to be logically expected.

4.10.10 Production Cost Calculation Conclusions

Through applying AA_{MAC}, overall program production costs were calculated by the three tools and models of TransCost, 4cost *aces* and PRICE to be 376 B€, 174 B€ and 198 B€ respectively. The final results for the commercial PRICE and 4cost *aces* tools present a strong program congruency at top level, as well as the lower $L2_{WBS}$. As was observed for development cost calculation, more pronounced variations were observed at the lower $L3_{WBS}$, although this is to be expected with application of different tools and furthermore at an early program phase. Again, a greater cost variation within the AA framework is a strong indicator of an increased margin of uncertainty associated with those respective costs, knowledge which should then be incorporated into associated risk planning and mitigation strategies within framework of the respective space-program being analysed.

Upon final analysis of AA_{MAC} obtained results in the specially developed AAInT spreadsheet, the TransCost model, however, was found not to be ideally suited for production cost estimation of all SpaceLiner case-study components. Lack of CERs which sufficiently addressed the specificity of the chosen SpaceLiner case-study necessitated production cost average values to be calculated for the SLO and SLB system elements. In each case, these averages were synthesised from two separate CERs relating to the aviation and space domains respectively. This approach sought to address the SpaceLiner philosophy for production outlined in Chapter 4.1.4. An equal weighting for each CER was then applied to estimate the production cost for the SLB and SLO elements, which were then aggregated with the SPC and SLME calculated production costs to obtain a program total. As such, the total TransCost result was roughly double of the results obtained by the commercial PRICE and 4cost *aces* tools.

The basic sensitivity analyses performed for LC influence, production quantity and enhanced engine reusability also logically confirmed associated production cost trends, as was to be expected with theory. Altering the LC had no effect on total program cost due to 4cost *aces* complex model mechanics, where an influence was observed on the T1 (TFU) cost. Through analyses of the surprising LC sensitivity results, the complex nature and application of LC theory became apparent. As such, it can be recommended that future work focus on expanding the simplified assumption of a basic and constant LC value across all elements of production. The LC value strongly hinges on the quantity of units to be produced, and should be adjusted in accordance with various production quantity cadences to reflect changes in automatisation and manual labour.

Concerning the production quantity sensitivity, a greater overall program production cost was achieved with an increase in units produced. Concurrently, the average unit production cost fell due to the LC effect. Through enhancing engine reusability, a production cost reduction was observed on both overall program level, as well as at average unit cost of production.

Overall, through application of AA_{MAC} and through consequent analyses of results using the AAInT spreadsheet, a production cost range has been established. Although one set of results from TransCost resulted in considerable variances to the PRICE and 4cost *aces* models, nevertheless a strong level of confidence is associated with the established cost range. As the program matures, the production cost estimates should be continually monitored and revised to incorporate any new information, mission and technical data.

4.11 OPERATIONS AND GROUND COSTS ANALYSIS

"Operations costs are "the most difficult part of a launch vehicles' cost estimation."

-Dr. Dietrich E. Koelle

The difficulty of estimation for the operations and ground (O&G) category of costs lies in the unique nature and therefore differing requirements for operational scenarios and ground infrastructure requirements for each program. However, categories of O&G costs for space programs can be qualitatively determined, grouped logically and outlined.

For the SpaceLiner case-study, while technical details are steadily approaching maturity, the operational scenarios and thus ground infrastructure requirements are still in the early stage. And while individual costs could be assigned at a preliminary nature to the various activities which can be anticipated for the SpaceLiner case-study, a total O&G cost remains extremely difficult to determine, with a large uncertainty and therefore high risk element.

Yet while it is too premature to establish a specific O&G scenario and scheme for the SpaceLiner concept, the necessary processes and more critically, the cost categories for developing an O&G cost estimate for a vehicle such as the SpaceLiner case-study, can be foreseen. These element which already been introduced in the WBS presented in Chapter 4.1.1, can be briefly discussed and defined at this early program phase. Consequently, when details do crystallise, the path and processes to hone in on representative O&G costs can be followed, with any necessary modification and changes made to update the status of the program at the future time.

For reusable systems, like the SpaceLiner case-study, complex relationships exist between the large number of O&G interrelated criteria, as shown in Figure 39. The TransCost manual segments operating costs into two sub-categories of direct and indirect operating costs (DOC and IOC, respectively).

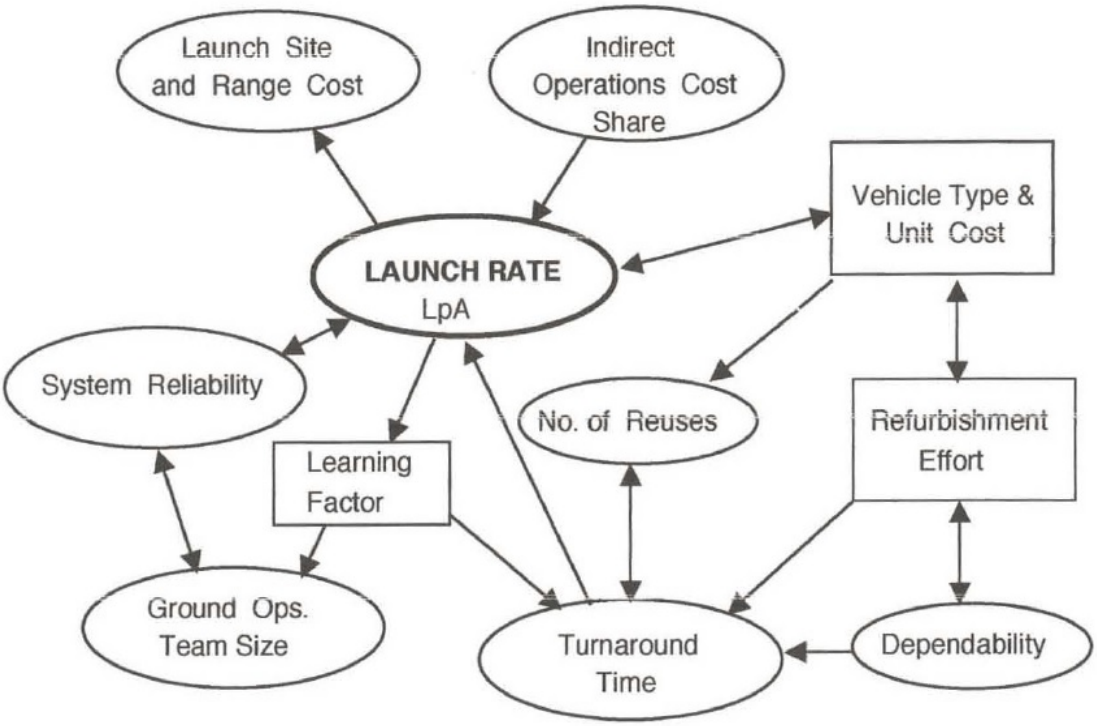


Figure 39: Major operational criteria and their interrelation for RLVs [102]

Operations costs can be roughly grouped into ground stations and associated costs, and personnel costs. Ground stations encompass any operating facilities, such as control centers and communication stations. Equipment such as antennas and computers, for example, form a large component of this. Software is also a considerable cost driver, and is commonly the most difficult and expensive component [132] of the ground cost infrastructure. The personnel category then encompasses maintenance costs, and any contract and government labor.

For the SpaceLiner case-study, given the fact that the purpose of the vehicle is passenger transport, it can be foreseen that the operational scenario would be a complex one. Some operational details for the concept are, in fact, emerging. Preliminary work has already been done to study and propose both potential spaceport configurations and locations for the SpaceLiner case-study, as well as preliminary operational requirements and activities [110]. Three possible spaceport configurations were also suggested for landing and launch (L/L) sites, being on-shore (inland), artificial island (off-shore), and an off-shore launch site with an on-shore landing capability. The concept of the artificial island is has already been well demonstrated by construction of the Kansai International Airport, shown in Figure 40, which has been operational since 1994 [86].

Figure 40: Kansai International Airport in Osaka Bay, Japan [86]

Given the three construction options, the study [110] also then identified various possible geographical locations optimising site remoteness requirements to address sonic boom issues, with nevertheless considering sufficient proximity to highly populated city-hubs for travel. The possible locations are summarised below in Table 75.

Looking at the spaceport itself, it is clear that the operational protocol would combine the processes standards from the commercial aviation industry of boarding and de-boarding of the

Table 75: Summary table of identified geographical locations for SpaceLiner L/L sites

Region	Locality	Type
Europe	northern Netherlands	on-shore (launch) / off-shore (landing)
Australia	Rockhampton, Queensland	on-shore
USA	California City	on-shore
Asia	Bayonglong, China	artificial island
Asia	Futaba, Japan	artificial island

aircraft, compounded with the complexity of integrating space technology within this routine. Therefore it is also worthwhile consulting other extensive literature from the aviation domain to determine the procedures and processes for passenger embarking and disembarking, as well as requirements for safety given the significant cryogenic propulsion loading of each proposed SpaceLiner vehicle. Integration of space vehicles into existing airspace infrastructure is also a crucial consideration.

A preliminary spaceport design has also been established, assuming that propellant production facilities, such as a LOX and LH2 production plants will be located on site. A possible schematic of an on-shore spaceport is shown below in Figure 41, with Figure 42 then showing the layout of a spaceport terminal building for the SpaceLiner case-study. Based on this design, an itinerary has been compiled for operations costs with respect to required infrastructure, resources and personnel to support a potential operational scenario. These are outlined in more details in Appendix J, and also include preliminary associated costs, as derived predominantly using the Operational cost segmentation presented in the TransCost manual.

In addition, to supplement further work required for the operations cost segment, a multitude of other sources exist which outline the operations for aircraft exist, including the NASA Air Cargo Operations Cost Database [92] as well as multiple, diverse literary sources for the interested reader [71, 144, 206, 229].

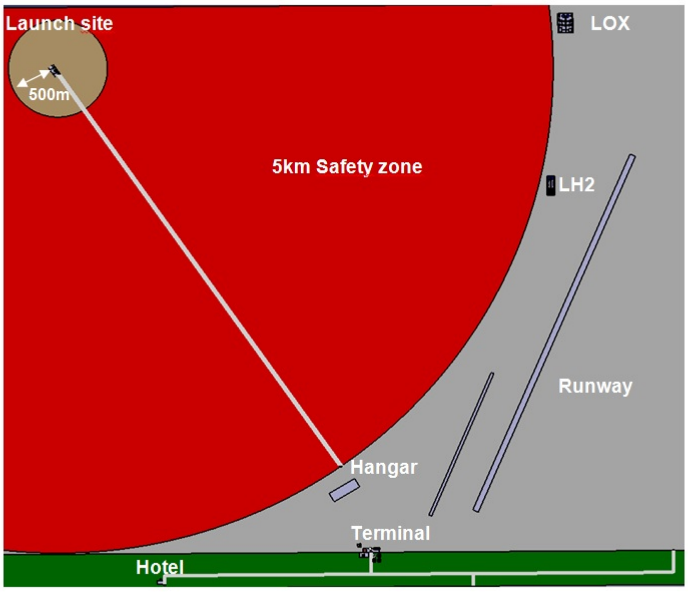


Figure 41: Proposed layout of the on-shore configuration spaceport [110]

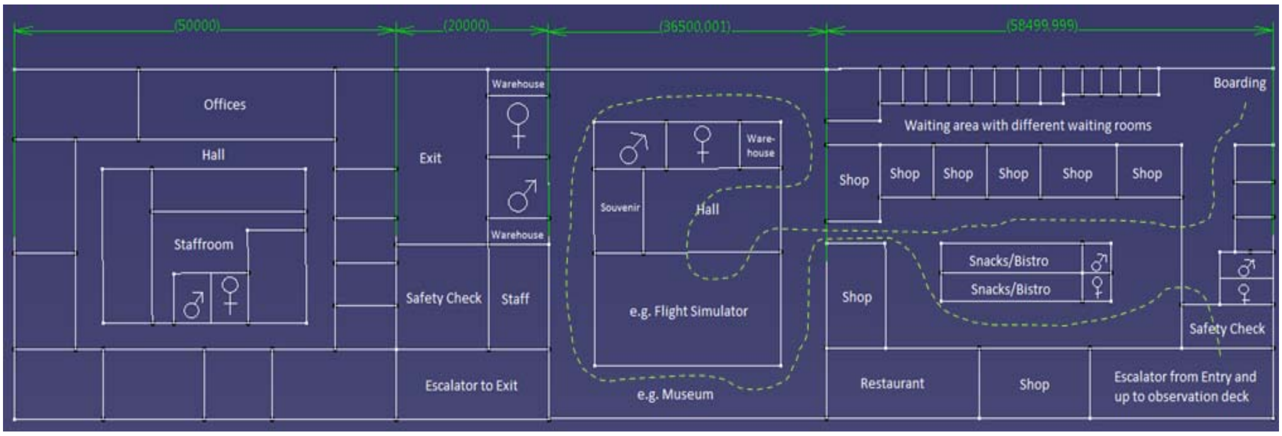


Figure 42: Sketch of proposed terminal layout [110]

Furthermore, Ashford directly addresses exploiting commonalities between the existing aviation segment and the emerging spaceplane movement in his paper [15]. He concludes that reusability is the crucial mechanism for cost effective access to space for the new space age, which depends on a combination of reusability and high traffic levels which space tourism and ultimately high speed passenger transport both have the potential to offer.

4.12 REPRESENTATIVENESS & RELIABILITY OF PRESENTED COST ESTIMATION

To address the critical point of resulting estimate reliability and associated confidence, it must be once more stipulated that the domains of cost engineering and especially estimation inherently always carry a margin of uncertainty, which varies throughout program phase. This principle has been described through the cone of uncertainty in Chapter 2.3. The 'accuracy' of a cost estimate can only be a measure of how representative the cost estimate is of all current parameters at a given point in time. Therefore, the term 'cost estimation accuracy' should be applied with caution and comprehension to the inevitable discrepancies which usually always exist between an estimate made at a certain point in time early on during a program (prior to pre-phase A), and a cost estimate which has been revised and has evolved, made for the same program at a later point in time, for example during the Systems Requirement Review.

As previously mentioned and emphasised, the cost estimate itself and the associated estimating process, are both dynamic and ongoing in nature. The cost engineer cannot influence external parameters which may influence a program, such as politics, economics and risk elements. Yet it is the main task of the cost engineer to factor in for risk and uncertainty in an initial estimate to the best of their ability, and consequently monitor and modify and adjust the estimate throughout the program lifecycle in line with internal circumstance, and external conditions, like any economic fluctuations and political influences. As such, a cost estimate can only be accurate at a particular, frozen moment in time, with respect to the availability of firm project documentation (such as a Statement of Work, SOW, and specifications) at that time, as well as the applicability of the cost estimation methodology or tools, and the experience of the estimator. Consequently, the term 'cost accuracy' can be seen in part as being synonymous with currency and accuracy of program information and the suitability of CEM and tool or model, both of which underpin a cost estimate representativeness, justifiability or defensibility of the and any assumption which were made during its compilation.

Two prominent and real industry examples are the Space Shuttle [91, 102] and the Concorde program, whose final development cost is quoted as being between six to ten times as high as initially predicted [31, 145, 160]. On a more global scale, a GAO report from 1993 to the US Congress showed that from 29 NASA programs surveyed, only 14% have been at or below the original cost estimate, 53% exceeded cost estimations by up to 100% while 33% showed cost growth of over 100% [102]. Furthermore, a more recent 2004 Congressional Budget Office study compared initial and revised NASA budgets for 72 programs between 1977 and 2000, finding that on average, a 61% increase on costs was incurred. It has been proposed that a prevalent and considerable problem in a competitive market environment where funds are obtained based on proposal victory, is that classical cost estimating standards are often compromised due to the originators of project proposals being afraid to present very realistic cost estimates which might risk proposal rejection [102].

The cost estimation task for the SpaceLiner case-study conducted within this Thesis is based on the currently available project documentation and the use of sophisticated cost models. The framework and processes described, set out, enhanced and applied for complex, early phase, unprecedented space program cost estimation presented in this Thesis is intended to increase reliability of cost estimation based on current standards. In line with industry best practice, high quality estimates should be credible, well documented, accurate and comprehensive. This Thesis strives to meet all the latter four criteria, with the introduction and development of the Amalgamation Approach for cost estimate redundancy. Nevertheless, a means is necessary to assess and class the reliability of the resulting estimate in terms of confidence.

Select approaches and measures exist in wider industry to classify cost estimation representativeness, commonly taking on the form of confidence classification matrices. A suitable example can be taken from the process industry, where a cost estimate classification matrix has been established and recently published by the prominent AACE organisation in November of 2011. The cost matrix is shown Table 76 below.

As can be seen, an estimate class is assigned based on the classification of various industry or project specific characteristics. While the matrix is specifically exclusive to process industries, and more specifically, for engineering, procurement and construction work [32], the same classification matrix principle and approach can be applied to ascertain cost estimation confidence within the space industry. A standard developed by the US Airforce, and as extracted from the Air Force Systems Command Manual [8], presents a matrix with four variables and four quantifications per level established to directly address cost estimation and the confidence level attributed to it. A direct excerpt from this document is presented in Figure 43, with super-imposed boxes indicating the numerical classification per category as is relevant to the SpaceLiner case study.

	Primary Characteristic	***Secondary Characteristic***		
ESTIMATE CLASS	**MATURITY LEVEL OF PROJECT DEFINITION DELIVERABLES** Expressed as % of complete definition	**END USAGE** Typical purpose of estimate	**METHODOLOGY** Typical estimating method	**EXPECTED ACCURACY RANGE** Typical variation in low and high ranges [a]
Class 5	0% to 2%	Concept screening	Capacity factored, parametric models, judgment, or analogy	L: -20% to -50% H: +30% to +100%
Class 4	1% to 15%	Study or feasibility	Equipment factored or parametric models	L: -15% to -30% H: +20% to +50%
Class 3	10% to 40%	Budget authorization or control	Semi-detailed unit costs with assembly level line items	L: -10% to -20% H: +10% to +30%
Class 2	30% to 75%	Control or bid/tender	Detailed unit cost with forced detailed take-off	L: -5% to -15% H: +5% to +20%
Class 1	65% to 100%	Check estimate or bid/tender	Detailed unit cost with detailed take-off	L: -3% to -10% H: +3% to +15%

Notes: [a] The state of process technology, availability of applicable reference cost data, and many other risks affect the range markedly. The +/- value represents typical percentage variation of actual costs from the cost estimate after application of contingency (typically at a 50% level of confidence) for given scope.

Table 76. AACE cost estimate classification matrix for process industries [32]

As already theoretically introduced in Chapter 2.2.1 and as illustrated in Figure 3 at the commencement of this Thesis, the estimated costs and the related confidence level, which inherently also defines risks, is strongly dependent on the three criteria of input data, the tools, models and methods applied, as well as experience and background of the estimator. From the break-down of criteria from the AFSCM matrix seen in Figure 43, it can be seen that confidence of an estimate is in this instance distinguished between four categories of *estimating conditions,* the *nature of the item* being costed and *item description*, and finally *cost methods and data*. Essentially, however, this is simply but a slight rearrangement on the key three criteria already established above, although the AFSCM matrix combines the two criteria of cost methods together with data, and also does not include the crucial facet of estimator experience. This fifth element is a most crucial dimension to consider, and should not be ignored, as will be discussed further in consequent Chapter 4.12.5.

The cost estimation for the hardware development and production phases of the SpaceLiner case-study which have been performed and detailed in this Thesis are optimally based on all currently available preliminary technical definitions, a systematic baseline project structure demonstrated in consolidation of a WBS, as well as establishment of a preliminary development schedule. In order to assure that the cost estimation prepared for the SpaceLiner project reaches a sufficiently high confidence level, which of courses reduces the financial risks, the above criteria have been stringently taken into account and are briefly discussed below. Additionally, classification of the resulting production and development cost estimates can be analogously compared to the confidence levels of Figure 43, although no numerical confidence interval is specifically defined. The confidence influencing criteria from theory as well as the AFSCM matrix are discussed individually within context of the SpaceLiner case-study, below.

CONF. LEVEL	ESTIMATING CONDITIONS	NATURE OF THE ITEM	ITEM DESCRIPTION	COST METHODS AND DATA
1 LOW	Estimating Time and Information Access Completely inadequate amount of time provided to make the estimate or there is a complete lack of access to useful data tend to make this estimate highly uncertain. Ground Rules and Assumptions No guidance was provided on ground rules and all assumptions made by the estimator were arbitrary.	State-of-the-Art The item is substantially beyond the current state-of the-art. Major development work is required. Production Experience No production of any kind has been started.	Specification Status No work on a specification has started. Operating Program Characteristics None of the OPC for using the item have been formulated.	Methods The estimate is almost a poor guess and little or no confidence can be placed in it. Data An almost total lack of current and reliable relevant data make the cost estimate completely uncertain.
2 MED LOW	Estimating Time and Information Access A very short due date or major problems of access to available data tend to make this estimate highly uncertain. Ground Rules and Assumptions Very little guidance was provided relative to ground rules. Most of the assumptions made by the estimator were considered quite arbitrary.	State-of-the-Art The item is slightly beyond the state-of-the-art and some development work will be required. Production Experience Experimental laboratory fabrication of a similar item is in process.	Specification Status Work on a specification is in an early stage and only general requirements are identified. Operating Program Characteristics The general outline of the OPC under which the item will be used has been only tentatively defined and many specific details are lacking.	Methods A highly arbitrary rule-of-thumb has been used. Data The data used to make the estimate highly suspect, very sparse in quantity, and characterized by major inconsistencies.
3 MED HIGH	Estimating Time and Information Access A more accurate estimate could have been made if freer access or more time had been available to research known data sources. Ground Rules and Assumptions Ground rules were generally adequate. Many of the assumptions were authenticated but a substantial number are considered questionable	State-of-the-Art The item is within the state-of-the-art but no commercial counterpart exists. Production Experience A prototype of the item has been produced.	Specification Status A specification for the item has not been completed but a specification on a similar item is available. Operating Program Characteristics The general outline of the OPC has been formulated but many specific details are lacking.	Methods A commonly used rule-of-thumb cost factor, but with no supporting back-up, has been used. Data The data used have been obtained from official or standard sources. Notable inconsistencies, lack of currency, gaps in data reduce the confidence in the estimate.
4 HIGH	Estimating Time and Information Access There were minor problems of access to available data and there was generally sufficient time to define and cost the item. Ground Rules and Assumption Major ground rules were provided and most of the assumptions were authenticated.	State-of-the-Art The item will involve a minor modification of commercial or standard aerospace issue items. Production Experience The item has been produced in limited quantity.	Specification Status A specification for the item has been prepared but is under review or revision. Operating Program Characteristics The OPC have been substantially defined, but are under review or revision.	Methods The basic method used to derive the cost is well documented, but no double-check or authentication has been possible. Data The data used are generally relevant and from a reputable source. They are incomplete, preliminary, or not completely current, however.

AIR FORCE SYSTEMS COMMAND MANUAL, AFSCM 173-1, "COST ESTIMATING PROCEDURES"

Figure 43: Air Force Systems Command Manual, AFSCM 173-1, "Cost Estimating Procedures" [8, 113]

4.12.1 Estimating Conditions

As can be seen, for the SpaceLiner case-study, the *estimating conditions* decisively fall within the medium-high (confidence 3) range. Estimating time for the task was sufficient. Also, the chosen case-study concept is currently at a very early stage. However, the technical reference documentation which has been established as the baseline is sufficiently precise, and thus suitable for a reasonable and representative cost estimation to be performed to reflect the current technical status. Where insufficient data was found, strategic assumptions based on analogy or discussion with experts and professionals (EJ) concerning scheduling, programmatic and operational aspects, as well as some technical aspects, were made and documented. The estimating confidence therefore lies in the medium-high category, with conditions expected to progressively improve during consequent progression into Phases A and B, also reducing the estimating risk. For the time being, any remaining uncertainty has been compensated by an appropriate cost margins

4.12.2 Nature of the Item

The nature of the item can then be categorised between the low (confidence 1) and medium-low (confidence 2) categories to reflect the considerable development effort still required for the project, as well as the state-of-the-art being status between ‘slightly’ and ‘substantially’ beyond existing technologies, as per definition in Figure 43. Here, while the philosophy of the concept centers on using no novel technologies, relying on existing state-of-the art technologies wherever possible, nevertheless the system design, integration of elements and utilisation of the SpaceLiner for passenger transport, is indeed novel and inherently carriers a certain amount of potential risk which has a reflection on the cost estimating confidence. In addition, the production status of the project is also addressed in the current classification, to indicate that no current SpaceLiner case-study units have been produced.

4.12.3 Item Description

The *item description* is between the medium-low and medium-high categories with a confidence level between 2 and 3. This indicates that specification work for the SpaceLiner case-study is in the early stages with general requirements firmly identified. Similar concepts, such as the Space Shuttle or the Buran vehicle, both of which are the only spacecraft of similar magnitude which have actually flown, as well as new innovative movements such as the Florida Space Port, can provide some existing and relevant specifications relevant for the case-study. Additionally, the Operating Program Characteristics have been roughly defined, with technical considerations presenting the biggest challenge.

4.12.4 Cost Methods & Data

Finally, in addition to data, at the heart of this Thesis are the *cost methods*. A high confidence of 4 can therefore be decisively assumed for this category.

Basic and well established CEMs were assumed for cost estimation formulation. Sophisticated and well renowned tools and models within the space sector which are both recognised and utilised worldwide by government agencies like NASA, ESA and DLR as well as industry have been independently applied for the SpaceLiner cost estimation with the Amalgamation Approach (AA_{MAC}) context. This novel approach was proposed, developed and implemented as an innovative cost estimation strategy within this Thesis as an additional measure to reduce the cost risk associated with early phase estimates. AA_{MAC} makes a strong and most notable contribution to boosting the confidence for this criterion through obtaining redundancy and thus a more structured and justified final cost estimate or range. Therefore here, it can in fact be deemed that the highest definition for the *Level 4 - high* certainty provided in the AFSCM matrix is in fact below the actual cost estimate status attained and presented in this Thesis work. The estimated results generated by the three cost models and tools are not identical but in a good sound order of magnitude of each other, with the top-level results for phases C and D providing a trustworthy, consistent, justifiable and reliable cost baseline with a high confidence rank. Furthermore, all methods, processes and underlying assumptions for development and production cost estimates have been clearly outlined and thoroughly documented for future reference.

It is also evident that the quality of technical data is crucial for qualitative cost estimation and its related confidence. As previously mentioned, while the chosen case-study concept is in an early program stage, the technical reference documentation which forms the technical baseline is sufficiently precise, and thus suitable for deriving a reasonable and representative cost estimate.

4.12.5 Estimator Experience & Competence

While there is no confidence level defined in the AFSCM matrix for this essential dimension, the background and the related experience of the estimator is an important prerequisite for a professional and qualitatively high cost estimation standard, and does indeed play a crucial role in cost estimate confidence. In fact this may be the most important contribution to achieve a high estimating confidence and consequently a reduced risk level. Throughout the compilation of this Thesis, a multitude of the highest level professional model users and direct industry and software professionals and experts were always closely consulted with, in regards to all matters associated with the three divers AA_{MAC} tools, data input and output interpretations, as well as theory and practical matters. All results have been consistently discussed and respectively reviewed in great detail and through countless iterations (see Chapter 4.9.7.1) in line with AA principles, thorough a dynamic dialog between the latter professionals and experts within the space domain, and across project management, scheduling and various engineering fields. Consequently the confidence level of the resulting cost estimate with respect to estimator experience and competence is considered to be very high, and the associated risk with this aspect, low. Further improvements in line with more crystallised program information are deemed necessary in the future, which is a task to be addressed in the consequent program phases.

4.12.6 Cost Estimate Confidence Conclusion

Synthesising just the four confidence figures presented in Figure 43, (*estimating conditions 3; nature of the item 1.5*; *item description 2.5; cost methods and data 4;)* yields an average confidence interval of the overall estimate of 2.75, lying between medium-low and medium high confidence. When adding the fifth essential dimension of cost estimator competency, as discussed in Chapter 4.12.5, this confidence average would be raised to 3, indicative of a firm **medium-high cost estimate confidence level**. This is the result of a systematic cost estimating approach based on a clear and detailed preliminary WBS, project schedule and consolidated with the innovative redundancy-infusing Amalgamation Approach to support the cost estimation for development and production costs.

It should be noted that the AFSCM matrix presented in Figure 43 adopts a qualitative rather than quantitative classification of the cost estimate confidence levels. A qualitative average definition for the SpaceLiner case study is achieved, that the cost estimation results derived within this Thesis bear medium-high confidence level at this early program phase. Given the diverse nature, scope and complexity of the various space programs, assigning specific quantitative values to such a matrix would be too general and therefore, non-constructive.

To assist the qualitative confidence level of the cost estimation, additionally, a cost estimate review checklist as outlined by a RAND Project AIR FORCE report, proposes some key points to be addressed by the cost estimator upon conclusion of the estimation procedure. This is shown below in Figure 44. Another complimentary diagram shows a similar 'best practices' criteria list for the James Webb Space Telescope (JWST), again with all qualitative measure of achievement for each category formulated based on the GAO assessment of NASA data.

At early program phase, it is difficult to specifically quantify confidence in a cost estimate. At a later program stage, for example a clear Phase A, when a cost estimate is based on data which is defined and frozen, quantification is possible. In 2009, NASA introduced a joint confidence level (JCL) analysis standard, which is an integrated quantitative probability uncertainty analysis that requires the project to combine its cost, schedule and risks [31]. The results then indicate the probability on whether a project's cost will be equal to or less than targeted cost, and that the schedule will be equal to or less than the targeted finish [213]. A JCL can only be conducted when clear inputs to the four categories of schedule, cost, risk and uncertainty of a project can be calculated [139].

For the SpaceLiner case study, and indeed for all programs at an early phase, JCL application is premature, and as such, quantitative cost estimate assessments are used. This Thesis has been compiled with a consistent and stringent focus on satisfying all criteria as pointed out in the best practices examples found in Figures 44 and 45.

Figure 44: Cost estimate review checklist from RAND Project AIR FORCE Guidelines and Metrics for Accessing Space System Cost Estimates report [65]

Completeness and consistency	Are all pertinent costs included in the estimate?
	Have the latest available actual costs been used to develop or check the estimate?
	Is the scope of the cost estimate clearly defined and consistent with the directed program?
	Is the estimate consistent with the latest schedule estimate?
	Has the estimate been summarized by appropriation and fiscal year?
	Are the OSD inflation indexes applied properly?
Reasonableness	Are the methods used to estimate each cost element appropriate?
	Does the estimate provide a coherent, organized, and systematic presentation of methodologies?
	Is the estimate developed from proper historical costs using accepted methods or a logical approach?
	Are the assumptions, engineering judgment rationale, and estimating relationships (including cost improvement slopes, production rates, usage rates, and so on) clearly stated and reasonable?
Documentation	Is the documentation clear and complete?
	Are the latest actual data values and sources clearly shown in the documentation?
	Can the methods used to develop the estimate be easily followed and replicated?

Characteristics	Best Practices Criteria	Overall assessment
Comprehensive	Include costs of the program over its full life-cycle, provide a level of detail appropriate to ensure that cost elements are neither omitted nor double-counted, and document all cost-influencing ground rules and assumptions.	◕
Well documented	Be supported by detailed documentation describing: • the purpose of the estimate, • the program background and system description, • the scope of the estimate, • the ground rules and assumptions, • all data sources, • estimating methodology and rationale, and • the results of the risk analysis. This documentation should show how the data used to derive the estimate can be traced back to, and verified against, their sources.	◑
Accurate	Be based on an assessment of most likely costs (adjusted for inflation), documented assumptions, and historical cost estimates and actual experiences on other comparable programs. Be checked for accuracy, double counting, and omissions. Be updated to reflect any changes.	◑
Credible	Discuss any limitations of the analysis because of uncertainty, or biases surrounding data or assumptions. Risk and uncertainty analysis should be performed to determine the level of risk associated with the estimate. Have results that are cross-checked against an independent estimate.	◑

● Met
◕ Substantially met
◑ Partially met
◔ Minimally met
○ Not met

Figure 45: Example of best practices criteria used to qualitatively assess the confidence of NASA's JWST by GAO [213]

5 THESIS FINAL CONCLUSIONS

“To most people, the sky is the limit. To those who love aviation, the sky is home.” – Anonymous

In summary, this Thesis outlined extensive cost engineering theory addressing the challenge of justifiable and representative cost estimation for a large scale, complex, international and unprecedented space program during the early program phase. During the process, CEMs suitable for early phase application were determined, and current models and tools were then reviewed, and outlined for specific program phases. The parametric approach was identified as being most suitable for early phase application.

The Amalgamation Approach was proposed and described, drawing from the crucial redundancy aspect usually inherent to mechanical hardware, and especially important for life-critical systems. Since cost is a criterion with the potential to make or break a new program, then cost can also considered here as a ‘life critical system’ within context of the program’s life – in which case cost estimation should also incorporate a redundancy aspect from the start of cost estimation formulation. Hence, the redundancy concept was transferred and applied to the cost estimation domain through the AA_{MAC} formulation of multiple (three) independent cost estimates in an iterative process, with the resulting cost estimates produced as a synthesis of three results. The aim here was to determine the program development (Phase C) and production (Phase D) cost ranges for the chosen case-study vehicle.

Three models and tools were selected to implement within the AA_{MAC} framework. These were the parametric TransCost, and the prominent 4cost *aces* and PRICE-H commercial models. A relevant and current industry case-study, the SpaceLiner, was then selected to demonstrate the innovative AA_{MAC} cost estimation method.

Two of the three classical program cost categories were the main target of this Thesis – the non-recurring development and the recursive production cost, with software efforts for both phases being omitted at this early stage of the case-study development, due to insufficiently defined specifications and a lack of SW requirements. Operations were also considered mainly at a qualitative level, although a very preliminary case-study operational scenario was also discussed.

In order to facilitate for the cost estimate, essential programmatic considerations were actualised in context of the SpaceLiner case-study. A detailed WBS was established, along with a baseline program schedule, both of which were consequently used as the essential backbone for the cost estimation.

Two key tools were programmed within the context of this Thesis work. The latest available TransCost 82. Model (Revision 4) was programmed into a dedicated TransCost Excel interface to allow for model testing and application. In addition, the Amalgamation Approach Interface (AAInT) tool was also created to support the AA_{MAC} theory and its application to the chosen SpaceLiner case-study. Through the development and application of AA, baseline cost estimates for the classical two categories of development and production program costs for a selected, real-life and current case-study, were calculated.

The proposed AA_{MAC} improves the confidence level associated with the final cost estimation range as it provides a comparative baseline form several costs, allowing the cost expert to identify and inconsistencies, and maximally justify and defend the final cost estimation result. Through use of the innovative and advanced AA_{MAC}, cost results were deemed to be in the medium-high confidence interval.

5.1.1 Summary of Results

The theory of cost engineering, and the more niche cost estimation function was very specifically addressed in this Thesis. The Amalgamation Approach was proposed and implemented as a means to immunise a single cost estimate with an internal and inherent redundancy check, and thus an increased confidence in contrast to a single cost estimate result. The AA_{MAC} development and production costs, as synthesised from three independent results and from multiple extensive analyses as intermediary steps to arrive at the final range, result in a more defensible, justifiable and consequently representative cost estimation. The overall program management function was also costed using an EBU approach combined with the EJ and analog CEMs. The summary of all results is shown below in Table 77.

Table 77: Summary of AA development and production results

B€ (2013 e.c.)	TransCost	4cost	PRICE
SpaceLiner Case-study Development	**31.4**	**28.0**	**26.7**
SpaceLiner Case-study Production **(∑)**	**375.8**	**208.0**	**237.7**
SpaceLiner Case-study Production **(ave. unit cost)**	**0.75**	**0.47**	**0.48**

From this, and applying AA theory, the final development and production cost ranges can be deduced, as is summarised per cost category in the sub-chapters below.

5.1.1.1 Case-study Development Costs Summary

AA results for the development Phase C of the SpaceLiner case-study yielded a cost range between 26 and 31 B€ (2013 e.c.), although firmly centered around the 28 B€ mark. At a top program level, the result congruency was very good, especially for such an early program phase as the case-study vehicle (±20%). On a lower level, more apparent cost variations were evident, although as stipulated, these would be the result of differences in AA model and tool inputs, definitions and internal model workings and mechanics. In addition, model user specificity and EJ bias would have contributed to variations. The higher cost of the TransCost model can also be attributed to the fact that the model is dedicated to orbital vehicles, while the case-study vehicle is a suborbital craft. Additionally, TransCost inherently also addresses software costs, which were not considered by the 4cost *aces* and PRICE tool calculations. A medium-high confidence range could be assigned to the development cost estimate.

5.1.1.2 Case-Study Production Costs Summary

The production costs, also using the AA theory and AA_{MAC} mode varied within the range from the highest TransCost figure of 376 B€, through to 238 B€ (PRICE) and 4cost *aces* 209 B€ (2013 e.c.) for total SpaceLiner case-study program costs. Complementing the total production costs were the average unit costs, calculated to be 752 M€ (TransCost), 475 M€ (PRICE) and 466 M€ (4cost), including an additional 20% margin for the commercial tools to allow for a relative comparison with TransCost, which already incorporates this margin.

Here, while an excellent congruence of results was observed between the two commercial models of PRICE and 4cost *aces*, the consistently (approximately 60%) higher TransCost model results indicated an increased level of uncertainty given the significant delta to both AA-employed models, as well as based on the theoretical and analytical justification for the considerable deviations. The cause of this uncertainty was primarily stemmed from the need to make necessary (and fully documented) assumptions to allow for the TransCost production cost estimate to be compiled in the first place. These assumptions were necessary to address that no TransCost CERs could be identified to sufficiently describe two of the four case-study elements to be produced - the SLO and SLB. As such, an equal and un-weighted average values were derived from two other CERs in each instance, forming a hybrid production cost estimate for the SLO and SLB components. Given that one of the two CERs results in highest production costs of all CERs contained in the TransCost manual, would also explain the considerably greater

TransCost production cost estimation results, indicative that they are not sufficiently representative of expected SpaceLiner production costs.

Total program production of 500 units was therefore calculated to lie within the 210 – 280 B€ range, while the average unit cost range was found to be between 465 M€ and 490 M€ at 2013 economic conditions. Furthermore, as was discussed and demonstrated theoretically in Chapter 4.12, the qualitative medium-high confidence range could be justifiably attributed to the above cost estimation figures and derived cost ranges.

5.1.1.3 Case-study Sensitivity Analysis Summary

Sensitivity analyses were conducted within the scope of both development and production cost estimations across all three AA_{MAC} models.

For the TransCost model, development cost sensitivities were performed between the complexity factors for the development standard (f_1), technical quality (f_2), as well as the team experience (f_3), as shown in Chapter 4.9.1.3. The purpose of the sensitivities was predominantly to establish a development cost range internal to the TransCost model estimation itself, with a development cost range between 31 and 39 B€ (at 2013 e.c.) deduced. Additionally, it was seen that increasing the technology development factor and reducing team experience, while increasing the number of engine test firings, increased the overall development cost by roughly 25% given the particular combination of complexity increments. For production costs, during the course of the estimation process, the uncertainty associated with the TransCost model was deemed too high due to assumptions which needed to be made. As such, the commercial tools were relied upon to derive a more certain production cost range.

For the commercial tools, given that results were highly congruent between the PRICE and 4cost *aces* tools, sensitivity analyses were performed using the 4cost *aces* tool only for both development and production costs. Development sensitivities were performed for the initial 4cost *aces* baseline costs, increasing prototype quantity and reducing team experience. As expected, it was shown that the prototype quantity constitutes a significant cost driver for the development Phase C, with a 36% and 56% delta to the 5-prototype model baseline for a prototype increase of 8 and 10 models respectively. A decrease in team experience during the development process by one logical model unit also increased the baseline cost by roughly 10% at each iteration, although this was not as pronounced as for the prototype quantity increase.

For the production cost sensitivities, the 4cost *aces* model was once again used to vary three key production process variables in Chapter 4.10.9; the LC values, the production quantity, and the engine reusability. Total program production costs and consequent average unit costs, as well as TFU values were calculated and contrasted with baseline values. While LC sensitivity results were surprising, a deeper analysis into the 4cost *aces* model mechanics revealed the complex albeit very logical interrelations and influence of key quantity, LC and TFU cost parameters on one another. The LC sensitivity analysis also highlighted that LC theory would need to be considered at a deeper level for the SpaceLiner vehicle case-study in the future, considering not only a fixed LC value throughout the production process, but a varying one, depending on production quantities.

Variance of production quantities logically revealed a cost increase to an increased production amount, and a decrease, with a decreased quantity produced. Finally, enhanced engine reusability also impacted the total production costs in a positive way, reducing them by 15% through a doubling of engine lifetime.

5.1.1.4 Case-study Operations & Ground Costs Summary

Within this Thesis, the operations and grounds (O&G) costs are presented and outlined in a theoretical way. With respect to the SpaceLiner case-study vehicle, operational and ground cost categories, like basic infrastructure, potential configuration and geographical locations of launch and landing sites based on the anticipated vehicle requirements are outlined in a qualitative and categorical way. Finally, a basic framework of operational activities is established and a preliminary breakdown of costs which encompass the O&G segment as tailored to the SpaceLiner case-study, are furthermore presented in Appendix J. The importance of expanding the current status of knowledge, definitions, and mission requirements as future work in order to mature this essential category of processes, requirements and associated costs, is also highlighted.

5.1.2 Future work

Much room for future work and development of the cost engineering and estimation domains lies in the years ahead. Given the constantly evolving and dynamically changing space industry and its environment, the function of a cost engineer within a project, and within the wider space industry, never ceases.

This Thesis establishes the fundamental baseline for cost estimation practices for unprecedented, large-scale and complex space programs in the early development phase. The theory is then demonstrated within the context of an actual industry case-study, the SpaceLiner. For this vehicle, which bridges the aviation and space industries, a parametric TransCost Excel tool was programmed, and the model itself extensively tested. A WBS was also established, based on which the newly proposed AA was applied to derive a baseline cost estimate for the hardware elements and components through the phases of development and production. As such, a strong and justified baseline of the cost estimation framework was established. Future work is therefore required both within the cost estimation domain, as well as, more specifically, for the SpaceLiner case-study example. Some key points are outlined below.

5.1.2.1 Amalgamation Approach

With respect to the proposed innovative Amalgamation Approach (including three modes of application) as a tool to maximise cost estimate representativeness and reduce uncertainty, it would be interesting to implement this approach alongside the classical, predominantly single-means cost estimate approach. Towards the end of the program, the results for both approaches should be confirmed and analysed, to determine whether AA results in an increased representativeness of the results, and to quantify this. Furthermore, it would then be relevant to implement this comparison across several large programs, and again, obtain quantitative measures of the AA method and any benefits thereof. Such a comparison, however, was beyond the scope of this Thesis work in terms of scale, and time. The duration of just the development phase of the complex, large and multi-faceted programs such as those addressed within this Thesis, already spans frequently over decades, and as such, is well beyond the scope of a single PhD work.

5.1.2.2 SpaceLiner Development & Production Cost Estimation

A strong baseline cost range has been established, supported by the amalgamation approach. Nevertheless, as the SpaceLiner case-study progresses through to a maturity where technical specifications are finalised and frozen, the cost estimate will need to be modified, and updated to reflect all the new information. In addition, in line with advancing program phases, the CEMs for the models and tools being used to compile the estimates, will also need to be updated appropriately. For example, the EBU CEM would be more applicable at a later stage, with a significant reduction of risk associated with the estimate itself if it is performed correctly, and in line with cost engineering principles.

Additionally, for the production costs in particular, as a clearer and more defined program schedule evolves, the production costs would need to be reassessed to reflect the timing element in terms of batch production. In addition, and as already thoroughly discussed in Chapters 4.10.1, 4.10.8.2 and 4.10.9.1, LC theory should then be fine-tuned, with respect to distinguishing between unique LCs for the initial batch of units produced, and consequently for those units produced in a set serial context. Here, a distinction should be made between elements with a production quantity of 500 (SLO, SLB and SPC) and those with a production quantity in the high thousands (SLME). The SLME with its significantly higher rate of production, would exhibit significantly less learning than the simplified and constantly assumed 85% due to higher quantities produced and thus higher level of automatisation.

5.1.2.3 Software Costs

In this Thesis, space hardware development and production costs were the focus. As such, software costs were excluded due to the specific nature of the cost calculation themselves, coupled with currently incomplete SW specifications and requirements for the SpaceLiner case-study. It is fully conceded that for a full program, software costs constitute an essential part of the function and are therefore critically important, and as such, the established WBS incorporates elements to address and later include these costs at a later stage. However in this Thesis the dedicated subset of software costs could not be calculated given the current early status of the SpaceLiner case-study. Furthermore, space hardware cost assessment is such an own, specific and extensive topic, and in excluding software costs in this Thesis, the integrity of the existing cost estimate is maintained.

For future assessment of software development and production costs, various separate and dedicated methods are available for application. These are as diverse and varied as the different CEMs for hardware, honing in on space hardware, and, in accordance with Boehm's compilation of models [27] include COCOMO, Putnam, Doty and Jensen models [202]. A software module from PRICE Systems, PRICE-S, is also available, as well as a software estimation ability from

4cost *aces*. However, all the latter require basic software inputs to reflect requirements, function and complexity of software.

5.1.2.4 SpaceLiner Operation & Ground Costs

Within this Thesis, the operations and ground costs (WBS elements 6000 and 7000) were discussed within a more qualitative context, although a preliminary consideration of some ground infrastructure and resources has also been considered [111]. As the SpaceLiner concept matures, and a clearer idea of trajectories evolves, then a more specific and dedicated analysis of these two WBS elements will need to be performed. Based on the results, a cost estimate of the proposed infrastructure for ground, as well as the operations procedures and regime, can also be compiled.

5.1.2.5 Sensitivity Analyses

Although some basic sensitivity analyses were presented in this Thesis, it would be interesting to conduct further sensitivities and trades to determine the most desirable cost scenario given various tradeoffs. In addition, the 4cost *aces* tool was used to conduct sensitivity analyses. It would be furthermore relevant to pursue sensitivity analyses using the other AA_{MAC} models and tools, allowing for contrasting of sensitivity results amongst them, too.

A proposed matrix of interesting trades is shown below in Table 78 Other than the baselines, the values shown in **bold** have already been addressed in this Thesis using the 4cost *aces* tool. In the table, the **ind* superscript refers to the AA commercial tool respective indices. For example, in the context of the applied 4cost *aces* tool, the *Production Environment* sensitivity refers to the 4cost *aces* specific variable *ENVIRD* input which describes the context and industry of the development effort (see Figure 33). The baseline value, as outlined in Chapter 4.9.3, was taken to be 2.0, with reasonable increments for this value being defined by the 4cost *aces* model as being 0.1. Therefore the table-indicated sensitivity suggestions of $+1^{ind}$; -1^{ind}; -2^{ind} thus refer to

ENVIRD values of 2.1 and 1.9 values of the ENVIRD 1.8 respectively. Since different models and tools may have different incremental cadences a ± is used to indicate direction of sensitivity variation of interest.

Table 78: Potentially interesting sensitivity analyses for the SpaceLiner case-study

Variable	Sensitivity Value
Mass	**nominal** (baseline); +10%; +20%; +30%
Prototype Quantity	**5** (baseline); 6; 7; **8**; 9; **10**
Team Experience	***ind.*** (baseline); **-1^{ind}; -2^{ind};** -3^{ind}
Production Quantity	**500** (baseline); 30; 100; **300**; 800; **850**; 1000
Development Environment	***ind.*** (baseline); $+1^{ind}$; -1^{ind}; -2^{ind}
Production Environment	***ind.*** (baseline); $+1^{ind}$; -1^{ind}; -2^{ind}
SpaceLiner SLO/SLB/SPC Reusability	**150 times** (baseline); 100; 250; 500;
SpaceLiner SLME Reusability	**25 times** (baseline); **50**; 75; 100;
Learning Curve	**85% Crawford LC** (baseline); *uniquely varied for quantity and specific element*

Like the tendency for costs to increase as a space program progresses, it is also known that mass increases. Furthermore, the two effects are often related. An increase in mass would influence costs, both development and production. Sensitivity analyses for the mass variable would therefore be interesting. Prototype model quantity variation significantly influences development costs as has been shown in this Thesis, so a wider range of sensitivities would also be beneficial. Team experience and the environments for development and production are also influential parameters on cost and should be studied further.

Finally the production quantity delta, including variances in the reusability capability of components, directly drives the recurring production cost. Linked closely with learning curve theory for production, as already discussed in Chapter 5.1.2.2, uniquely developing and implementing varying LC values for various production quantities and specific elements, would also be interesting.

In addition, modeling production quantities which integrate the production schedule in terms of batch numbers, frequency of production as well as different reusability capabilities for the SLO, SLB, and SPC should be attempted in the future. This step, however, would hinge on an unambiguous and clearly defined production schedule.

5.1.2.6 WBS & Program Schedule Iterations

A baseline program schedule in conjunction with a detailed four level WBS were derived and presented in this Thesis (Chapters 4.1.1 and 4.1.2). The WBS elements are the outcome of activities that take time to complete. As such, it is important to respect the underlying relationships of time precedence among them [175], highlighting the high level of interdependency between a WBS and a program schedule. In their baseline formulation, many assumptions were made to bridge any gaps inherent to a highly complex concept still in an early program phase, which is still developing and constantly changing. However, as any project matures, and more information becomes available, both the WBS and schedule can and should undergo respective iterations and modifications to be reflective of changes and progress. Such changes are especially pronounced and can be significant during the early program phases, as they also occur at a lower cost. The importance of developing a program schedule consistently with the project's objectives, working at the lowest available WBS level, is outlined by Shishko, through six steps to achieve congruency and concord between the WBS and a network schedule which illustrates activities, their interdependencies and duration, as well as key product milestones. Such a detailed network schedule should also be compiled for the SpaceLiner case-study as the concept matures.

5.1.2.7 Financing

Within context of cost engineering and financial considerations for the case-study, as is indeed the case for any large-scale, complex program, the financing element is a highly interesting and crucial consideration. For government programs, the funding comes from the federal sources. However for entities who operate independently of government funding, investment must be sought elsewhere. In the space industry, it is well known and documented that many cost overruns are the direct result of complex governmental structures and cost-consuming interfaces. The recent emergence and flurry of the establishment of privately funded spin-off or independent companies, however, offers attestation to the fact that the smaller, leaner and more efficient internal company structures lend themselves to more efficient processes and operations. The most prominent example of such a company would arguably be SpaceX, who are reportedly achieving unprecedented cost-savings across their development, production and operational activities [193] would be the prime and most current example of such an organisation.

While it is beyond the scope of this work to delve into possible financing sources , it is nevertheless very important to mention the various potential financing sources and schemes relevant to a concept such as the SpaceLiner case-study. Of course the type of financing source and arrangement hinges on the nature of the space program. Sources of finances for the non-recursive research and development Phases A to C as well as the recursive production and operational Phase D might come from the venture capital market, or from shareholder investment, private equity funds through inclusion in risk capital, or bank loans. For the development phase, financial support could also be sought from R&D agencies [122]. An interesting financing structure to explore here would also be the Public-Private Partnership (PPP) structure where a strategically phased mix of public and private funds are combined. Public funds support early investment while still involving the private sector in design and development activities. The resulting operational product is then carried further by private investors [148].

5.1.2.8 Budget, Resource Planning

Within this Thesis, costs were considered at a very top level, using parametric cost estimation, which also assumes an average WYr cost for personnel within the aerospace industry provided in the TransCost manual [102]. As the program matures, the EBU CEM also becomes increasingly more appropriate for cost estimation in the later program phases, and costs must be further broken down and looked at a lower level from a budgeting and resource planning context. This is also reflective of a sufficiently detailed and advanced program definition and status. Such a baseline budget is developed from the WBS and program schedule and should be addressed systematically. Specifically, the project's work force and other resource needs should be combined with the appropriate workforce rates and other financial and programmatic factors to obtain cost element estimates, which, as outlined by Shishko [175], include:

- Direct labour costs
- Overhead costs
- Other direct costs (travel, data processing etc.)
- Subcontract costs
- Material costs
- General and Admin costs
- Cost of money (interest payments, if applicable)
- Fee (if applicable)
- Contingency

After costs have been baselined, it is then important to impose measures of cost control, including project cost and schedule status reporting. Another vital aspect here is then cost and schedule risk planning, and a function of high project level budgeting and resource planning should incorporate for allowance of adequate contingency funds to cover any unforeseen events.

5.1.2.9 Risk Assessment & Planning

The risk assessment presented and discussed in this Thesis (Chapters 4.1.11 and 4.12) was incorporated at a very basic and qualitative level due to the early program phase, as well as still crystallising program details for the chosen SpaceLiner case-study. At this early stage mitigation of financial risks of the SpaceLiner project has been achieved through a proposed cost margin of 20 percent. As with any maturing program, and in line with the four step risk assessment and mitigation process described in Chapter 4.1.11 and shown in Figure 18, risk assessment and consequent mitigation strategy would require a more detailed, in-depth and systematic approach when the technical and programmatic assumptions underpinning this work and case-study addressed in this Thesis are replaced with mature, fixed data, and when specifications and requirements are clearly decided upon and set. Risk avoidance and work around strategies should then be developed, alongside with a translation of the risk into more precise cost terms, which should be factored into the budget and resource planning component of the program as explained in Chapter 5.1.2.8. Since the areas of schedule, cost and risk assessment are all linked and interdependent, at a more mature stage, a method such as the joint confidence level (JCL) analysis standard adopted by NASA and briefly discussed in Chapter 4.12, could be implemented.

Appendix A – SpaceLiner WBS Breakdown

The WBS, as introduced in Chapter 4.1.1, and as shown in Figure 12, for the development Phase C, at two levels of detail, is expanded to one lower level of detail here. The production WBS is almost identical, and is therefore omitted.

It must also be noted that although the operations and ground segments were not considered in terms of quantified costs, the concept for each of these critical work packages and elements of overall program configuration, were nevertheless considered and components established at a basic level. For the operational scenario, this is only very preliminary, and assumes two key airport locations, being in Europe, and Australia, in accordance with the SpaceLiner case-study established reference trajectory and route.

Table 79: Established WBS for the SpaceLiner PMO element 1000

C - 1000	SpaceLiner OVERALL SYSTEM
PM	1100 Overall Project Management Office (PMO)
	1110 Program Management (PM)
	1120 Systems Engineering & Design Management
	1130 Product Assurance Management
	1140 Project Control Management
	1150 Documentation & Configuration Management
	1160 Project Risk Management
	1170 Logistics & Transportation Management
	1180 Communication& Reporting
	1190 External Support
Other*	1200 Total Project Travel inc. all sub-systems

**the travel component is only relevant for the development phase, and as such, is not shown on the top level WBS schematic presented in Figure 12*

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Table 80: Established WBS for the SpaceLiner SLO element 2000

C - 2000	SpaceLiner ORBITER (SLO)
PM	*2100 SLO Project Management Office (PMO)*
	2110 Project Management (PM)
	2120 Project Control Management (PCM)
	2130 Systems Engineering & Design Management (SEDM)
	2140 Product Assurance Management (PAM)
	2150 Documentation & Configuration Management (DCM)
	2160 Project Risk Management (PRM)
HW	2200 Propulsion (SLME)
	2210 Engine Assembly
	2220 Engine Support Structure
	2230 Feed System
HW	2300 Structures & Mechanics
	2310 Main Tanks Assembly
	2320 Upper I/F Adaptor
	2330 Lower I/F Adaptor
	2340 SLO Equipment Bay
	2350 Body Flaps & Actuators
	2360 Landing Gear
HW	2400 TPS/TC
	2410 Thermal Protection
	2420 Active Thermal Elements
SW	*2500 Flight Control System*
	2510 ADCS
	2520 RCS
	2530 Flight Control Software
HW	2600 Avionics
	2610 On-board Computer (OBC)
	2620 Communications Equipment
	2630 Health Monitoring
HW	2700 Power & Housekeeping
	2710 Batteries
	2720 Converters
	2730 Cabling & Connectors
	2740 Sensors
AIT	2800 SLO AI&T
	2810 AIT Planning & Management
	2820 MU/BMM

	2830 STM *2840 EQM* *2850 PFM 1* *2860 PFM2*

Table 81: Established WBS for the SpaceLiner SLB element 3000

C - 3000	SpaceLiner BOOSTER (SLB)
PM	*3100 SLB Project Management Office (PMO)*
	3110 Project Management (PM) *3120 Project Control Management (PCM)* *3130 Systems Engineering & Design Management (SEDM)* *3140 Product Assurance Management (PAM)* *3150 Documentation & Configuration Management (DCM)* *3160 Project Risk Management (PRM)*
HW	3200 Propulsion
	3210 Engine Assembly *3220 Engine Support Structure* *3230 Feed System*
HW	3300 Structures & Mechanics
	3310 Main Tank Assembly *3320 Upper I/F Adaptor* *3330 Lower I/F Adaptor* *3340 Body Flaps & Actuators* *3350 Landing Gear*
HW	3400 TPS/TC
	3410 Thermal Protection *3420 Active Thermal Elements*
SW	*3500 Flight Control System*
	3510 ADCS *3520 RCS* *3530 Flight Control Software*
HW	3600 Avionics
	3610 On-board Computer (OBC) *3620 Communications Equipment* *3630 Health Monitoring*
HW	3700 Power & Housekeeping
	3710 Batteries *3720 Converters* *3730 Cabling & Connectors*

	3740 Sensors
AIT	3800 SLB AI&T
	3810 AIT Planning & Management *3820 MU/BMM* *3830 STM* *3840 EQM* *3850 PFM 1* *3860 PFM2*

Table 82: Established WBS for the SpaceLiner SPC element 4000

C - 4000	SpaceLiner PASSENGER CABIN / RESCUE CAPSULE (SPC)
PM	*4100 SPC Project Management Office (PMO)*
	4110 Project Management (PM) *4120 Project Control Management (PCM)* *4130 Systems Engineering & Design Management (SEDM)* *4140 Product Assurance Management (PAM)* *4150 Documentation & Configuration Management (DCM)* *4160 Project Risk Management (PRM)*
HW	4200 Propulsion (CSM capsule solid motors)
	4210 Engine Assembly *4220 Engine Support Structure*
HW	4300 Structures & Mechanics
	4310 Main Body Assembly *4320 Body Flaps & Actuators* *4330 Windows*
HW	4400 TPS/TC
	4410 Thermal Protection *4420 Active Thermal Elements*
SW	*4500 Flight Control System*
	4510 ADCS *4520 RCS* *4530 Flight Control Software*
HW	4600 Avionics
	4610 On-board Computer (OBC) *4620 Communications Equipment* *4630 Health Monitoring*
HW	4700 Power & Housekeeping
	4710 Batteries *4720 Converters*

	4730 Cabling & Connectors *4740 Sensors*
HW	4800 Life / Passenger Support Systems
	4810 Climate Control *4820 Seats* *4830 Interior* *4840 Parachutes* *4850 Inflight Information /Communication System*
AIT	4900 SPC AI&T
	4910 AIT Planning & Management *4920 MU/BMM* *4930 STM* *4940 EQM* *4950 PFM 1* *4960 PFM2*

Table 83: Established WBS for the SpaceLiner software and AIT element 5000

C - 5000	AIT
	5100 PMO
	5200 PROTO 01- Mockup & Breadboard Model (MU/BMM)
	5300 PROTO 02 - Structure & Thermal Model (STM)
	5400 PROTO 03 - Engineering & Qualification Model (EQM)
	5500 PROTO 04 - Flight Model 1 (PFM 1)
	5600 PROTO 05 - Flight Model 2 (PFM 2)

Table 84: Established WBS for the SpaceLiner ground segment element 6000

C - 6000	GROUND SEGMENT
PM	6100 PMO
	6200 Launch Pad
	6210 Europe *6220* Australia
	6300 Landing Runway
	6310 Europe (prime) *6320* Europe (b/u) *6330* Australia (prime) *6340* Australia (b/u)

6400	Passenger Buildings
6410	Europe (prime)
6420	Europe (b/u)
6430	Australia (prime)
6440	Australia (b/u)
6500	Ground Control Stations
6510	Europe (prime)
6520	Europe (b/u)
6530	Australia (prime)
6540	Australia (b/u)
6600	Booster In Air Capture
6610	Europe
6620	Australia
6700	Maintenance & Refurbishment Facilities
6710	Europe
6720	Australia
6800	Ground Support Equipment (GSE)
6810	*Mechanical (MGSE)*
6811	SLO MGSE
6812	SLB MGSE
6813	SPC MGSE
6820	*Electrical GSE (EGSE)*
6821	SLO EGSE
6822	SLB EGSE
6823	SPC EGSE
6900	Ground Transport Infrastructure & Support
6910	*Passengers*
6920	*Vehicles / Equipment*
6921	Europe (prime)
6922	Europe (b/u)
6923	Australia (prime)
6924	Australia (b/u)

Table 85: Established WBS for the SpaceLiner operations/flight support element 7000

C - 7000	FLIGHT SUPPORT/OPERATIONS SEGMENT	
	7100	PMO
	7200	Flight Control
	7210	*Ascent flight control*
	7211	SLO
	7212	SLB
	7220	*Return flight control*
	7221	SLO
	7222	SLB
	7230	*Range Safety*
	7300	Training, Qualification, Education
	7310	*Crew, personnel & staff*
	7311	Europe
	7312	Australia
	7320	*Passengers*
	7321	Europe
	7322	Australia

Appendix B – SpaceLiner Model Matrices

Table 86: SLB Model Matrix qualitatively showing case-study prototype philosophy described in Chapter 4.1.3

	Type →	Test Models			Prototypes		
	Proto Fraction →	*paperwork*	0.5	0.8	1.0	1.2	1.2
	Model Code →	00	01	02	03	04	05
D-3000 SLB (Booster)	WBS Element ↓	DES	MU/BBM	STM	EQM	PFM 1	PFM 2
Propulsion (SLME)	**3200**	100	x	x	x	x	x
Engine Assembly	*3210*	100	x	x	x	x	x
Engine Support Structure	*3220*	100	x	x	x	x	x
Feed System	*3230*	100	x	x	x	x	x
Structures & Mechanics	**3300**	100	x	x	x	x	x
Main Tank Assembly	*3310*	100	x	x	x	x	x
Upper I/F Adaptor	*3320*	100	x	x	x	x	x
Lower I/F Adaptor	*3330*	100	x	x	x	x	x
Body Flaps & Actuators	*3340*	100	x	x	x	x	x
Landing Gear	*3350*	80	n/a	x	x	x	x
TPS/TC	**3400**	100	x	x	x	x	x
Thermal Protection	*3410*	100	x	x	x	x	x
Active Thermal Elements	*3420*	100	n/a	x	x	x	x
Flight Control System	**3500**	80	n/a	x	x	x	x
ADCS	*3510*	80	n/a	x	x	x	x
RCS	*3520*	100	n/a	x	x	x	x
Flight Control Software	*3530*	100	n/a	n/a	x	x	x
Avionics	**3600**	80	x	x	x	x	x
On-board Computer (OBC)	*3610*	COTS	n/a	n/a	x	x	x
Communications Equipment	*3620*	COTS	n/a	n/a	x	x	x
Health Monitoring	*3630*	80	x	x	x	x	x
Power & Housekeeping	**3700**	100	n/a	n/a	x	x	x

Batteries	*3710*	COTS	n/a	n/a	x	x	x
Converters	*3720*	80	n/a	n/a	x	x	x
Cabling & Connectors	*3730*	80	n/a	n/a	x	x	x
Sensors	*3740*	COTS	n/a	n/a	x	x	x
SLB AI&T	**3800**	100	n/a	X	x	x	x

Table 87: SPC Model Matrix qualitatively showing case-study prototype philosophy

	Type →	**Test Models**			**Prototypes**		
	Proto Fraction →	***paperwork***	**0.5**	**0.8**	**1.0**	**1.2**	**1.2**
	Model Code →	**00**	**01**	**02**	**03**	**04**	**05**
D-4000 SPC (Cabin/Rescue Capsule)	**WBS Element ↓**	**DES**	**MU/BBM**	**STM**	**EQM**	**PFM 1**	**PFM 2**
Propulsion (SREs)	**4200**	100	x	x	x	x	x
Engine Assembly	*4210*	80	x	x	x	x	x
Engine Support Structure	*4220*	100	x	x	x	x	x
Structures & Mechanics	**4300**	100	x	x	x	x	x
Main Body Assembly	*4310*	100	x	x	x	x	x
Body Flaps & Actuators	*4320*	100	x	x	x	x	x
Windows	*4330*	100	x	x	x	x	x
TPS/TC	**4400**	100	x	x	x	x	x
Thermal Protection	*4410*	100	x	x	x	x	x
Active Thermal Elements	*4420*	100	n/a	x	x	x	x
Flight Control System	**4500**	100	n/a	x	x	x	x
ADCS	*4510*	100	n/a	x	x	x	x
RCS	*4520*	100	n/a	x	x	x	x
Flight Control Software	*4530*	100	n/a	n/a	x	x	x

Avionics	**4600**	100	x	x	x	x	x
On-board Computer (OBC)	*4610*	COTS	n/a	n/a	x	x	x
Communications Equipment	*4620*	80	n/a	n/a	x	x	x
Health Monitoring	*4630*	80	x	x	x	x	x
Power & Housekeeping	**4700**	100	n/a	n/a	x	x	x
Batteries	*4710*	COTS	n/a	n/a	x	x	x
Converters	*4720*	80	n/a	n/a	x	x	x
Cabling & Connectors	*4730*	80	n/a	n/a	x	x	x
Sensors	*4740*	COTS	n/a	n/a	x	x	x
Life / Passenger Support Systems	**4800**	100	n/a	x	x	x	x
Climate Control	*4810*	80	n/a	x	x	x	x
Seats	*4820*	100	n/a	n/a	x	x	x
Interior	*4830*	80	n/a	X	x	x	x
Parachutes	*4840*	100	n/a	n/a	x	x	x
Inflight Information /Communication System	*4850*	COTS	n/a	x	x	x	x
SPC AI&T	**4900**	100	n/a	x	x	x	x

APPENDIX C – TRANSCOST WORK YEAR COSTS [102]

	Year	USA (US $)	Europe (ECU/AU)	Japan (Million ¥)	% increase based on USA	% increase based on EUROPE	% increase based on JAPAN
1	1960	26000	18000				
2	1961	27000	18900		0.04	0.05	
3	1962	28000	20000		0.04	0.06	
4	1963	29000	21000		0.03	0.05	
5	1964	30000	22000		0.03	0.05	
6	1965	31000	23200		0.03	0.05	
7	1966	32300	24400		0.04	0.05	
8	1967	33200	25700		0.03	0.05	
9	1968	34300	27400		0.03	0.06	
10	1969	36000	29100		0.05	0.06	
11	1970	38000	31000		0.05	0.06	
12	1971	40000	33050		0.05	0.06	
13	1972	44000	35900		0.09	0.08	
14	1973	50000	38700		0.12	0.07	
15	1974	55000	43600		0.09	0.11	
16	1975	59500	50000		0.08	0.13	
17	1976	68000	55100		0.13	0.09	
18	1977	72000	60500		0.06	0.09	
19	1978	79700	65150		0.10	0.07	
20	1979	86300	71800		0.08	0.09	
21	1980	92200	79600		0.06	0.10	
22	1981	98770	86700		0.07	0.08	
23	1982	105300	92400		0.06	0.06	
24	1983	113000	98300		0.07	0.06	
25	1984	120800	104300	14.6	0.06	0.06	
26	1985	127400	108900	15.2	0.05	0.04	0.04
27	1986	132400	114350	15.8	0.04	0.05	0.04

28	1987	137700	120000	16.4	0.04	0.05	0.04
29	1988	143500	126000	17.1	0.04	0.05	0.04
30	1989	150000	133000	17.6	0.04	0.05	0.03
31	1990	156200	139650	18.1	0.04	0.05	0.03
32	1991	162500	145900	18.6	0.04	0.04	0.03
33	1992	168200	151800	19	0.03	0.04	0.02
34	1993	172900	156800	19.5	0.03	0.03	0.03
35	1994	177200	160800	20	0.02	0.02	0.03
36	1995	182000	167300	20.5	0.03	0.04	0.02
37	1996	186900	172500	21	0.03	0.03	0.02
38	1997	191600	177650	21.5	0.02	0.03	0.02
39	1998	197300	181900	22	0.03	0.02	0.02
40	1999	203000	186300	22.6	0.03	0.02	0.03
41	2000	208700	190750	23.2	0.03	0.02	0.03
42	2001	214500	195900	23.8	0.03	0.03	0.03
43	2002	222600	201200	24.4	0.04	0.03	0.02
44	2003	230400	207000	25	0.03	0.03	0.02
45	2004	240600	212800	25.6	0.04	0.03	0.02
46	2005	250200	219200	26.3	0.04	0.03	0.03
47	2006	259200	226300	26.9	0.03	0.03	0.02
48	2007	268800	234800	27.5	0.04	0.04	0.02
49	2008	278200	243600	28.2	0.03	0.04	0.02
50	2009	286600	252700	29	0.03	0.04	0.03
51	2010	296000	261000	28.9	0.03	0.03	0.00
52	2011	303400	268800	30.4	0.02	0.03	0.05
53	2012	312000	275500	31.2	0.03	0.02	0.03
54	*2013**	*320000*	*285000*	*32*	*0.03*	*0.03*	*0.03*
55	*2014**	*334893*	*299572*	*33*	**Average Value**	**Average Value**	**Average Value**
					0.046540498	0.051128871	0.028189892

**estimated values based on extrapolation of average calculated values*

APPENDIX D – TRANSCOST 8.2 COMPLEXITY FACTORS

This Appendix shows the full list of TransCost complexity factors and their values, including the full, official definitions of each. It is important to note that the information presented here graphically, is derived from the newest available handbook version to date, the TransCost 8.2 [102].

- **f_0 Systems Engineering Factor**

The f_0 complexity factor addresses systems engineering complexity in terms of stage integration for vehicles which have multiple stages, taking into account this number of stages (N). It is applicable for both development and production efforts, and is determined by the simple formula:

$$f_0 = 1.04^N \; . \qquad (A1)$$

- **f_1 Development Standard Factor**

The f_1 complexity factor addresses the development cost category, and describes program novelty - namely, the status of the current development effort with respect to other similar projects conducted in the past. Classification is then assigned a numerical factor, shown below in Table 88.

Table 88: Development standard factor classification for f_1

Development standard factor	f_1
first generation system, new technology	1.3
new technology	1.2
new design, some new technology	1.1
nominal average project	1.0
project similar to existing ones, no new technology	0.9
project very similar to existing ones, no new technology	0.7
modification of existing project	0.6
variation of existing project	0.4

- **f_2 Technical Quality Factor**

The f_2 complexity factor is applicable only to the development effort. It is not a universal factor, but influenced by the technical characteristics unique to each project. It is therefore based on relative net mass fraction, performance, or other drivers, such as the number of qualification firings required in the case of engine development. It is therefore specific to each system and component which needs to be costed.

For liquid propellant rocket engines, the f_2 factor is influenced by the number of required qualification firings, and takes on the form:

$$f_2 = 0.026 \cdot \ln(N_q)^2 \,. \qquad (A2)$$

For expendable ballistic stages and transfer vehicles as well as for reusable ballistic launch vehicles, the f_2 factor is calculated through identification of the net mass fraction (NMF), which is calculated using:

$$Net\ Mass\ Fraction\ (NMF) = k^*, \qquad (A3)$$

$$dry\ mass\ = total\ mass\ - propellant\ , \qquad (A4)$$

$$net\ mass = dry\ mass - (residuals + gases)_{cut-off} - M_{engine}, \qquad (A5)$$

$$k^* = \frac{net\ mass}{usable\ propellant\ mass}\,. \qquad (A6)$$

- **f_3 Development Standard Factor**

The f_3 complexity factor adjusts for team experience during the development phase only. This aims to capture a higher development effort resulting from program undertaking by an inexperienced team, or the more efficient execution by a team which has dealt with a similar project previously. The respective factors for this are show below in Table 89.

Table 89: Team experience factor classification for f_3

Team experience factor	f_3
No relevant experience	1.4
Few relevant experience	1.3
Largely new activities	1.2
Partially new activities	1.1
Some related experience	1.0
Single similar project	0.9
Multiple similar projects	0.8
Superior project experience	0.7

- **f_4 Learning Effect Factor**

The f_4 complexity factor is applied in production cost CERs to addresses the learning effect and consequent cost reduction seen through series production. The learning factor was defined by T. P. Wright in 1936, is based on cumulative average cost, and takes into account the reduction of effort for fabrication of "follow-on" units to the theoretical first unit (TFU). For example, a learning factor of 0.80 implies that doubling the number of units produced will reduce the cost to 80%. A variation on the Wright learning curve theory is the Crawford system, which assumes ordinate values based on the unit values, as opposed to a cumulative average of those values. While the Wright system was utilised more broadly in earlier years, more recently, many companies and industries have adopted the Crawford system [202]. Similarly, the TransCost model also uses the Crawford system. A comparison of the two systems is shown in Figure 46.

For the learning curve value itself, the typical learning factor values applicable to space systems and also the aviation sector are between 0.75 and 1.0, dependent on unit mass and annual production rates - namely, the learning factor, *p*, decreases with lower unit size/mass and with higher production rates [102]. In practical meaning, for both latter conditions, this means an increase in learning, and a reduction in unit production costs. Production conditions also contribute and influence to this trend. For the aerospace sector, the learning factor is given to be 0.85 by NASA documents [102, 137, 224], which is the also confirmed in wider literature [78, 100-102, 217].

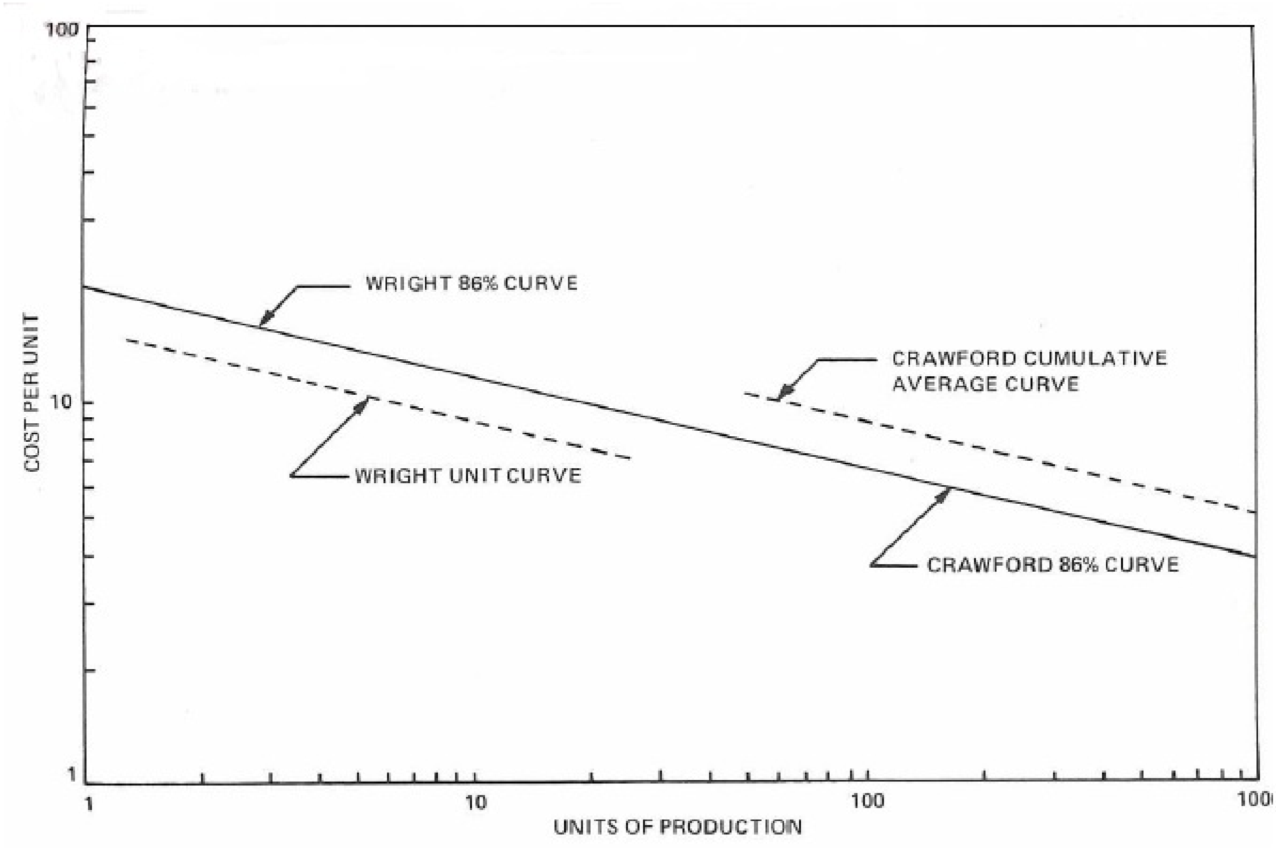

Figure 46: Graphical representation and comparison of Wright vs Crawford curves [202]

Here, it must also be noted that TransCost provides a different Learning Factor Model for liquid propulsion rocket engines to highlight the greater impact of engine size (mass) and production rates on the effective learning factor, *p*. The numerous relationships are shown below in Figure 47, which has been derived from visual analysis of the relevant TransCost data points depicting the curves. Being an empirical model, the specific organisational conditions and unique technical and commercial circumstances of the manufacturer as well as production scenario and organisation may influence these trends. Furthermore, the underlying assumption is that the learning effects are only observed for production of **identical** units without technical changes nor modifications.

For the SpaceLiner case-study, an assumption about the annual production quantity of the engines had to be made to determine the unique rocket engine LC. In line with large aircraft production rates, taking an initial value of 25 SpaceLiner vehicles per year, results in 275 engines produced per year, each with a mass of 3300kg. As can be seen in Figure 47, the TransCost model, being a dedicated launched systems model, does not factor in for such a high quantity of production, and as such, the chart shows a maximum of 100 units produced per year. From the chart, the formulae per mass category of engine were furthermore derived. This is summarised in in Table 90 below.

Table 90: TransCost formulas for empirical learning factor (LF) for rocket engines

Engine Mass	***TransCost Formula for LF (p)***
10 kg	p = -0.057 ln(x) + 0.975
25 kg	p = -0.056 ln(x) + 0.9848
50 kg	p = -0.056 ln(x) + 0.9936
100kg	p = -0.055 ln(x) + 1.0015
200 kg	p = -0.054 ln(x) + 1.0096
400 kg	p = -0.054 ln(x) + 1.0175
800 kg	p = -0.053 ln(x) + 1.0251
1600 kg	p = -0.053 ln(x) + 1.0361
3200 kg	p = -0.053 ln(x) + 1.0464
6500 kg	p = -0.052 ln(x) + 1.0546
10000 kg	p = -0.052 ln(x) + 1.0615

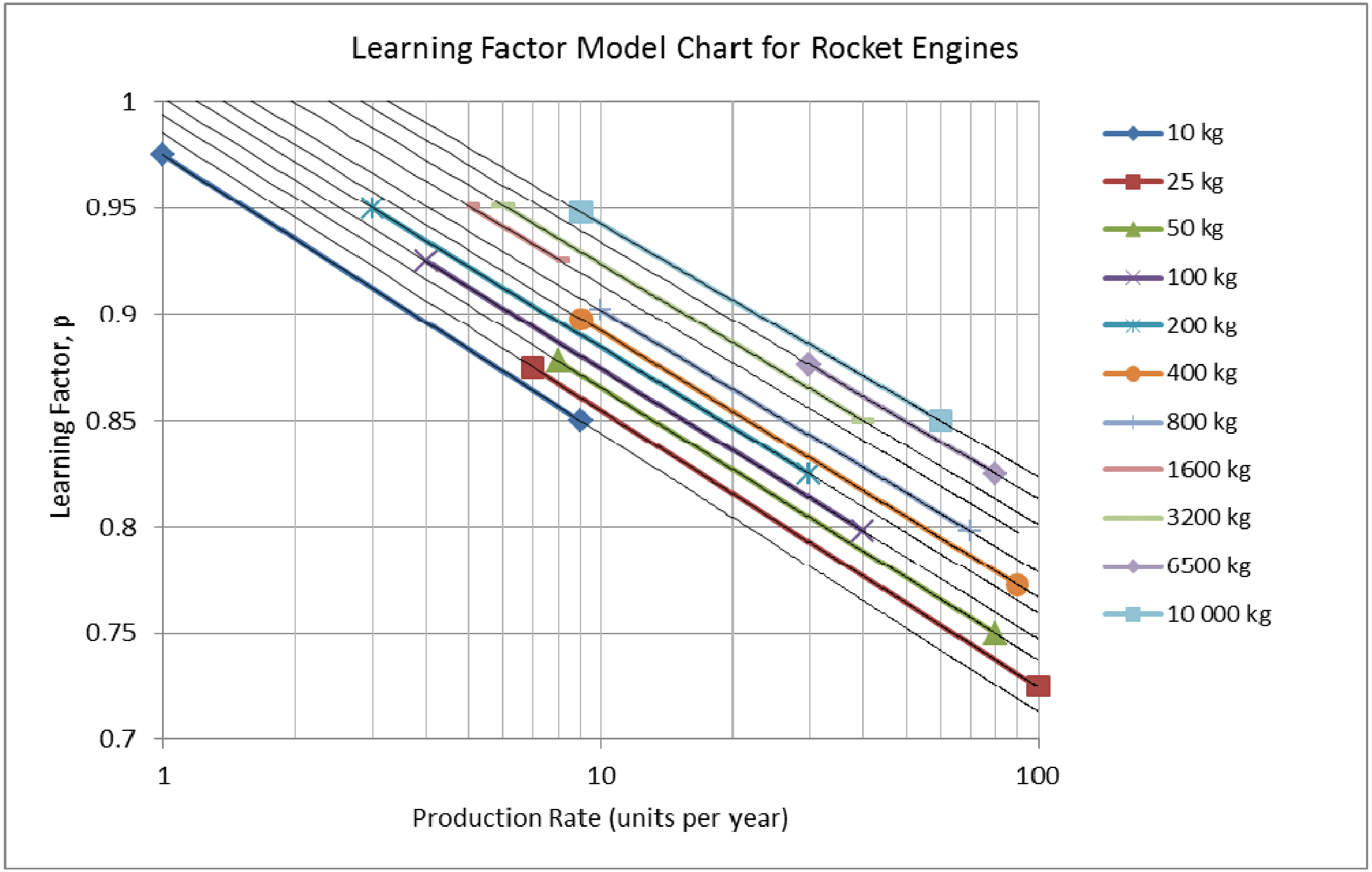

Figure 47: Empirical learning factor model chart for rocket engines with the learning factor (p) plotted against unit size (mass) and annual production rate [102]

Extrapolation the learning curves of an increased amount of production units beyond the TransCost stated production quantity range of 100 units would introduce unnecessary and unjustified uncertainty at this stage. The graph in Figure 47 implies that through increasing the number of units produced annually, more learning is observed, thus also bringing the production costs down. However, for the large quantities of the SpaceLiner engines which are expected, and in line with theory, this learning would have a plateau. Furthermore, the learning curve, as derived from research within the aviation domain has shown that even for civilian aircraft the learning curve is in the range of 80 – 85%. As such, the standard 85% LC value is adhered to within context of the SpaceLiner case-study in Chapter 4.10.2.

- **f_5 Refurbishment Costs Factor**

This factor applies to RLVs which require refurbishment efforts as a result of their operations. The components incurring the costs are shown in Figure 48.

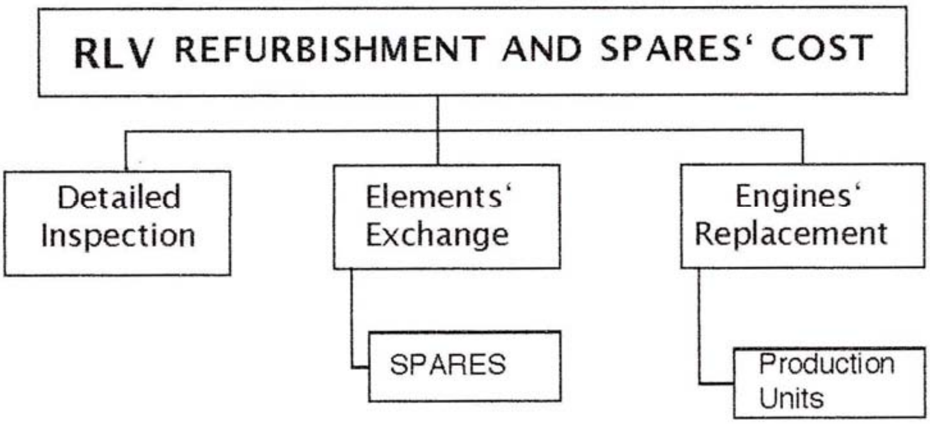

Figure 48: Refurbishment Cost Elements [102]

Little precedent exists in the space industry outside the Space Shuttle Orbiter, and the X-15 rocket plane for actual refurbishment costs, although aviation examples are more readily found. The f_5 factor is consequently expressed as a proportionate cost of the TFU, and is dependent on the vehicle technology and design, as well as the number of flights that a vehicle performs during its lifetime. The formula for the refurbishment cost, R, is given below as:

$$R = f_5 \cdot TFU \; . \qquad (A7)$$

- **f_6 Cost Growth Deviation from Optimum Schedule Factor**

The term 'optimum schedule' is a subjective one. The scope and expanse of the program as well as novelty, as well as team cohesion and experience all affect its duration and the optimum schedule defined at program commencement. From historic data and through a first, empirical approach, TransCost derive that a delay to the schedule by 20% will result in a 10 to 15% cost increase, and some 30 to 35% for a 40% schedule delay on an original timeline. A quantitative representation of schedule delays and their resulting cost penalties is shown in Figure 49 below.

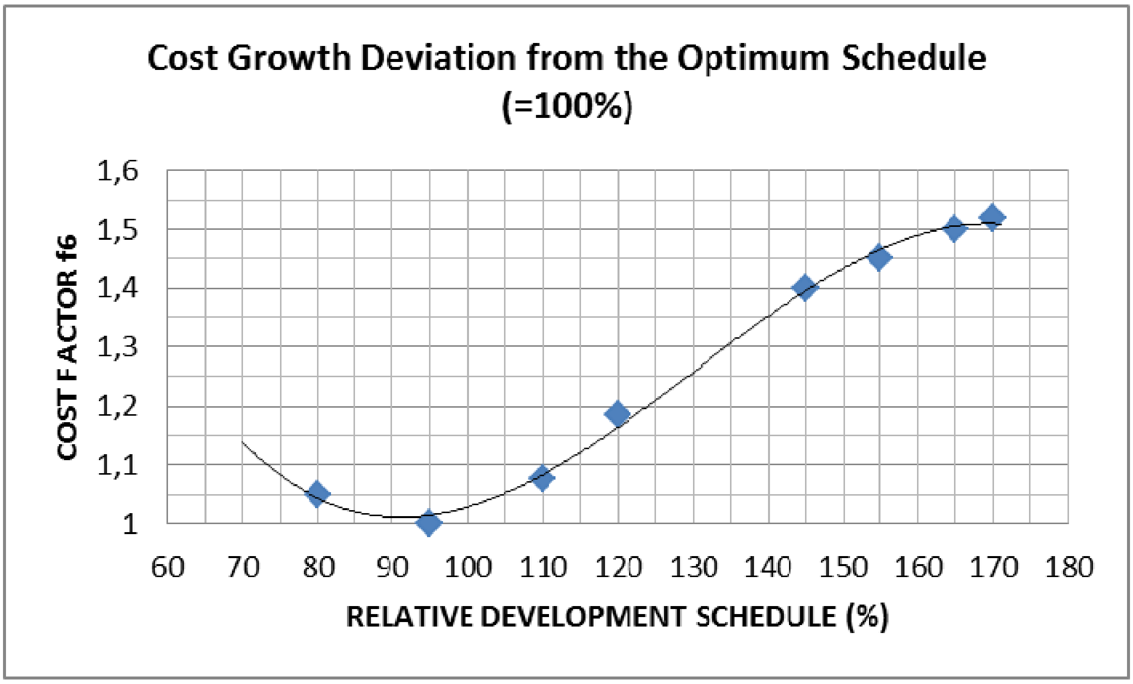

Figure 49: f_6 factor for cost growth by deviation from the optimum schedule [102]

- **f_7 Cost Growth for Parallel Contractor Organisations Factor**

The f_7 factor considers program organisation, and relates to the classical prime-contractor / subcontractor relationship. It has been proven in practice that breaking from this traditional contract organisation with several parallel contractors without one clearly defined prime can be detrimental to project cost. From historical precedence, TransCost presents an empirical model based on the number of parallel, major contractors participating in a program, and the influence on cost. The f_7 formula is therefore shown below:

$$f_7 = n^{0.2}, \tag{A8}$$

with all associated numerical values also shown in Table 91 below.

Table 91: Most common values for f_7

Cost Growth for Parallel Contractor Organisations		f_7
1	(n) parallel organisations = 1	1.14869835
2	(n) parallel organisations = 2	1.24573094
3	(n) parallel organisations = 3	1.31950791
4	(n) parallel organisations = 4	1.37972966
5	(n) parallel organisations = 5	1.43096908
6	(n) parallel organisations = 6	1.47577316
7	(n) parallel organisations = 7	1.51571657
8	(n) parallel organisations = 8	1.55184557
9	(n) parallel organisations = 9	1.58489319
10	(n) parallel organisations = 10	1.14869835

- **f_8 Regional Productivity Factor**

TransCost quantitatively defines values for various countries involved in the space sector with respect to their productivity levels. This encompasses and reflects aspects like knowledge, advanced materials and processing technologies, education level and dedication to work. The various combinations and permutations then result in varying levels of output versus time. TransCost takes a reference project database for US projects and derives a numerical factor, albeit admittedly subjective, a fact also clearly conceded within TransCost. The numerical factor values, and their basic derivation, is shown below in Table 92.

Table 92: The 1980-1999 regional productivity model defining complexity factor f_8

	Effective Working Hrs / Yr (1)	$(1)^{0.7}$ (2)	Relative Education (3)	Relative Dedication (4)	Relative Productivity (2)*(3)*(4)	WYr Correction Factor f_8
USA	1847	193	1	1	193 = 1.00	1.00
Europe (ESA)	1583	174	1.20	1.08	225 = 1.16	0.86
Germany	1568 1674*	172 181	1.30 1.30	1.13 1.13	253 = 1.31 265 = 1.37	0.76 0.73
France	1611 1561*	176 172	1.30 1.30	1.10 1.10	251 = 1.30 246 = 1.27	0.77 0.79
Japan	2052	208	1.13	1.80	424 = 2.19	0.46
Russia	1600 1650*	175 179	0.75 0.85*	0.70 0.85*	92 = 0.47 129 = 0.67	2.11 1.50
China	1958	201	0.85	0.95	163 = 0.84	1.19

**) Post-2000 values*

- **f_9 Cost Impact of Sub-contractorship Factor**

The number of subcontractors involved with an industrial prime contractor under a standard program scheme, impacts program cost. The two key cost factors to be influenced are the prime contractor's management and control effort, and the profit which is charged by the subcontractors.

The following two charts show the TransCost relationship of the latter two cost factors quantitatively given the value of subcontracted work, and the number of subcontractor firms. The increases observed from each graph need to be added to obtain the total cost increase due to the f_9 factor.

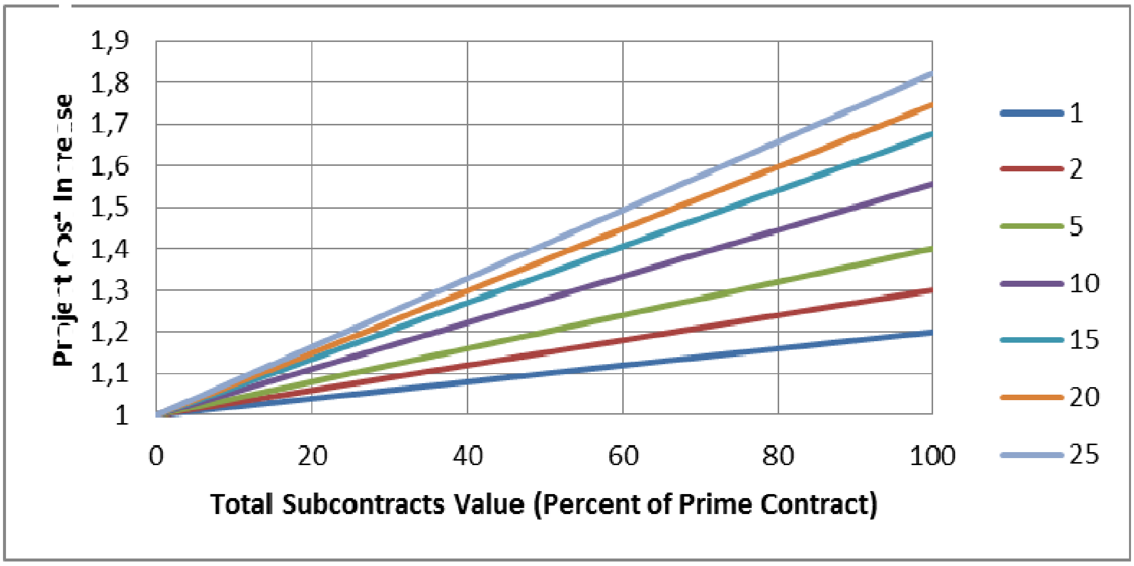

Figure 50: Management Cost Impact of Sub-contractorship

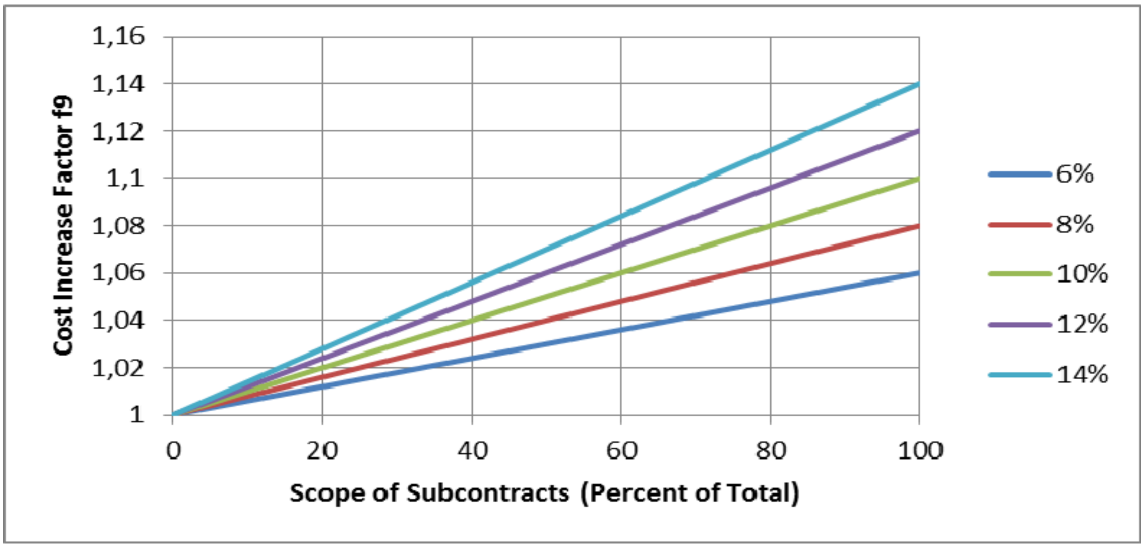

Figure 51: Cost Increase by Sub-contractors' Profit

- **f_{10} Cost Reduction by Past Experience Factor**

This factor addresses cost reductions resulting from past experience, the "lessons learned" and data collected from previous works and program involvement. This includes utility of modern computing tools and application of systems engineering principles. The attributed cost reduction for this factor lies between 15 to 25%. As such, f_{10} is commonly in the range of 0.85 and 0.75.

- **f_{11} Non-Governmental Development Cost Reduction Factor**

This impact factor applies only to commercial, non-governmental projects which have no government contracts' requirements and no customer interference. As a result, the high costs involved with government requirements, procedures requirements and the associated personnel (i.e. lawyers, administrative staff) are significantly reduced. From heuristic experience, it has been shown that purely from a commercial basis, without governmental specifications, requirements, procedures and reporting, a significant saving of 45 – 55% is achievable. The resulting commercial development cost correction factor f_{11} is therefore 0.45 – 0.55.

APPENDIX E – RLV TRANSCOST DEVELOPMENT COST CALCULATIONS

1. Space Shuttle STS Configuration

The Space Shuttle is arguably the closest realised and functional 'reusable' (albeit only partly so) launcher system to date. As such, it is also perhaps the most interesting and relevant RLV for which to outline and detail the cost estimation process and logic for. Information pertaining to this program is also more readily available than for other vehicles.

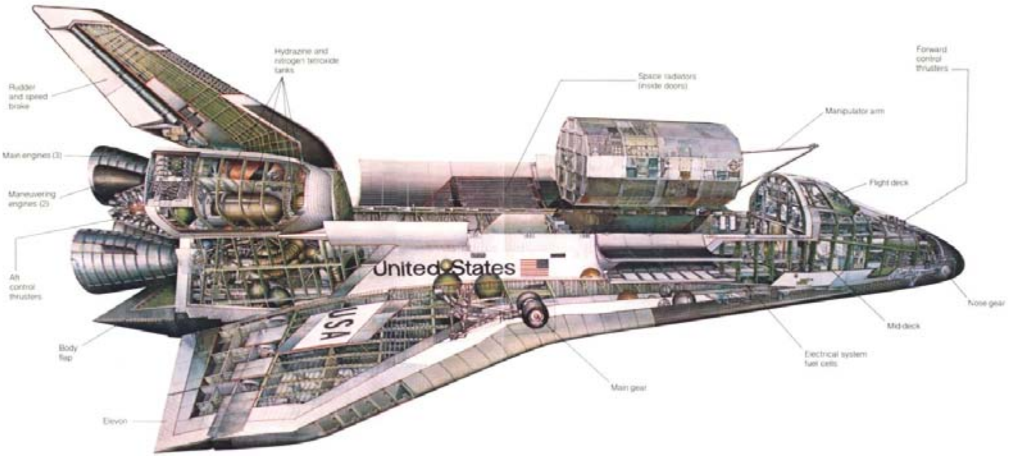

Figure 52: Space Shuttle Columbia STS1 detailed drawing [195]

The Space Shuttle Columbia Orbiter configuration, as shown above in Figure 52, was chosen as the vehicle for this analysis because it was used for the prototype flight on April 12, 1981, and as such, conforms to the development definition of a new launcher system incurring full development costs.

Within the scope of this calculation, we consider that the Space Shuttle Columbia development program extended across the timeframe of 1972 until 1981. After this, in accordance with the TransCost definition, the development phase concludes after the first prototype is completed, which for the case of Columbia, was in 1981 with a maiden flight. Major Shuttle components which needed to be developed include:

- Orbiter (Columbia)
    - SSME
    - RCS/OMS Module (AJ10-190 Engine)
- Solid Rocket Boosters (SRBs)
- Shuttle External Tank

1.1 Space Shuttle Component Break-down Structure

The component breakdown structure and the Excel TransCost spreadsheet screenshots with all relevant inputs and complexity factors are presented below. Here, all mass data was extracted from predominantly two sources, *[96]* and *[91]*.

Table 93 through to Table 98 below present the details of all calculations performed for each Space Shuttle system and component, with all applied complexity factors, shown.

1.2 Space Shuttle Calculation Assumptions

Some key assumptions also had to be made within the scope of the cost estimation with regards to numerous inputs, complexity factors, as well as currency conversions. The key assumptions are outlined below, and are also annotated in **red** with association to the fields which the assumptions affect in the tables above:

A1. For the SSME, f_1 and f_3 complexity factors were taken to be 1.3 and 0.85 respectively. In addition, the value for the number of test firings (730 firings) was also assumed. The latter values were taken directly from the TransCost Handbook. They were assumed for the Excel model too in an attempt to understand the sensitivity of the factors within the context of the project and as calculated by the TransCost model.

Table 93: TransCost CER for the SSME

TC 7.3 Chapter 2.32		Liquid Propellant Rocket Engines with Turbopumps				TC, pg. 35
CER	**=**	**277 * M^0.48 * f1 * f2 * f3**		Engine Dry Mass (M)		3180
	=	16601.70	WYr	f1	**A1.**	1.3
for f2 calculation				f2	**A1.**	1.13
Nq (# qual. firings) =		730	**A1.**	f3	**A1.**	0.85
COST M$ (2011 e.c.)		**5211**		*NORP*		*10*

Table 94: TransCost CER for the AJ10-190 OMS Aerojet Engine

TC 7.3 Chapter 2.33		Pressure Fed Rocket Engines				TC, pg. 39
CER	**=**	**167 * M^0.35 * f1 * f3**		Engine Dry Mass (M)		118
	=	829.25	WYr	f1	**A2.**	1.1
				f3	**A2.**	0.85
COST M$ (2011 e.c.)		**260**		*NORP*		*7*

Table 95: TransCost CER for the Orbiter Columbia

TC 7.3 Chapter 2.49		Crewed Space Systems			TC, pg. 78
CER	**=**	**1113 * M^(0.383) * f1 * f3**		Reference Mass (M) **A5.**	72277
	=	124455.17	WYr	f1	1.4
				f3	1.1
COST M$ (2011 e.c.)		**39066**		*NORP*	*6*

Table 96: TransCost CER for the light-weight version External Tank

TC 7.3 Chapter 2.43		**Expendable Ballistic Stages & Transfer Vehicles**				***TC, pg. 49***
CER	**=**	**100 * M^(0.555) * f1 * f2 * f3**		Vehicle DRY Mass w/o Engines (M)		35000
	=	77910.18	WYr	f1	***A3.***	1.1
for f2 calculation				f2		1.94
M_NET		758562		f3	***A3.***	1.1
M_engine =		0				
M_propellant		732266	***A4.***			
% Res. Gas at c/o		0.8				
Res. Gas at c/o		5858.13				
Usable Prop Mass		726407.87				
M_dry		32154.13				
NMF specific		0.04				
NMF average		0.085				
COST M$ (2011 e.c.)		**24456**		*NORP*		*12*

Table 97: TransCost CER for the RCS-OMS Propulsion Module

TC 7.3 Chapter 2.42		**Liquid Propellant Propulsion Systems/Modules**		***TC, pg. 47***	
CER	**=**	**14.2 * M^(0.577) * f1 * f3**		DRY Mass with Engines (M)	307
	=	425.36	WYr	f1	1.1
				f3	1
COST M$ (2011 e.c.)		**134**		*NORP*	*8*

Table 98: TransCost CER for the SRM Boosters

TC 7.3 Chapter 2.41		**Large Solid-Propellant Rocket Boosters**		***TC, pg. 44***	
CER	**=**	**10.4 * M^(0.60) * f1 * f3**		Booster Net Mass (M)	84126
	=	9375.44	WYr	f1	1
				f3	1
COST M$ (2011e.c.)		**2943**		*NORP*	*5*

A2. For the AJ10-190 development costs, the complexity factors f_1 and f_3 were defined as being 1.1 and 0.85 respectively. The f_1 value was taken as 1.1 to reflect the reusability element of the engine, while the 0.85 f_3 value was consistent and in line with the TransCost SSME f3 definition and logic.

A3. For the External Tank development cost calculations, the f_1 factor was chosen to be 1.1 to reflect similarity between the Saturn V SII stage. Furthermore, the f_3 factor was taken to be 1.1 to reflect the team experience existing also from the Saturn V program.

A4. For the f_7 complexity factor, which is the factor that reflects cost increase associated with an increased number of contractor organisations, this number was assumed to be 5. Arguably, and upon consultation with the opinion of Dr. E. Koelle [103], only three main contractors were involved in the Shuttle design phase, being Rocketdyne, North American Rockwell and ATK-Thiokol. Dr. E. Koelle maintains that companies like United Space Boosters and Michoud Facility came only later for the production and operations phase. However, the entire organisation of contractors is rather difficult to assess, including the role of NASA-MSFC and the changes versus time.

However, existing literature suggests and identifies 4 main contractors for the development phase of the Space Shuttle [54]. Being a worst-case scenario to the previously suggested 3 contractors, the more extreme option is taken for the sake of this document.

Therefore, for the f_7 complexity factor, which is the factor that reflects cost increase associated with an increased number of contractor organisations, this number was assumed to be 4. These were taken to be four key known companies listed below [54]:

1) Rocketdyne

• *Shuttle SSME Contract (1972 April 21) - Rocketdyne receives the contact for development of the shuttle main engine. By the end of the century the total value will have exceeded $5.6 billion*

2) North American Rockwell

• *Shuttle orbiter contract (1972 July 7)- North American Rockwell received NASA contract NAS9-14000, valued at $2.6 billion, for development of the space shuttle orbiter. Included are two flight articles, the STA Structural Test Article, and the MPTA Main Propulsion Test Article. Later production of two additional orbiters will be added, bringing the final contract value to $ 5.815 billion by 1996.*

3) ATK- Thiokol

• *Shuttle solid rocket booster contract (1973 August 16) - United Space Boosters and Thiokol receive the contract.*

4) Boeing Michoud

• *Shuttle external tank contract (1973 August 16) - Boeing Michoud received the production contract, using facilities already built for Saturn V first stage construction. By 1996 the contract will have totaled $6.7 billion and covered the production of 120 external tanks.*

A5. The mass for the Orbiter, Columbia, was taken from reference [91] for OV-102, found on pg. 440.

1.3 Space Shuttle Development Cost Summary

Table 99 shows a summary of the effort (WYr) as well as the costs for the various Space Shuttle components (at both 1978 as well as 2011 e.c.) which needed to be developed within the scope of the program. Literary costs for the OMS/RCS could not be identified. Within the scope of this exercise and compared with the scale of the costs of the other Shuttle components and stages, their exclusion from the total Shuttle cost was therefore deemed insignificant to the overall results.

In Table 99 it must be highlighted that the bottom "C_D TOTAL" row is **not** purely the sum of all above components – but is rather the sum, with the f_x factors applied to it. As per the TransCost 7.3 model definition and application, the additional TransCost factors are applied to the sum of the constituent elements for the Space Shuttle system.

Table 99: Space Shuttle Columbia development cost breakdown per element

Shuttle Element	Calculated Effort (WYr)	Calculated Cost 1978 e.c. (M$)	Literary Cost 1978 e.c. (M$)	Delta (TC / Literature)
SRB	9 375	747	988	-24%
SSME	16 601	1 323	1 077	23%
Orbiter	124 455	9 919	9 000	10%
External Tank	*77 910*	*6 209*	*562*	***+1 078%***
OMS/RCS	1 255	100	-	-
C_D TOTAL	***342 631***	**27 308**	**18 000**	**3*%**

** this is the average Delta value of SRB, SSME and Orbiter only, since the External Tank TransCost value is clearly excessively high and is therefore non-representative and an anomaly, as is explained and discussed further in the analysis below*

These factors, f_x, are outlined below, and their chosen values stated:

- *f_0 = 1.08*

(f_0 = 1.04 number of stages, in the case of the Space Shuttle, 2)

- *f_6 = 1.0*

(assume no deviation from optimum schedule)

- *f_7 = 1.32*

(f_7 = n 0.2; with n being the number of parallel contractor organisations, in this case taken to be 4)

- *f_8 = 1.0*

(TransCost stated country productivity factor for the US)

Upon analysis of the resulting costs as well as the respective cost deltas observed between TransCost results and literary values, it can be seen that the TransCost model provides a good correlation and ROM outcomes to the various Shuttle stages and components. This is because it is generally considered that for cost estimation, being a dynamic discipline, a rough range of ±20% deviation is a reasonable value [100], particularly early on in a program phase. Therefore the only significant and notable deviation which can be observed here is that for the Shuttle External Tank (ET), highlighted in italics in Table 99. Purely from logic, the delta between literary values and the TransCost calculated ET development cost of 1178% appears to be excessive, and requires a deeper analysis and understanding to justify this discrepancy. Within the context of this work, the author of TransCost handbook, Dr. Dietrich E. Koelle, was contacted directly and the discrepancy outlined. The response received outlined the fact that the Shuttle ET, although a separate component in its own right, is not, however, classed as a stage within context of the TransCost model. It is rather defined as a sub-system, and as such, applying the system-based CERs is inappropriate. TransCost, by its definition, is purely a higher-level, system based model which therefore can results in grossly over- or under-exaggerated estimates for any sub-systems (depending on the technology associated), as was exactly the case with the Shuttle ET. This highlights the importance of knowing the mechanics and features of a given cost model, and to be able to identify any shortcomings or gaps, and address these accordingly. In this instance, another estimation methodology would therefore be required to formulate a more justifiable, defensible development cost estimate for the Space Shuttle ET than purely the TransCost CER. For the sake of consistency within the context of this study, an available literary figure for ET development was taken based on the official NASA annual budget figures, which stated that the total ET development costs between 1974 and 1982 were $562M, or an equivalent of 7030 WYr [103]. Here, loosely calculating a ratio figure between the TransCost calculated amount and literature, we get the Shuttle Tank Structure Ratio (STSR):

$$STSR = \frac{6209}{562} = 11.0\,. \tag{A9}$$

Table 100 below presents the modified values for each Space Shuttle system and component. Since the Shuttle ET is not a suitable element to be calculated by TransCost, the identified literary values were simply assumed and entered into this table for completeness and to allow for a cost to be attained for the overall system. These appear written in brackets within the table. Total WYr and total cost amounts are therefore derived. Furthermore, Figure 53 provides a visual representation of the costs on a component and stage basis.

Consequently, the top-level TransCost formula for the overall Space Shuttle cost is:

$$C_D = f_0\ (CERs) \cdot f_6 \cdot f_7 \cdot f_8\,. \tag{A10}$$

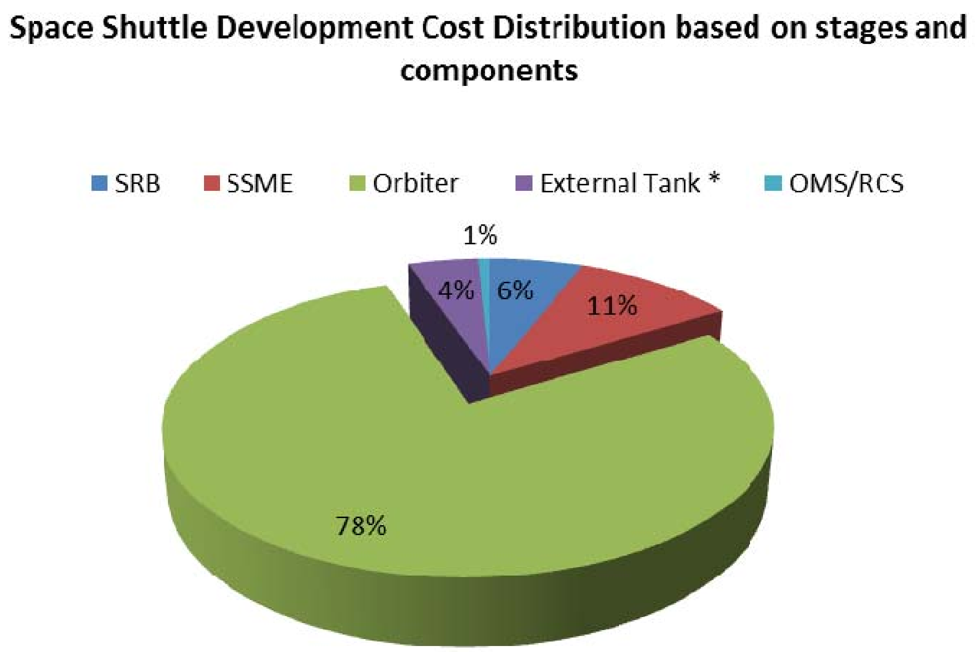

Figure 53: Visual representation of development cost distribution for the various Shuttle systems and components based on the TransCost calculation

Table 100: Space Shuttle Columbia development cost breakdown for respective stages and components updated for ET lesson learnt*

Shuttle Element	Calculated Effort (WYr)	Calculated Cost 1978 e.c. (M$)	Literary Cost 1978 e.c. (M$)	Delta (%)
SRB	9 375	747	988	-24%
SSME	16 602	1 323	1 077	23%
Orbiter	124 455	9 919	9 000	10%
External Tank*	*7 030**	-	*562**	-
OMS/RCS	1 255	100	-	-
C_D TOTAL (w/f_x)	***226 518***	**18 053**	**18 000**	**3%****

** this value is **not** calculated by TransCost, but rather assigned, as taken from literature*
*** this is the average Delta value of SRB, SSME and Orbiter only*

The final development costs of the Space Shuttle system, as calculated using the TransCost 7.3 model, are shown below in Table 101. Only USD values are important, and so only these values are shown. The 2011 USD equivalent is calculated using the TransCost WYr rates, and represents how much the same development program would have cost if undertaken in the US under 2011 economic conditions.

Table 101: Development costs of the Space Shuttle as calculated using TransCost 7.3

C_D =	226 518	WYr
=	18.01	Billion USD (1978 e.c.)
=	71.1	Billion USD (2011 e.c.)

1.4 TransCost & Literary Space Shuttle Costs

As previously highlighted, locating fixed, accurate, concrete, relevant, justifiable and transparent cost data poses a significant challenge. In particular, for a program as complex as the Shuttle, with its various delays, complicated and extensive structure of government involvement and numerous contractors and subcontractors, cost categories, especially segmented by program phase, are very difficult to identify. Keeping the latter points in mind, nevertheless, for a program of such high visibility and profile, certain more global figures can be found, and these are used for the comparison and 'benchmarking' with the calculated TransCost result.

Literature indicates that during 1970's, early calculations made in the preliminary phases of the Shuttle program predicted development costs to be $7.45B, or $43 billion if converted to a 2011 e.c. value [142]. It is unclear which costing methodology was used to arrive at this figure. It is, however, well known and has been repeatedly shown that costs are more likely to overrun than under-run [211], with the initial cost estimate baseline generally tending to increase as the program develops. Additionally and now also retrospectively, early Space Shuttle program estimates fell significantly short of the final expenditure and incurred spending [80, 91]. As such, it is more desirable to find a more recent cost estimate. At a slightly later date, at 1981 e.c., a revised development cost figure exists, being $18B [91]. Taking this more recent $18B figure, and once again converting it to a 2011 value results in an amount of roughly **$57B for Shuttle development at 2011 economic conditions.** This figure is therefore extracted and taken as the reference literary value for the comparison with TransCost values.

Reverse engineering the $18B at 1981 e.c., and applying respective TransCost US WYr cost for 2981 ($98,770 per WYr), we obtain the implied literary value of ***182, 240WYr.***

Comparing this to the TransCost calculated development effort of 226,518 WYr as shown in Table 101 it can be seen that the TransCost figure constitutes an increase of 24% over the literary development cost. However, this margin is perfectly reasonable, since be its own definition, the TransCost model does take into account on average a +20% margin for expected development costs. This is an important lesson to be taken away from this particular example. Additionally, it is highly logical to assume that this initial $57B literary figure, which was technically a pre-program estimate in itself, would have been exceeded in reality. So, the resulting TransCost development effort cost of $71.1B (with the logical adjustment for ET), being more than the initial literary cost estimate, but less than the overall program cost, is highly logical and congruent with reality.

Furthermore, from a retrospective stance, furthermore, the ultimate **overall** Shuttle program budget is now being quoted as being a total of $196 billion at 2011 e.c. [91]. Here it must be emphasised that this $196B amount represents the overall total Space Shuttle program cost, including production and operations, as well as most probably ground infrastructure, and vehicle maintenance and refurbishment, all of which bore significant expenditures. It is therefore not dedicated to solely the development cost. A segmented breakdown of the separate development, production and operations component is not explicitly available.

Given that a separate development component, which is the figure of interest within the scope of this report, is unavailable, it is interesting from a cost analysis perspective to calculate the percentage of overall program budget which would have been attributed to Space Shuttle development. Development costs would have been a significant part of the total cost, lying somewhere between the first estimated amount, but well below the overall quoted $196B. So, working with the $196B (2011 e.c.) figure, and applying a reverse engineering approach to this total amount, we use the fact that TransCost defines one US 2011 e.c. WYr as being $313,898. Therefore the stated **overall** Shuttle Program cost translates into a work effort amount of ***624,407 WYr.***

Comparing this directly with the calculated TransCost development effort amount of 226,518 WYr, indicates that roughly 36% of overall program budget was attributed to development costs. As previously mentioned, although development costs are non-recurring costs borne once off at program commencement, in case of new, complex and large scale systems, they constitute a significant proportion of overall program costs. The TransCost derived figure is not an unreasonable calculation from a ROM/EJ perspective.

In summary, the TransCost model development cost figure calculated within the context of this exercise is $71.1 USD at 2011 e.c. This is in comparison to the literary value of $57B USD at 2011 e.c. TransCost result is in high congruence with literary values. This is, however, after the ET structures were adjusted, with a key lesson learned that TransCost is insufficient for providing cost estimates for such stages. In terms of the literary overall Shuttle development cost, the TransCost value lies above the initial literary estimate, but well below overall program cost. In fact, it forms a 36% portion of overall program budget, which is a reasonable ROM percentage. So, TransCost delivers a solid estimate which bears a fairly logical congruence at least from a ROM perspective, to the initial cost estimate value produced at commencement of the Shuttle program.

2. Energia-Buran Configuration

The Energia-Buran System was primarily developed, designed and built in direct response to the American Space Shuttle, which was seen as a significant military threat to the Soviet Union [80]. The Buran orbiter stage is shown in technical detail in Figure 54.

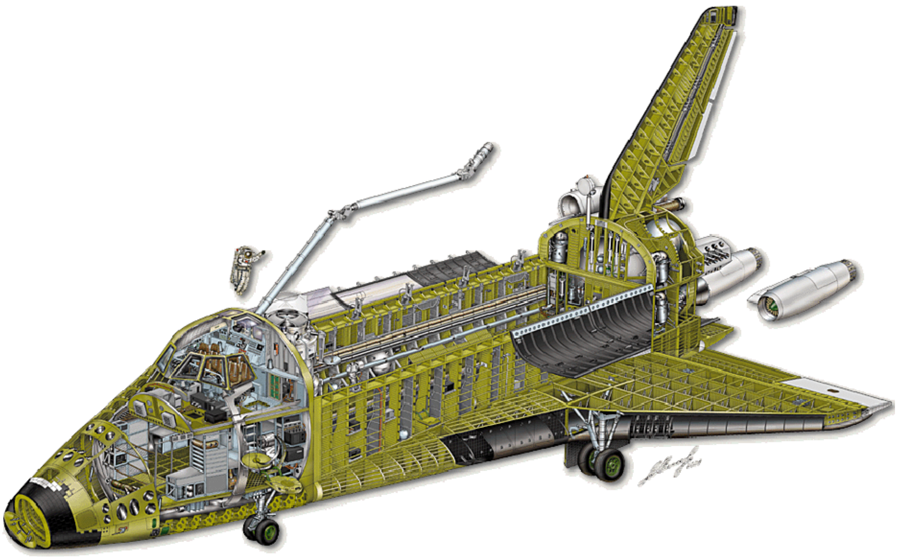

Figure 54: A techno-graphics, 3D rendered layout of the Buran Orbiter [131]

For the sake of this calculation, it is considered that the Buran program development was commenced in 1974 and ran until 1993, when the program itself was terminated due to political pressures and an associated lack of funding. Although in 1988 Buran successfully completed one unmanned orbital flight, the program never became justifiably operational, and therefore the entire duration of the program that was actualised, can be taken as its development phase. This was the case within the context of this study. The Buran-Energia system used only liquid propellants, with Energia being a dedicated Energia core stage. The Energia launcher was a two stage vehicle:

- Stage 1, Block A, 11S25, 4 strap-on boosters, RD-170 Engines
- Stage 2, Block Ts Central, 4 RD-0120 Engines

Here, and quite obviously, despite the multiple RD-170 and RD-0120 engines on the stages, only one development cost per engine group/type is incurred.

The Buran Orbiter did not have any own main engines for the ascent phase itself, although it did feature an own propulsion system, called the Combined Engine Installation or ODU (RCS/OMS Unit, the 17D11) with 17D12 OMS engines and thrusters designed for on-orbit maneuvers and attitude control functions. A key, major difference with respect to Buran's RCS/OMS systems and the Space Shuttle was that the Energia-Buran system only used LOX/Kerosene liquid propellants which had numerous advantages over the Space Shuttle Orbiter. It was a much safer alternative for handling on ground, as well as improving orbital maneuvering performance to that of the Space Shuttle. Historically, it was the first time that such propellant types were used in any type of orbital maneuvering and attitude control system [80].

In line with the TransCost 7.3 development cost process and structure, the separate component data was entered into relevant CERs, and individual costs were determined. The individual costs of each element were then summed up, and additional TransCost defined factors applied to obtain a resulting, overall system development cost.

2.1 Buran-Energia Excel Component Break-down

The component breakdown structure and the Excel TransCost spreadsheet screenshots with all relevant inputs and complexity factors are presented in Tables 102 through to 108 below.

Table 102: TransCost CER for 17D11Buran OMS/RCS propulsion

TC 7.3 Chapter 2.42		**Liquid Propellant Propulsion Systems/Modules**			*TC, pg. 47*
CER	**=**	**14.2 * M^(0.577) * f1 * f3**		DRY Mass with Engines (M)	18023
	=	6861.53	WYr	f1	1.3
				f3	1.3
COST M€ (2011 e.c.)	**1842.21**	***A2.***		*NORP*	*8*

Table 103: TransCost CER for Energia rocket (core) Stage 2, Block B (LH2/LOX)

TC 7.3 Chapter 2.43		**Expendable Ballistic Stages & Transfer Vehicles**			*TC, pg. 49*
CER	**=**	**100 * M^(0.555) *f1*f2* f3**		Vehicle DRY Mass w/o Engines (M)	37200
	=	40878.51	WYr	f1	1.1
				f2	0.94
for f2 calculation				f3	1
M_NET	847000				
M_engine	12800				
M_propellant	797000				
% Res. Gas at c/o	3				
Res. Gas at c/o	23910				
Usable Prop Mass	773090				
M_dry	61110				
NMF specific	0.08				
NMF average	0.072				
COST M€ (2011 e.c.)	**9555.97**	***A2.***		*NORP*	*12*

Table 104: TransCost CER for Buran orbital vehicle

TC 7.3 Chapter 2.49		**Crewed Space Systems**		*TC, pg. 63*	
CER	=	**1113 * M^(0.383) * f1 * f3**		Vehicle DRY Mass w/o Engines (M)	61000
	=	148433.72	WYr	f1	1.4
				f3	1.4
COST M€ (2011 e.c.)	**35396.64**	*A2.*		*NORP*	*6*

Table 105: TransCost CER for Energia rocket Stage 1, Block A, 11s25 (Kerosene/LOX)

TC 7.3 Chapter 2.43		**Expendable Ballistic Stages & Transfer Vehicles**			*TC, pg. 49*
CER	=	**100 * M^(0.555) * f1 * f2 * f3**		Vehicle DRY Mass w/o Engines (M)	15250
	=	21916.35	WYr	f1	1.1
				f2	1.06
for f2 calculation				f3	0.9
M_NET	365000				
M_engine	9750				
M_propellant	340000				
% Res. Gas at c/o	3				
Res. Gas at c/o	10200				
Usable Prop Mass	329800				
M_dry	25450				
NMF specific	0.07				
NMF average	0.079				
COST M€ (2011 e.c.)	**5892.78**	*A2.*		*NORP*	*12*

Table 106: TransCost CER for 17D12 engine OMS Buran orbital propulsion system

TC 7.3 Chapter 2.32		Liquid Propellant Rocket Engines with Turbopumps			TC, pg. 35	
CER	**=**	**277 * M^0.48 * f1 * f2 * f3**			Engine Dry Mass (M)	230
	=	1329.70	WYr		f1	0.8
for f2 calculation					f2 (# test firings basis)	0.55
Nq (# qualification firings)		100	***A1.***		f3	0.8
COST M€ (2011 e.c.)		**357.53**	***A2.***		*NORP*	*10*

Table 107: TransCost CER for 11D122 Energia core engine RD-0120

TC 7.3 Chapter 2.32		Liquid Propellant Rocket Engines with Turbopumps			TC, pg. 35	
CER	**=**	**277 * M^0.48 * f1 * f2 * f3**			Engine Dry Mass (M)	3200
	=	22306.94	WYr		f1	1.2
for f2 calculation					f2 (# test firings basis)	1.16
Nq (# qualification firings)		800			f3	1.2
COST M€ (2011 e.c.)		**5997.80**	***A2.***		*NORP*	*10*

Table 108: TransCost CER for RD-180, booster stage engine

TC 7.3 Chapter 2.32		Liquid Propellant Rocket Engines with Turbopumps			TC, pg. 35	
CER	**=**	**277 * M^0.48 * f1 * f2 * f3**			Engine Dry Mass (M)	9750
	=	38079.41	WYr		f1	1.2
for f2 calculation					f2 (# test firings basis)	1.16
Nq (# qualification firings)		800	***A3.***		f3	1.2
COST M€ (2011 e.c.)		**10238.64**	***A2.***		*NORP*	*10*

2.2 Energia-Buran Calculation Assumptions

Some key assumptions also had to be made within the scope of the Buran-Energia System cost estimation with regards to numerous inputs, complexity factors, as well as currency conversions. The key assumptions are outlined below, and are also annotated in **red** with association to the fields which the assumptions affect in the tables above:

A1. For the 17D12 Engine OMS Buran Orbital Propulsion System, the number of test firings could not be established from literature/documentation. The number of test firings was therefore assumed to be 100.

A2. TransCost provides a table of Work Year (effort) values which are associated with specific economic years. The available currencies included are the USD, the Euro and the Japanese Yen. Since the Russian currency of rubles is not included, the entirety of the Buran cost calculation was performed using USA (USD) values and WYr amounts, as stated in TransCost. In turn, this approach was foreseen to make the final costs comparable with those which were calculated for the Space Shuttle.

A3. For the RD-170 engine, information pertaining to the number of test firings was not found, and therefore a value had to be assumed. This was taken to be 800, being the same value which was found in literature [100] for the test firings performed for the RD-0120.

A4. For the Buran Orbital Vehicle, the vehicle dry mass without engines was defined as being **61,000kg**, which was calculated based on information obtained from the Buran website [54]. Presuming that the data provided on the website is correct, the basic calculation for vehicle dry mass is as follows:

$$\textit{max total mass - payload - propellant = vehicle dry mass,} \qquad (A11)$$

and

$$105T - 30T - 14T = 61T.$$

A5. For calculation of the Buran OMS/RCS propulsion system, it was not possible to find a relevant literary figure. As such, a reference was found in a dedicated Shuttle- Buran book [80] which stated that the "*Buran OMS/RCS system 1100kg heavier than Shuttle due to increased piping*". And while the Space Shuttle mass for the relevant OMS/RCS component was known, being 306kg, the mass of the Buran OMS/RCS subsystem could then be derived to be 1407kg.

A6. For the f_7 complexity factor, which is the factor that reflects cost increase associated with an increased number of contractor organisations, this number was identified in literature as being 1206 [228], with this number referring to all the participating subcontractor organisations. For use in the TransCost calculation, it was necessary to establish only the prime contractors, which were determined to be 5, being:

- NPO Energia (prime contractor and core Block B stage)
- NPO Yuzhnoye (booster rocket construction in the Ukraine)
- CADB (Kosberg) (RD-0120 LOX/LH2 engines)
- MiG Molniya (Buran orbiter vehicle)
- Energomash (Gluschko) (RD-170 booster engines)

2.3 Buran-Energia System Summary

The following Table 109 shows a summary of the effort (WYr) per Buran-Energia component to be developed. Here, again a note should be made regarding the two distinctly different 'TOTAL' values shown in the bottom two **rows**. The first 'TOTAL' is a sum of the individual CER values with **no** TransCost programmatic complexity factors applied **except for** the country productivity factor for Russia, f_8. This represents the difference in country productivity, and translates this into cost. The second value incorporates the other programmatic factors, which affect development costs on a total system level, being f_0, f_6, f_7 to give the 'C_D TOTAL'.

Table 109: Development WYr effort summary Energia-Buran system components

Buran-Energia Element	Calculated Effort (WYr)
RD-0120 (core Energia engine)	47 068
17D12 (OMS engine)	2 806
RD-170 (Booster engine)	80 348
Energia Block A (Stage 1) Boosters	46 243
Energia Block B (core Stage 2) Boosters	74 990
Buran Orbiter Vehicle	313 195
RCS/OMS Propulsion Unit	3 319
TOTAL	*567 969*
C_D TOTAL (w/f_x)	**881 492**

In this case, the additional TransCost factors which are then imposed on the sum of the constituent elements for the Buran-Energia system, are all outlined below, and their chosen values stated and explained:

- $f_0 = 1.12$

(f0 = 1.04 number of stages, in the case of the Buran-Energia system, 3)

- $f_6 = 1$

(assume no deviation from optimum schedule)

- $f_7 = 1.38$

(f_7 = n 0.2; with n being the number of parallel contractor organisations, in this case stated as being 5 [103])

- $f_8 = 2.11$

(TransCost stated country productivity factor for US, as initial reference)

There is a significant increase on the individual WYr amounts, and the CD value, as can be seen in Table 109. The f8 country productivity factor for Russia (stated as being 2.11 for pre-year 2000) is quite high compared to Europe's 0.86 and 1.00 (reference) for the US, and is the key factor to influence the top-level system WYr total for the case of Russia. However, the WYr amount must not be looked at as an individual, standalone variable, but rather as a combination between the WYr amount, country productivity and the relevant WYr cost for that respective country.

Nevertheless, the total WYr amount for Buran is still very high if compared with the previously calculated Space Shuttle WYr effort of 226,518WYr. One obvious reason is explained by the past lessons learned based on the Shuttle example described in Chapter 0, namely that TransCost is not ideally suited for cost estimation of tank-like structures. Therefore, before proceeding to comparisons between the TransCost derived figures and literary values, we need to do a quick re-calculation for the tank-like structures of the Buran-Energia system.

2.4 Shuttle Lessons Learned Applied to Buran-Energia

A critical analysis point derived from this study pertains to the TransCost CER for *Expendable Ballistic Stages and Transfer Vehicles*. Looking back to the Space Shuttle development cost calculation described in Chapter 0, a key lesson learned was the limitation of *CER 2.43 for Expendable Ballistic Stages and Transfer Vehicles*, and its non-suitability for calculating development costs of tank-like structures [103]. This CER is relevant and was used to calculated costs of the Energia Block A, Stage 1 liquid boosters, as well as the Block B core stage.

As was identified and discussed in Chapter 0, a problem which arises with use of CER 2.43, is the resulting gross over-estimation for a simpler tank structure. In other words, and a critical lesson learned, is that CER 2.43 is intended to describe a full stage, reflecting the associated complexity of avionics, electrical components, and integration, rather than a simple tank structure. As such, and while a result is calculated using TransCost, upon further analysis, it is evident that this CER is inapplicable for the either of the Energia stages. The result of the existing Energia stage TransCost calculation is therefore an over-inflated development cost which exceeds realistic and literary stated development values. Prior to continuing with analyses of the Buran-Energia system, we seek to amend this inconsistency in the existing calculation to allow for effective comparisons of the system.

Recalling that having a literary development cost for the Space Shuttle External ET, as well as a calculated TransCost value using the CER 2.43 (resulting in an as-anticipated over-estimation), the STSR ratio was calculated. Recalling, for the Shuttle example, the calculated value for the ET was 77 910 WYr, costing roughly $6,209 M at 1978 e.c., while the literary figure was actually $562 M. If we once again calculate a loose ROM ratio of discrepancy between the CER calculated result, and the literary figure, we obtain an STSR value of 11.05.

We assume this ratio to be a ROM figure with which TransCost overestimates tank structure values (despite this being just one data point). If we then we can also seek to apply the STSR to the Buran-Energia system calculation, we can now quickly recalculate the total Buran vehicle development costs to remove the over-estimated tank-like structures, and obtain a more representative cost estimate. Here, we must also recall that the Buran-Energia system also had **two elements** which were classed as external tank structures, but had been calculated with CER 2.43. Therefore, we can now apply the STSR to the two Buran tank structure elements of:

- Energia Block A (Stage 1, Kerosene/LOX) Boosters
- Energia Block B (core Stage 2, LH2/LOX) Boosters

Taking the STSR ratio and applying it to the Buran example for both the Stage 1 and Stage 2 boosters, yields quite different values to the original system elements, and of course the overall development cost calculation, as shown below in Table 110.

Table 110: Revised calculation of tank-like components

Buran-Energia Tank Element	Old TransCost Value (WYr)	New STSR Derived Value (WYr)
Energia Block A (Stage 1) Boosters	21 916	1 984
Energia Block B (core Stage 2) Boosters	35 540	3 217

Table 111 below shows the revised summary of the effort (WYr) as well as the costs for the various Buran-Energia components (at 2011 e.c.) which needed to be developed within the scope of the program, with the newly derived STSR applied to the two booster components, which are shown in **red**.

After this more representative summary of component and overall system development costs was finally established, it was possible to then make a comparison between TransCost calculated and literary values of Buran-Energia development.

Table 111: Summary of development WYr effort and associated costs for Energia-buran system components, modified by application of STSR

Buran-Energia Element	Calculated Effort (WYr)
RD-0120 (core Energia engine)	47 068
17D12 (OMS engine)	2 806
RD-170 (Booster engine)	80 348
*Energia Block A (Stage 1) Boosters**	***1 984***
*Energia Block B (core Stage 2) Boosters**	***3 217***
Buran Orbiter Vehicle	313 195
RCS/OMS Propulsion Unit	3 319
C_D TOTAL (w/f_x)	**701 408**

** This value is the original TransCost calculated value using CER 2.43, then with application of the STSR*

2.5 TransCost & Literary Buran-Energia Costs Compared

While exact cost figures are difficult to find, yet alone justify, in literature, the development of the Buran vehicle itself is stated as being approximately **20 Billion Russian rubles** at the time of program cancellation on July, in 1993 from one source [219]. Another source suggests that the launcher vehicle development was 1.3 Billion Russian rubles, involving work of 1206 subcontractors and 100 government ministries, with a 6 Billion ruble economic impact, while the overall Buran program cost 14.5 Billion rubles at 1988 e.c. [54].

For the sake of the present analysis, here we will presume the more recent figure of 20 Billion Russian rubles at 1993 e.c. At the historical exchange rate in 1993 [41], the **average** exchange rate of the Russian ruble is stated as being equivalent to 0.9762 USD, and therefore the equivalent amount in USD for this can be defined as **19.524 Billion USD (1993 e.c.).**

A *first* approach would be to use the TransCost conversion table, while conceding here that accuracy is sacrificed due to a lack of data for the Russian ruble WYr rates. In this instance, a single US work year costing 172,900 USD (1993 e.c.). With some basic reverse engineering, this implies that the Buran program, up to its development, and including the first three prototypes, had effectively incurred a WYr effort of 112,920 WYr.

However upon further consideration, it must be noted that by simply converting the ruble amount to US dollars, and assuming all other factors to be the same, is a fairly simplistic and non-representative presumption to be making. This is because, logically, salary rates as well as country productivity between the US and Russia, were quite different. For example, rates per WYr in Russia within the space sector in particular, are arguably significantly lower than for the US. This can be supported by a quick ROM comparison of Astronaut salaries in the US with the Russian counterpart Cosmonauts [190]. It is stated that "NASA astronaut salaries range from $60,000 to $130,000 a year – two to four times more than their Russian counterparts with the same experience" [190]. In contrast, it is reported that Russian cosmonauts receive a $1000 per month wage ($12,000 p.a.) while ESA astronaut salaries start at $6,370 per month and can go up to $10,480 per month. Assuming that this comparison is accurate and representative, doing a simple calculation to obtain a representative salary ratio between the US, Europe and Russia yields:

Table 112: Cosmonaut and astronaut salaries for Russia, US and Europe

COUNTRY	SALARY (p.a.)
Russia	$12,000
US (NASA)	$95,000 (mean)
Europe (ESA)	$101,000 (mean)

The resulting Salary ratios are therefore established:

- **Ratio EU** = Europe / US: **1.063**
- **Ratio ER** = Europe / Russia: 8.417
- **Ratio UR** = US / Russia: 7.917

It is interesting to compare the salary ratios, in a simple ROM analysis to determine whether this ratio loosely holds and is in congruence with the ratios between WYr values, as stated in the TransCost handbook. If so, then the ratios can be used as a guide, to determine values for the Russian WYr cost. This approach is seen to be most suitable to address the lack of stated WYr values which are relevant for Russia.

The TransCost WYr values provided for Europe and the US for 1993 are:

- USA WYr – **$**172,900
- Europe (ESA) WYr – **€**156,800

When converted at the exchange rate from 1993 (€/USD 1.1243 [105]) this equates to:

- USA WYr – \$172,900
- Europe (ESA) WYr – **\$**176,290

Once again, calculating the resulting ***TransCost WYr*** cost ratio for Europe/US for 1993, we obtain:

$$\frac{\$176{,}290\ \ (\textit{Europe WYr Cost})}{\$172{,}900\ \ (\textit{USA WYr Cost})} = 1.0196\ \ (\approx \mathbf{1.02})$$

The calculated ratio value of **1.02** is very close to the ratio obtained for Europe/US space sector salaries, and therefore firmly confirms the Europe/US **Ratio EU** value of **1.06** previously obtained. Hence it is not unreasonable to extrapolate the salary ratio and therefore obtain a WYr amount for Russia which can then be used within the Buran calculation. After obtaining a positive confirmation of salary ratios being indicative of WYr cost ratios for TransCost, we can therefore derive values for the Russian WYr.

As previously calculated, the Europe / Russia salary ratio (Ratio ER) is 8.417. We will assume this ratio to correspond, or at least be reflective of the different costs of labour between Russia and Europe. By extrapolating this ratio to a similar correspondence of WYr costs provided in TransCost, we can derive the Russia WYr value. Then, for 1993, taking the European WYr cost as being \$176,290 in TransCost, and applying our salary ratio, implies that a Russian WYr amount costs an equivalent of:

\$20,945 – calculated Russian WYr $_{EUR/RUS}$ *cost (1993 e.c.)*

Alternatively, taking the US WYr cost as being \$172,900, and applying the US/Russia (Ratio UR) of 7.917, implies that a Russian WYr amount costs an equivalent of:

\$21,840 – calculated Russian WYr $_{US/RUS}$ *cost (1993 e.c.)*

An average of the two values, which will be taken as the Russian WYr value for 1993, yields:

$21,390 – calculated Russian WYr$_{AVE}$ cost

Alternatively, if we use the conversion rates between the ruble and USD for the year 1993 (1USD buys 1.025roubles [41]), we then obtain a ruble WYr cost for Russia for the year 1993, being roughly:

21,930 Russian rubles – calculated Russian WYr$_{AVE}$ cost

Consequently, Table 113 below shows the total, top level revised Buran-Energia development costs with the STSR imposition for tank-like structures. Implementing the above calculated amounts, it must be realised that the productivity rates between Russia, the US and Europe all differ (for which the TransCost manual stipulates a productivity factor value, f_8). Because of the significantly higher f_8 factor for Russia (directly affecting C_D), the WYr C_D for the Buran calculation is much greater than the WYr amount calculated for the Space Shuttle development. But despite the high WYr count, the Russian WYr cost is markedly lower that the US, resulting in a most reasonable overall system development cost which is well congruent with literary values.

Table 113: TransCost 7.3 development costs for Buran-Energia System under Russian conditions

C_D =	701 408	WYr
=	15.4	Billion Russian rubles (1993 e.c.)

While initially, the WYr total (C_D) amount may appear high, since absolute costs of labour in Russia have been determined to be markedly lower due to a lower cost per WYr of effort in Russia, the resulting costs are ROM congruent and agreeable with literary figures. The overall cost is presented in rubles only to allow for a logical comparison to be made with ruble values of the Buran-Energia program which were found in literature and previously already discussed in this chapter.

This TransCost Buran calculation is reasonably congruent with the literary figures assumed to be the comparative benchmark for the development cost of the Buran program of 20B rubles at 1993 e.c. at the time of program cancellation. Admittedly, with the Buran examples, it must be conceded that exact program figures are very challenging to obtain. In addition, the financial situation in Russia makes conversion rates between years, and also the calculation of the cost of Russian WYr very difficult.

The newly determined development WYr values for the Buran-Energia system using the STSR, as described in this Chapter, are consequently used for the comparison between the Space Shuttle system in the following chapter.

2.6 Space Shuttle & Buran-Energia Development Comparison

Now that the development costs for the two shuttle systems were calculated, it was an interesting exercise to compare the two results. While some elements of the Shuttle and Buran are indeed directly comparable, others are fairly different so to make a comparison is a little more challenging. Therefore some data processing and manipulation was required to achieve this purpose.

2.6.1 Generic Shuttle-Buran Comparison

To facilitate for a comparison to be made, it was necessary to establish and then group the individually standing and separately costed components into clear general categories which, after being summed, would then be tangibly comparable. This was achieved by grouping elements based on their functionality within each of the Shuttle and Buran launcher systems. The groups themselves were in fact similar to the CER groupings established in TransCost model. The launcher system functionality groups identified were:

- Engines
- Boosters
- Orbiter
- External Tank
- RCS/OMS Units

After this was achieved, all the components for the Buran-Energia, and the Shuttle had to then, fairly logically, be assigned to each category. The respective WYr effort figures and costs derived from TransCost, were filled in for each category and the amounts tallied to arrive at an overall category WYr effort figure and therefore cost.

The two key numerical results which are of importance within context of this analysis, are the WYr effort amounts, and their respective costs, in the home currency of the development effort, for the chosen year. In this respect, the logical pairing of the information pairs had to be *strictly* maintained in order to result in a meaningful result. In order to be representative, the f_8 country productivity complexity factor also had to be taken into account for each the US developed Shuttle system, and the Russian Buran. This is because the overall program cost comprises of a pairing of inputs between the WYr amount (a unit-less amount of effort) as well as then the WYr rate for that respective country, in that country's respective currency.

It is also important to point out that the Shuttle development phase was considered to be concluded in 1981. The development phase of the program began in 1972, and therefore a middle value year of 1978 was chosen, to represent the peak of development initiatives. As such, the USD costs are calculated using data for 1978 economic conditions (as seen in Table 114). For Buran, as seen in Table 115, the costs are calculated for 1993 economic conditions, since this was the year the program was cancelled, and is also the year for which historical Russian ruble exchange rates are available, and the WYr rate previously calculated in Chapter 0.

For both Buran and the Space Shuttle, *the TransCost calculated values for tank-like structures were ignored*, and instead, the literary value (Shuttle) and the STSR derived Buran values were substituted and used. Also very important to note is that the country productivity factor, f_8, is included in **each WYr calculation**, being 1.0 for the Space Shuttle and 2.11 for the Buran-Energia case. For this comparison, since it is really on an elementary level, other programmatic factors, namely f0, f6 and f7, are ignored as they affect the entire vehicle and its total integration.

The total WYr and cost amounts and results seen in the above tables represent a descriptive "mid-step" in the cost analysis process, and are to be interpreted independently of each other. They should not be directly compared before a final monetary value can be derived for a common year. This is because the f8 factor skews the total net WYr amounts per component (Russia having a lower productivity level than the US). Additionally, the currencies are also presented in rubles for the Buran, and in USD for the Shuttle, respectively.

Table 114: Functionality-based groupings of Space Shuttle development effort & costs

Components	SHUTTLE	WYr (w/f_8)	Cost (M$ 1978 e.c.)
Engine	SSME	16 602	1 323
	OMS Engine	829	66
Boosters	RSRM Boosters	9 375	747
Orbiter	Shuttle Orbiter	124 455	9 919
External Tank	External Tank	***7 030***	560
RCS/OMS Units	RCS/OMS Unit	425	34
TOTAL (with f_8)		**158 717**	**12 650**

Table 115: Functionality-based groupings of Buran-Energia development effort & costs

Components	BURAN	WYr (w/f_8)	Cost (M Russian rubles 1993 e.c.)
Engine	Energia (core RD-0120)	47 068	5 996
	17D12 OMS	2 806	357
	Energia (RD-170)	80 348	10 236
Boosters	Energia Block A Boosters	***1 860***	500
Orbiter	Buran Orbiter Vehicle	313 195	39 901
External Tank	Energia Block B Boosters	***3 217***	811
RCS/OMS Units	RCS/OMS Unit	3 319	423
TOTAL (with f_8)		**451 936**	**9 909**

2.6.2 Technical Shuttle-Buran Comparison

While top-level complexity factors are interesting, to remove any influence of country productivity and schedule delay (programmatic factor influences), and for the sake of a direct technically oriented comparison, a calculation based on comparable components, as already established above, can be made when the programmatic factors of f_6, f_7 and f_8 are set to 1.0. The f_0 systems engineering and integration factor remains as previously stated for each launch system, since this relates purely to technology. As such, only the WYr amounts are of interest for this part of the comparison, which is shown below in Table 116.

From the obtained results, and having removed programmatic factors, we can see that based on technical criteria alone, the Buran-Energia development effort is 137% the effort calculated for the Space Shuttle. A significant difference can be seen between the "Booster" category, as well as the Orbiters. Overall, it is not unreasonable to expect the Buran-Energia program to have incurred greater development costs, since the system required for development of two liquid stages and two liquid propellant engines for Block A and Block B. In contrast, the Shuttle system incurred development costs only for the SSME and ET. Furthermore, it is well known that solid propellant stages are significantly less complex than liquid propelled stages of the Buran. Therefore the TransCost result is in good congruence with the expected outcome.

*Table 116: Purely technical comparison of TransCost calculated work effort for Shuttle and Buran-Energia, **ignoring** programmatic factors f_6 and f_8*

Grouping	BURAN	WYr	SHUTTLE	WYr
Engine	Energia (core RD-0120) 17D12 OMS	22 307 1 330	SSME OMS Engine	16 602 829
Boosters	Energia (RD-170)* Energia Block A Boosters	38 079* 1 984	RSRM Boosters	9 375
Orbiter	Buran Orbiter	148 434	Shuttle Orbiter	124 455
External Tank	Energia Block B Boosters	3 217	External Tank	7 030
RCS/OMS Units	RCS/OMS Unit	1 573	RCS/OMS Unit	425
TOTAL		**216 924**		**158 717**

** Here, while the RD-170 is an engine, it has been grouped with the 'Booster' segment for Buran to make the Block A Boosters comparable with RSRM solid Shuttle Boosters.*

2.6.3 Discussion of the Shuttle-Buran Cost Comparison

With respect to literary figures, the TransCost calculated Buran development cost figure is closely matching the reported development cost of the program when programmatic factors and exchange rates are calculated. This is also the case for the Space Shuttle program, with TransCost providing a most reasonable development cost estimate which is logical and ROM with literary figures. The congruence is only evident if the TransCost calculated tank structures are taken out and replaced with literary values. A vital lesson learned is that a new CER should be established for tank-like structures. Also, in terms of the technical program figures shown in Table 116 above, while the WYr effort required for the Buran-Energia system appears higher than that of the Space Shuttle, this result is to be expected based on the higher complexity of the Buran-Energia system liquid stages and engines which were developed.

3. ASTRA Hopper Concept

ASTRA Hopper internal and industry-generated cost analyses documents were identified [17, 48, 49, 158]. These presented cost estimations and a detailed LCC breakdown for the ASTRA Hopper program, shown in Figure 55. Therefore the cost information contained therein was used as a benchmark to compare the resulting TransCost numbers with the existing documented estimation.

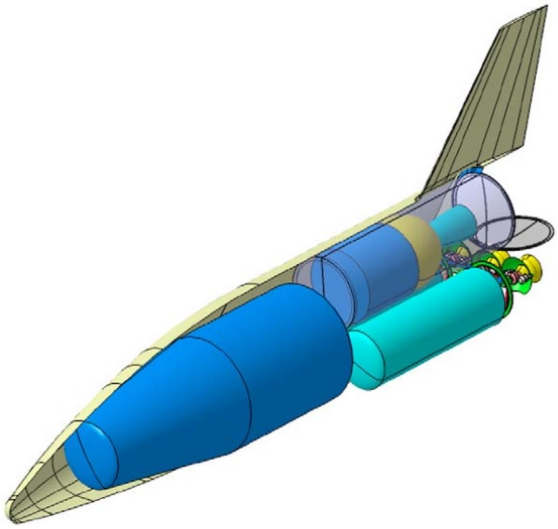

Figure 55: Hopper, the sub-orbital, single stage concept [17]

3.1 ASTRA Hopper Configuration

The Hopper launch vehicle comprises of the following elements, for which the development costs are applicable:

- Upper stage HUS24 (expendable)
    - Upper stage Vinci engine
- Reusable first ASTRA Hopper stage
    - Vulcain 3R main stage engine

Although the Vinci engine already exists, the development effort which is meant in the context of the ASTRA Hopper configuration is the development cost which would be incurred for a horizontal launch of the vehicle. Also, here, as with the LFBB stage from the ASSC2-Y9 program, the focal element for cost estimation is of course the reusable ASTRA stage. Furthermore, the development costs are calculated predominantly in 2002 e.c. since this was considered to be the timeframe of the Hopper development period. Of course this has no bearing on the effort amount, since this is merely a measure of effort, and as such is irrelevant for which year this work effort is converted into a monetary amount. The final costs, however, are all given in 2011 e.c. values to assist for a relevant comparison to be made.

3.2 ASTRA Hopper Excel Component Break-down

The component breakdown structure and the Excel TransCost spreadsheet screenshots with all relevant inputs and complexity factors for Hopper are presented below in Table 117 through to Table 120.

3.3 ASTRA Hopper Calculation Assumptions

Some key assumptions also had to be made within the scope of the Hopper and ASTRA cost estimation with regards to numerous inputs, complexity factors, as well as currency conversions. The key assumptions are outlined below, and are also annotated in **red** with association to the fields which the assumptions affect in the tables below.

A1. For the Vinci engine development cost estimation, an f_{12} delta development factor was assumed to account for the fact that the engine is merely a modification to previous engine developments. The prominent delta here is the fact that the vehicle is a horizontally starting one. Arguably, this f_{12} value was taken to be 0.1.

Table 117: TransCost CER for Vinci (upper stage HUS-24) engine

TC 7.3 Chapter 2.32		**Liquid Propellant Rocket Engines with Turbopumps**			***TC, pg. 35***
CER	**=**	**277 * M^0.48 * f1 * f2 * f3 * f5**	Engine Dry Mass (M)		556
	=	129.14 WYr	f1		0.4
			f2 (# test firings basis)		0.70
for f2 calculation			f3		0.8
Nq (# qualification firings)	180		*f12*	***A1.***	*0.1*
COST M€ (2011 e.c.)	**36.06**		*NORP*		*10*

Table 118: TransCost CER for upper stage (HUS-24)

TC 7.3 Chapter 2.43		**Expendable Ballistic Stages & Transfer Vehicles**			***TC, pg. 49***
CER	**=**	**100 * M^(0.555) * f1 * f2 * f3**	Vehicle DRY Mass w/o Engines (M)	***A4.***	3900
	=	8110.98 WYr	f1	***A5.***	1.2
			f2		0.69
for f2 calculation			f3		1
M_NET	34200	***A4.***			
M_engine	556				
M_propellant	23100	***A4.***			
% Res. Gas at c/o	3.15	***A4.***			
Res. Gas at c/o	727.65	***A4.***			
Usable Prop Mass	22372.35				
M_dry	4071.65				
NMF specific	0.18				
NMF average	0.125				
COST M€ (2011 e.c.)	**2 262.58**		*NORP*		*12*

Table 119: TransCost CER for Vulcain 3R (main stage) engine

TC 7.3 Chapter 2.32		Liquid Propellant Rocket Engines with Turbopumps				TC, pg. 35
CER	**=**	**277 * M^0.48 * f1 * f2 * f3 * f5**		Engine Dry Mass (M)		2520
	=	3644.61	WYr	f1		0.7
				f2 (# test firings basis)		0.73
for f2 calculation				f3		0.8
Nq (# qualification firings)		200	***A2.***	*f12*	***A3.***	*0.75*
COST M€ (2011 e.c.)		**1 016.67**		*NORP*		*10*

Table 120: TransCost CER for ASTRA Hopper (reusable) stage

TC 7.3 Chapter 2.45		Winged Orbital Rocket Vehicles				TC, pg. 63
CER	**=**	**1420 * M(0.35) * f1 * f2 * f3**		Vehicle DRY Mass w/o Engines (M)	***A6.***	51480
	=	76575.78	WYr	f1		1.3
				f2		0.93
for f2 calculation				f3		1
M_NET (w/engines)		59040	***A7.***			
M_propellant		392800	***A8.***			
M_payload		0				
NMF specific		0.1503055				
NMF average		0.145				
COST M€ (2011 e.c.)		**21 361.05**		*NORP*		*8*

A2. For the Vulcain 3R calculation, a number of 200 test firings was taken. A value of 500 test firings was identified in literature (ref. [100] page 37) for the Vulcain 1. It was therefore deemed appropriate to reduce the number of test firings for a modified Vulcain engine.

A3. For the Vulcain 3R calculation also, an f_{12} delta development factor was also assumed. This was taken to be a value of 0.75 to reflect an approximate 75% modification to the existing Vulcain engine family. As mentioned previously for the ASSC2-Y9 vehicle concept, while the Vulcain 3 engine exists, the 3R version must be reusable, which incurs the delta. In addition, for this ASTRA concept, the engine should be horizontally starting. Therefore f_{12} is greater than the f_{12} assumed for the ASSC2-Y9.

A4. For the HUS-24 upper stage, data for masses was predominantly obtained from [17], pp. 8 and 46 - 47.

A5. For the HUS-24 upper stage, an f1 factor of 1.2 was taken, to reflect the fact that horizontal takeoff for the stage is a novel technological concept which would result in a higher development cost.

A6. For the ASTRA Hopper stage calculation, the vehicle dry mass (without engines) was calculated by the following: Hopper Primary Stage Dry Mass – (3 x Vulcain 3R Mass) where the Vulcain 3R mass was found from ref. [17], pp. 51.

A7. For the ASTRA Hopper stage, the net mass (with engines) figure was extracted from ref. [17], pp. 51.

A8. For the ASTRA Hopper stage, the propellant mass figure was extracted from ref. [17], by summing the ascent and start-up propellant values.

A9. For the ASTRA Hopper stage, the payload technically is the main stage, and as such, the mass for the payload within the calculation was given as zero.

In addition, it is interesting to note that the mass of the Vulcain 3R engines for the LFBB (Table 11) and Hopper (

Table 119), as entered into the TransCost CERs, is different (2370 kg and 2520 kg for LFBB and Hopper respectively). Although the mechanics of the engine itself are the same, the difference arises due to a difference in the nozzle extension.

3.4 ASTRA Hopper Summary

Following the breakdown of individual components on a technical level, the additional TransCost programmatic factors which are then imposed on the sum of the constituent elements for the Hopper system, are all outlined below, and their chosen values stated:

- $f_0 = 1.08$

(f_0 = 1.04 number of stages, in the case of the Hopper, 2)

- $f_6 = 1$

(here, assume no deviation from optimum schedule)

- $f_7 = 1.00$

(f_7 = n 0.2; with n being the number of parallel contractor organisations, in this case assumed to be 1)

- $f_8 = 0.86$

(TransCost stated country productivity factor for ESA)

The following table shows a final summary of the effort (WYr) as well as the WYr with country productivity factor, f_8 for Europe of 0.86 imposed on each element. The f_8 imposition is important for a direct and relevant comparison to be made for the cost of each element on a technical level with literary values, since the country productivity factor plays a significant role on overall costs. This is an intermediary step, and at this stage the costs are ignored since the effort amount is the key figure of interest.

Table 121: TransCost summary of calculated ASTRA Hopper development work effort and costs, with imposition of f_8

Components	WYr	WYr (w/f_8)
Vinci Engine	129	111
Vulcain 3R Engine	3 645	3 134
HUS-24 Upper Stage	8 111	6 975
Astra Hopper Stage	76 576	65 855
TOTAL	**88 461**	**76 076**

At an overall, system level, with all additional TransCost factors applied, the top-level TransCost formula for the total development cost introduced in *Eq. 2*, is once again applied. Here, it must be noted that although the f_8 factor is shown, it has already numerically been integrated in the previous step at an element level. This is in line with a key change between TransCost 7.3 and the consequent 8.1 and 8.2 versions.

The final development cost of the ASTRA Hopper system, as calculated using the TransCost 7.3 model, was 22.97 B€ at 2011 economic conditions, being the equivalent of 82,280 WYrs.

3.5 ASTRA Hopper Comparison with Literary Figures

Several key internal documents [48-50, 158] were identified to act as a literary comparison for the TransCost derived calculation. These was independent, overall LCC calculations made for the industry using the parametric PRICE-H software [152, 153, 209].

Key data extracted from the ASTRA report [158] for the comparison with TransCost values is shown in Table 122.

As discussed previously within context of the LFBB, the above table once again does not explicitly state development costs of the Vulcain 3R, but rather absorbs this cost into the overall Hopper primary stage amount of €3988 M. The exact cost of the Vulcain 3R is included in the industry-developed cost estimation spreadsheet [49] and estimates the total development cost of the Vulcain 3R engine as being €664 M at 2002 economic conditions.

Table 122: Industry estimated ASTRA Hopper development costs [158]

	M€	Remarks
Project Office		
Vehicle System	303	
Mgmt & Ownership	605	
DDT&E		
Hopper Primary Stage	3988	
HUS-24	318	
Flight SW	218	200 men x 5 years
Proto-Flight Units		
1 x Hopper Primary Stage	523	later used in the operating fleet
2 x HUS	52	2 test flights
Ground Segment	951	
Total Development Phase	**6958**	

Extracting relevant information here, and ignoring software costs, a comparative table between TransCost and literary values is shown below in Table 123. By definition, TransCost development cost already includes the first prototype of the vehicle, while in literature, it is stated separately. Therefore, the literary development cost as well as the cost of that prototype, are summed up in the comparison.

Table 123: TransCost (TC) & industry (L) estimate ASTRA Hopper Figures

Components	Literary Cost M€ (2002 e.c.)	TransCost Cost M€ (2002 e.c.)	Delta TC/L (%)
Vinci Engine	n/a	22	n/a
Vulcain 3R Engine	618	631	2
HUS-24 Upper Stage	370	1403	279
Astra Hopper Stage	4511	13250	194
Flight SW	218	*included	n/a
TOTAL	**5717**	**15306**	**168**

**the Vinci engine already exists, and therefore it is considered a small delta development only, and excluded from development calculations.*

Finally, from the independent industry cost estimate, the total stated development cost of overall cost components, is 5.717 B€. In contrast, the TransCost calculated development cost, expressed in a monetary value at 2002 e.c., is 15.31 B€, as summarised below in Table 124.

Table 124: Development costs of the ASTRA Hopper system as calculated using TransCost 7.3 and as identified in an independent industry cost estimate

		Literature	TransCost		Delta TC/L (%)
C_D	=	5.72	15.31	B€ (2002 e.c.)	168

As can be seen, the TransCost estimation seems to be more than a factor of 1.5 greater than the complimentary industry-based estimation performed using the PRICE software. The Vulcain 3 engine component as calculated by TransCost seems to be fairly congruent with the

PRICE industry cost estimation. The other two components of the HUS-24 upper stage and the Astra Hopper stage, however, appear to deviate significantly. This needs to be examined further. However a lesson learned here is that TransCost appears to provide strongly indicative ROM figures for engine category. While there are considerable deviations between literature stated values for other stages, since it is impossible to gain access to detailed assumptions nor internal working and factors of the PRICE cost estimation, it cannot be clearly determined whether the PRICE estimation is too low, or whether the TransCost estimate is too high. However, from an EJ perspective, however, it appears that TransCost does produce very high costs for stages like tank-like structures and LFBB vehicles. For example, here, application of the AA_{VAL} mode of the AA (i.e. cost assessment with another third, independent tool) would be beneficial to assist indication of which of the two existing estimates was more indicative of actual costs.

APPENDIX F – SPACELINER MASS DATA

This data was obtained from DLR-SART Department internal space transportation systems (STSM) in-house tool used for SpaceLiner 7.1.

		Mass [kg]
Stage # 1	Booster of SpaceLiner 7-1 update 11-2012	
1. 1	Structure group:	
1. 1. 1	Nose	1800
1. 1. 2	Hypersonic Vehicle Body (HASA)	7056.651
1. 1. 3	Body-flap (Protected Structure)	341.85
1. 1. 4	LOX tank (WAATS)	17742.899
1. 1. 5	Tank	23962.223
1. 1. 6	Landing Wing Structure	15707.97
1. 1. 7	Fins / Vertical Stabilizer	1488.774
1. 1. 8	Wing Control Flaps	2112.399
1. 1. 9	Thrustframe Rocket Engines	4720.136
1. 1.10	Launch Table Support	2500
1. 1.11	Fwd Stage Attachment	1400
1. 1.12	Aft Stage Attachment	1100
1. 1.13	Fwd Crossfeed Fairing	250
1. 1.14	Aft Crossfeed Fairing	250
	Mass Structure group: w/o margins	80432.902
	Mass Structure group: including 14.0 % margins	91693.509
1. 2	Subsystem group:	
1. 2. 1	Engine Equipment	1698.143
1. 2. 2	GOX-pressurisation p	2750
1. 2. 3	GH2-pressurisation p	1400
1. 2. 4	LOX tank-press-system	780
1. 2. 5	LH2 tank-press-system	650
1. 2. 6	Undercarriage / Landing Gear	5560.912
1. 2. 7	Electrics	2702.505
1. 2. 8	Avionics	300
1. 2. 9	Hydraulics	400
1. 2.10	ECS	200
1. 2.11	Primary Power	400
1. 2.12	Separation System	2119.83
	Mass Subsystem group: w/o margins	18961.389

	Mass Subsystem group: including 14.0 % margins	21615.984
1. 3	Propulsion group:	
1. 3. 1	Rocket Main Engines	26500
1. 3. 2	LOX-main feedline	2350
1. 3. 3	LOX-manifold pmp	550
1. 3. 4	LH2-main feedline	165
1. 3. 5	LH2-manifold pmp	580
1. 3. 6	LOX-crossfeed pm	450
1. 3. 7	LH2-crossfees pm	500
1. 3. 8	Fill-Drain-Dump-line	500
1. 3. 9	RCS Engines	584
	Mass Propulsion group: w/o margins	32179
	Mass Propulsion group: including 12.0 % margins	36040.48
1. 4	Thermal Protection Group:	
1. 4. 1	TPS FRSI 401-500K	2873.57
1. 4. 2	TPS FRSI 501-600K	1379.37
1. 4. 3	TPS AFRSI 601-700K	1056.85
1. 4. 4	TPS AFRSI 701-800K	629.38
1. 4. 5	TPS AFRSI 801-900K	549.78
1. 4. 6	TPS TABI 901-1000K	1794
1. 4. 7	TPS TABI 1001-1100K	2154.77
1. 4. 8	TPS TABI 1101-1200K	480.59
1. 4. 9	TPS TABI 1201-1300K	2427.94
1. 4.10	TPS TABI 1301-1400K	1561.99
1. 4.11	TPS TABI 1401-1500K	473.22
1. 4.12	TPS TABI 1501-1600K	180.35
1. 4.13	TPS CMC 1601-1700K	1481.6
1. 4.14	TPS CMC 1701-1850K	116.19
1. 4.15	Cryogenic Insulation	850
1. 4.16	Cryogenic Insulation	2000
	Mass Thermal Protection Group: w/o margins	20009.6
	Mass Thermal Protection Group: including 14.0 % margins	22810.944
	Stage Mass empty: (stage coordinates)	151582.892
	Stage Mass empty incl. margin: (global coordinates)	172160.917
	Stage Structural Index:	
	Orbit/De-orbit propellant:	800
	Residual propellant:	2016

	Reserve propellant:	3500
	Stage Mass @ burn out:	178476.917
	Difference to MECO Mass from Trajectory Analysis:	3431.083
	RCS propellant /inert flow mass:	0
	Ascent propellant:	1283500
	GLOW Stage Mass:	1461976.92
Stage # 2	Orbiter of SpaceLiner 7-1 with passenger rescue capsule update 12-2012	
2. 1	Structure group:	
2. 1. 1	Hypersonic Vehicle Body (HASA)	14487.357
2. 1. 2	LOX tank (WAATS)	3282.74
2. 1. 3	Tank	4418.6
2. 1. 4	Landing Wing Structure	19049.586
2. 1. 5	Fins / Vertical Stabilizer	3988.981
2. 1. 6	Wing Control Flaps	1887.139
2. 1. 7	Body-flap (Protected Structure)	304.326
2. 1. 8	Thrust frame Rocket Engines	1007.756
2. 1. 9	Launch Table Support	870
	Mass Structure group: w/o margins	49296.484
	Mass Structure group: including 14.0 % margins	56197.992
2. 2	Subsystem group:	
2. 2. 1	Engine Equipment	443.45
2. 2. 2	GOX-pressurisation p	1005.9
2. 2. 3	GH2-pressurisation p	155
2. 2. 4	LOX tank-press-system	195
2. 2. 5	LH2tank-press-system	150
2. 2. 6	Electrics	2323.417
2. 2. 7	Hydraulics	300
2. 2. 8	Primary Power	400
2. 2. 9	Main Gear	3300
2. 2.10	Nose Gear	585
2. 2.11	Cabin incl. Passengers	29790.21
2. 2.12	Separation Motor	3070.1
2. 2.13	Nose WaterTank+Cooling	140
2. 2.14	Left wing Water Tank	160
2. 2.15	Right wing Water Tank	160
	Mass Subsystem group: w/o margins	42178.077
	Mass Subsystem group: including 14.0 % margins	48083.008

2. 3	Propulsion group:	
2. 3. 1	Rocket Main Engines	6600
2. 3. 2	LOX-main feedline	350
2. 3. 3	LOX-manifold pmp	135
2. 3. 4	LH2-main feedline	65
2. 3. 5	LH2-manifold pmp	145
2. 3. 6	LOX-crossfeed	250
2. 3. 7	LH2-crossfeed pm	350
2. 3. 8	Fill-Drain-Dump-line	500
2. 3. 9	RCS Engines	584
	Mass Propulsion group: w/o margins	8979
	Mass Propulsion group: including 12.0 % margins	10056.48
2. 4	Thermal Protection group:	
2. 4. 1	Cryogenic Insulation	583.5
2. 4. 2	Cryogenic Insulation	230.9
2. 4. 3	passive TPS	25465.074
2. 4. 3. 1	FRSI(530K TOP + estimation) T<=600K	762.187
2. 4. 3. 2	AFRSI(530K) 601K<=T<=700K Wing/Body	1121.247
2. 4. 3. 3	AFRSI(530K) 601K<=T<=700K Fin	226.976
2. 4. 3. 4	AFRSI(530K) 701K<=T<=800K Wing/Body	1941.013
2. 4. 3. 5	AFRSI(530K) 701K<=T<=800K Fin	719.511
2. 4. 3. 6	AFRSI(530K) 801K<=T<=900K Wing/Body	825.383
2. 4. 3. 7	AFRSI(530K) 801K<=T<=900K Fin	167.542
2. 4. 3. 8	TABI(530K) 901K<=T<=1000K Wing/Body	827.274
2. 4. 3. 9	TABI(530K) 901K<=T<=1000K Fin	14.809
2. 4. 3.10	TABI(530K) 1001K<=T<=1100K Wing/Body	478.341
2. 4. 3.11	TABI(530K) 1001K<=T<=1100K Fin	20.51
2. 4. 3.12	TABI(530K) 1101K<=T<=1200K Wing/Body	1494.763
2. 4. 3.13	TABI(530K) 1101K<=T<=1200K Fin	1.552
2. 4. 3.14	TABI(530K) 1201K<=T<=1300K Mass	2120.838
2. 4. 3.15	TABI(530K) 1301K<=T<=1400K Mass	7655.554
2. 4. 3.16	AETB-12(530K) 1401K<=T<=1500K Mass	4670.872
2. 4. 3.17	AETB-12(530K) 1501K<=T<=1600K Mass	1678.912
2. 4. 3.18	CMC(530K) 1601K<=T<=1700K Mass	519.434
2. 4. 3.19	CMC(530K) 1701K<=T<=1850K Mass	218.355
2. 4. 4	active TPS leading edge	680
2. 4. 5	active TPS nose	25
2. 4. 6	active TPS margin	250
	Mass Thermal Protection Group: w/o margins	27234.474

	Mass Thermal Protection Group: including 14.0 % margins	31047.3
	Stage Mass empty: (stage coordinates)	127688.035
	Stage Mass empty incl. margin: (global coordinates)	145384.78
	Stage Structural Index:	
	Orbit/De-orbit propellant:	12800
	Residual propellant:	1770
	Reserve propellant:	1750
	Stage Mass @ burn out:	161704.78
	Difference to MECO Mass from Trajectory Analysis:	-34379.804
	RCS propellant /inert flow mass:	0
	Ascent propellant:	215000
	GLOW Stage Mass:	376704.78
	SpaceLiner 7-1 Reference mission 13.12.2012	
	Total Vehicle Mass empty:	279270.927
	Vehicle Mass empty incl. margins:	317545.697
	Total Lift-off Mass:	1838681.7
	Gross Lift-Off Mass:	1838681.7
	* = user provided mass input	
	** = stsm super-component data set	

APPENDIX G – 4COST *ACES* ENGINEERING DIFFICULTY (ENGDIF) VALUES

Engineering Difficulty (ENGDIF HW/SW)								
	Team	Top Team	experienced Team	Task known, done before	"Standard" Team	Task little known	no experience	New Team
TASK		10	7	6	5	4	3	1
very simple	1	0,283	0,825	1,020	1,217	1,414	1,612	2,010
simple	2	0,447	0,894	1,077	1,265	1,456	1,649	2,040
standard -	4	0,825	1,131	1,281	**1,442**	1,612	1,789	2,154
standard +	5	1,020	1,281	1,414	**1,562**	1,720	1,887	2,236
new Task	6	1,215	1,441	1,562	1,696	1,844	1,999	2,332
new task +	8	1,612	1,789	1,887	2,000	2,126	2,226	2,562
Task new no references	10	2,010	2,154	2,236	2,332	2,441	2,561	2,828

Figure 56: Typical 4cost relation and values between Team and Task functions

APPENDIX H – 4COST *ACES* TOOL KEY INPUTS & OUTPUTS

Table 125: 4cost aces key hardware inputs for both development and production cost calculation as discussed in Chapters 4.9.3 and 4.10.3

Level	Component	We	Wm	Qty	Envird	Envirp	Newrepe	Newrepm	Techyear	Engdif	Indexe	Indexm
2	1.0 SpaceLiner 7.1 - Baseline	105.0000	439365.0058	500	2	1.868	0.54	0.76	125	1.580	6.431	5.1985
3	2000 SpaceLiner Orbiter	10.0000	130890.0011	500	2	1.884	0.61	0.78	125	1.508	6.510	5.0518
4	2200 Propulsion		43950.0011	500	2	2.000		0.37	125	1.196		4.9612
5	Engine Equipment		450.0000	500	2	2.000		0.80	125	1.165		4.5000
5	GOX pressurisation		1000.0000	500	2	2.000		0.80	125	1.165		4.5000
5	GH2 pressurisation		155.0000	500	2	2.000		0.80	125	1.165		4.5000
5	LOX Tank pressurisation system		195.0000	500	2	2.000		0.80	125	1.165		4.5000
5	LH2 Tank pressurisation system		150.0000	500	2	2.000		0.80	125	1.165		4.5000
5	Main Engines		3300.0000	6000	2	2.000		0.90	125	1.215		5.0000
5	RSC Engines		200.0000	1500	2	2.000		0.20	125	1.106		3.9000
5	LOX /LH2 Feed Lines		1800.0000	500	2	2.000		0.90	125	1.195		4.8000
5	I&T		17836.9598	500	2	2.000		0.37	125	1.196		3.2484
4	2300 Structure & Mechanic		57000.0000	500	2	1.800		0.61	125	1.759		5.1363
5	Hypersonic Vehicle Body		14500.0000	500	2	1.800		0.90	125	1.259		5.4100
5	LOX Tank WAATS		3300.0000	500	2	1.800		0.80	125	1.178		4.6300
5	LH2 Tank		4400.0000	500	2	1.800		0.80	125	1.178		4.6300
5	Landing Wing Structure		19000.0000	500	2	1.800		0.90	125	1.195		4.8000
5	Fins / Vertical Stabiliser		4000.0000	500	2	1.800		0.90	125	1.155		4.4000
5	Wing Control Flaps		1900.0000	500	2	1.800		0.90	125	1.155		4.4000

5	Body Flap		300.0000	500	2	1.800		0.90	125	1.155		4.4000
5	Thrust frame Rocket Engine		1000.0000	500	2	1.800		0.55	125	1.128		4.1300
5	Launch Table Support		885.0000	500	2	1.800		0.55	125	1.125		4.1000
5	Separated Motor		3070.0000	500	2	1.800		0.50	125	1.155		4.4000
5	Hydraulics		300.0000	500	2	1.800		0.90	125	1.195		4.8000
5	Water Tanks		460.0000	500	2	1.800		0.55	125	1.155		4.4000
5	Main Gear		3300.0000	500	2	1.800		0.50	125	1.214		4.9900
5	Nose Gear		585.0000	500	2	1.800		0.50	125	1.215		4.9900
5	I&T		19370.7458	500	2	1.800		0.61	125	1.759		3.3479
4	2400 TPC/TC		27250.0000	500	2	1.800		1.00	125	1.161		4.4677
5	Cryogenic Insulation		810.0000	500	2	1.800		0.90	125	1.155		4.4000
5	Active TPS – Thermal Protection System		970.0000	500	2	1.800		0.90	125	1.195		4.8000
5	Passive TPS - Thermal Protection System		25470.0000	500	2	1.800		0.90	125	1.155		4.4000
5	I&T		27250.0000	500	2	1.800		1.00	125	1.161		3.0457
4	2700 Power & Electrical	10.0000	2690.0000	500	2	1.800	0.57	0.63	125	1.467	6.795	4.3208
5	Power & ECS	10.0000	390.0000	500	2	1.800	0.50	0.20	125	1.652	6.800	4.5000
5	Cabling etc.		2300.0000	500	2	1.800		0.90	125	1.135		4.2000
5	I&T	10.0000	2690.0000	500	2	1.800	0.57	0.63	125	1.467	4.758	2.9307
4	I&T	10.0000	38115.7896	500	2	1.884	0.61	0.78	125	1.508	4.625	3.2798
3	3000 SpaceLiner Booster	50.0000	284080.0046	500	2	1.874	0.34	0.57	125	1.528	6.403	5.1575
4	3200 Propulsion (Main Engine w/o Development)		172030.0046	500	2	2.000		0.23	125	1.063		4.9193
5	GOX/LH2/LOX tank press.		7300.0000	500	2	2.000		0.80	125	1.165		4.5000
5	Main rocket Engines Booster with Engineering / Development		2945.0000	27000	2	2.000		0.00	125	1.063		5.0000
5	LOX /LH2 Feed Lines		5100.0000	500	2	2.000		0.80	125	1.135		4.2000
5	RSC Engines		200.0000	1500	2	2.000		0.50	125	1.106		3.9000
5	I&T		38172.2735	500	2	2.000		0.23	125	1.063		3.1584

4	3300 Structure & Mechanics		88500.0000	500	2	1.800		0.79	125	1.559		5.0385
5	Nose		1800.0000	500	2	1.800		0.88	125	1.155		4.4000
5	Hypersonic Vehicle Body (HASA)		7000.0000	500	2	1.800		0.90	125	1.195		4.8000
5	Body Flap		350.0000	500	2	1.800		0.90	125	1.155		4.4000
5	LOX Tank		17750.0000	500	2	1.800		0.80	125	1.178		4.6300
5	LH2 Tank		24000.0000	500	2	1.800		0.80	125	1.178		4.6300
5	Landing Wing Structure		15700.0000	500	2	1.800		0.90	125	1.232		5.1600
5	Fins / Vertical Stabiliser		1500.0000	500	2	1.800		0.90	125	1.232		5.1600
5	Wing Control Flaps		2100.0000	500	2	1.800		0.90	125	1.232		5.1600
5	Thrust frame Rocket Engine		4700.0000	500	2	1.800		0.55	125	1.125		4.1000
5	Launch Table Support		2500.0000	500	2	1.800		0.55	125	1.125		4.1000
5	Fwd Stage Attachment		1400.0000	500	2	1.800		0.90	125	1.145		4.3011
5	Aft Stage Attachment		1100.0000	500	2	1.800		0.90	125	1.145		4.3011
5	Fwd/Aft Cross feed fairing		500.0000	500	2	1.800		0.90	125	1.145		4.3011
5	Separation System		2150.0000	500	2	1.800		0.88	125	1.219		5.0355
5	Hydraulics		400.0000	500	2	1.800		0.90	125	1.195		4.8000
5	Landing Gear		5550.0000	500	2	1.800		0.50	125	1.232		5.1600
5	I&T		39462.4621	500	2	1.800		0.79	125	1.559		3.3228
4	3400 Thermal Protection		20000.0000	500	2	1.800		1.00	125	1.201		4.8479
5	Cryogenic Insulation		2850.0000	500	2	1.800		0.90	125	1.195		4.8000
5	TPS-Thermal Protection System		17150.0000	500	2	1.800		0.90	125	1.195		4.8000
5	I&T		18134.9062	500	2	1.800		1.00	125	1.201		3.2798
4	3600 Booster Avionics	30.0000	270.0000	500	2	1.800	0.01	0.01	125	1.549	6.440	4.5000
5	Mechanical		270.0000	500	2	1.800		0.01	125	1.165		4.5000
5	Electronic	30.0000		500	2	1.800	0.01		125	1.593	6.440	
5	I&T	30.0000	270.0000	500	2	1.800	0.01	0.01	125	1.549	4.480	3.0466
4	3700 Power & Electrical	20.0000	3280.0000	500	2	1.800	0.57	0.63	125	1.448	6.796	4.6769

5	Power & ECS	20.0000	580.0000	500	2	1.800	0.50	0.20	125	1.652	6.800	4.9500
5	Cabling etc.		2700.0000	500	2	1.800		0.90	125	1.165		4.5000
5	I&T	20.0000	3280.0000	500	2	1.800	0.57	0.63	125	1.448	4.759	3.1895
4	I&T	50.0000	73804.0275	500	2	1.874	0.34	0.57	125	1.528	4.520	3.3488
3	4000 SpaceLiner Passenger Cabin/Emergency Rescue Capsule	45.0000	24395.0000	500	2	1.800	0.47	0.65	125	1.607	6.464	4.8084
4	4200 Cabin Propulsion		2920.0000	500	2	1.800		0.06	125	1.186		4.0167
5	Two RCS engines		140.0000	1000	2	1.800		0.10	125	1.106		3.9000
5	Retro rockets		200.0000	1000	2	1.800		0.10	125	1.106		3.9000
5	Pitch motor		90.0000	500	2	1.800		0.10	125	1.106		3.9000
5	Separation System		430.0000	2500	2	1.800		0.10	125	1.102		3.8600
5	I&T		2270.5328	500	2	1.800		0.06	125	1.186		2.6704
4	4300 Cabin Structure		8100.0000	500	2	1.800		1.00	125	1.185		4.2711
5	Body Structure		1400.0000	500	2	1.800		0.90	125	1.135		4.2000
5	Body Flap		140.0000	500	2	1.800		0.90	125	1.135		4.2000
5	Crew Compartment		6560.0000	500	2	1.800		0.90	125	1.135		4.2000
5	I&T		6973.5027	500	2	1.800		1.00	125	1.185		2.8642
4	4400 Cabin TPC/TC		4600.0000	500	2	1.800		0.90	125	1.165		4.5000
4	4600 Cabin Avionics	30.0000	270.0000	500	2	1.800	0.12	0.41	125	1.412	6.000	4.3000
5	Mechanical		270.0000	500	2	1.800		0.50	125	1.145		4.3000
5	Electronic	30.0000		500	2	1.800	0.10		125	1.524	6.000	
5	I&T	30.0000	270.0000	500	2	1.800	0.12	0.41	125	1.412	4.143	2.9059
4	4700 Cabin Power & Electrical	5.0000	715.0000	500	2	1.800	0.26	0.63	125	1.419	6.795	4.3830
5	Power & ECS	5.0000	195.0000	500	2	1.800	0.20	0.20	125	1.652	6.800	4.5000
5	Cabling etc.		520.0000	500	2	1.800		0.90	125	1.135		4.2000
5	I&T	5.0000	685.3557	500	2	1.800	0.26	0.63	125	1.419	4.758	2.9556
4	4800 Cabin Life Support	10.0000	7790.0000	500	2	1.800	0.55	0.55	125	1.652	6.800	5.1000

4	I&T	45.0000	10693.9504	500	2	1.800	0.47	0.65	125	1.607	4.526	3.1467
3	Software				2				125			
4	SpaceLiner in flight				2				125			
4	Booster				2				125			
4	Ground				2				125			
4	I&T				2				125		-0.868	-0.8682
3	I&T	105.0000	79858.0793	500	2	1.868	0.54	0.76	125	1.580	3.945	2.8990

Table 126: 4cost aces hardware key outputs for both development and production cost calculation, as discussed in Chapters 4.9.3 and 4.10.3

Level	Component	DevTotal	PrdTotal	ModAmuc3 (no SW)	T1ModT1
2	1.0 SpaceLiner 7.1 - Baseline	20349615819.12	173975134435	388049773	787675863
3	2000 SpaceLiner Orbiter	7914158354.65	52450668999	120123236	276660919
4	2200 Propulsion	971657394.05	27955026537.94	57853370	142337306
5	Engine Equipment	40054100.04	247828421.07	575765	1417332
5	GOX pressurisation	74150001.06	487798709.83	1123897	2784606
5	GH2 pressurisation	17703879.25	100380878.23	236170	575440
5	LOX Tank pressurisation system	21096528.65	121952374.09	286098	698749
5	LH2 Tank pressurisation system	17266465.12	97628479.82	229790	559701
5	Main Engines	572785140.08	24940979564.28	4252294	19634652
5	RSC Engines	11294856.36	127113693.89	92272	318117
5	LOX /LH2 Feed Lines	179837797.22	1243472660.05	2846621	7124869
5	I&T	37438543.94	508644341.24	1092166	9324936
4	2300 Structure & Mechanic	5098116951.39	19214273048.39	48624781	108776767

5	Hypersonic Vehicle Body	2199396189.15	8553066665.40	21504926	49261268
5	LOX Tank WAATS	221579900.29	830831137.95	2104822	4735017
5	LH2 Tank	277834675.27	1057145704.66	2669961	6020129
5	Landing Wing Structure	1231199004.37	4618905877.45	11700210	26280980
5	Fins / Vertical Stabiliser	217022424.78	667056954.12	1768159	3968515
5	Wing Control Flaps	114062278.36	360507066.56	949139	2147832
5	Body Flap	27843978.82	78411249.51	212510	468721
5	Thrust frame Rocket Engine	38371238.44	143419506.50	363582	853502
5	Launch Table Support	33545684.80	124219923.32	315531	739250
5	Separated Motor	127744064.40	535999534.59	1327487	3190457
5	Hydraulics	44577545.83	139408898.11	367973	801068
5	Water Tanks	29875843.88	116744055.93	293240	666811
5	Main Gear	299823503.92	1.367215208.11	3334078	7837362
5	Nose Gear	73490195.94	313922831.10	774826	1805837
5	I&T	161618701.03	305552379.46	934342	6407375
4	2400 TPC/TC	1132112002.47	3839100028.12	9942424	21480581
5	Cryogenic Insulation	59332683.81	178186634.12	475039	1063278
5	Active TPS-Thermal Protection System	110881282.73	375200501.24	972164	2150314
5	Passive TPS-Thermal Protection System	854650562.24	3082084813.96	7873471	18266982
5	I&T	108478223.09	203418256.04	623793	4428698
4	2700 Power & Electrical	479696950.17	785053319.50	2529501	4025286
5	Power & ECS	341626523.12	423818174.25	1530889	2158707
5	Cabling etc.	102323052.36	314010197.65	832667	1866579
5	I&T	35712887.84	46679636.58	164785	932094
4	I&T	233062026.02	657216065.85	1780556	12858356
3	3000 SpaceLiner Booster	9862864569.81	114039825746.37	247806100	462099065
4	3200 Propulsion Main Engine (w/o development)	648512463.59	80970112487.42	163237255	273940412

5	GOX/LH2/LOX tank press.	348939036.63	2633252538.07	5964383	14959821
5	Main rocket Engines Booster with Engineering / Development	93336273.02	75874984055.23	2813641	19100885
5	LOX /LH2 Feed Lines	177171289.97	1216674545.00	2787692	6880193
5	RSC Engines	14599538.51	127113693.89	94475	318117
5	I&T	14645714.18	723278514.13	1475849	13902531
4	3300 Structure & Mechanics	6274502557.24	24366729714.70	61282466	137193875
5	Nose	108134118.05	344750555.27	905769	2054167
5	Hypersonic Vehicle Body (HASA)	524726396.53	1988567479.41	5026588	11343212
5	Body Flap	31302250.68	89064220.24	240733	532259
5	LOX Tank	837767326.93	3399725831.29	8474987	19284928
5	LH2 Tank	1065194014.84	4377046293.10	10884481	24807048
5	Landing Wing Structure	1603858381.14	6526236028.44	16260189	37406142
5	Fins / Vertical Stabiliser	241952135.75	838005725.84	2159916	5031688
5	Wing Control Flaps	316546141.00	1117497254.36	2868087	6707334
5	Thrust frame Rocket Engine	122302326.45	482110130.44	1208825	2858554
5	Launch Table Support	74883856.98	288710724.37	727189	1714291
5	Fwd Stage Attachment	79698282.30	242788593.97	644974	1446016
5	Aft Stage Attachment	66303578.68	199129216.12	530866	1186544
5	Fwd/Aft Cross feed fairing	36405256.99	104154868.17	281120	621555
5	Separation System	273960499.63	1009060278.44	2566042	5793561
5	Hydraulics	55690167.55	177701496.49	466783	1020458
5	Landing Gear	578213908.85	2679161100.99	6514750	15386094
5	I&T	257067995.23	499766652.34	1513669	10467213
4	3400 Thermal Protection	1446919446.37	5381388690.85	13656617	29435887
5	Cryogenic Insulation	258030324.35	890921066.91	2297903	5325456
5	TPS-Thermal Protection System	1070278599.23	4236316997.41	10613192	24110433

5	I&T	118802698.02	253746689.35	745099	5324857
4	3600 Booster Avionics	344435065.93	578315852.08	1845502	3044855
5	Mechanical	11337207.43	85964545.15	194604	492303
5	Electronic	324080232.13	461244774.70	1570650	2552552
5	I&T	9025744.60	31106504.71	80265	662429
4	3700 Power & Electrical	885206958.60	1530128305.54	4830671	7834678
5	Power & ECS	641067675.71	883139095.89	3048414	4512849
5	Cabling etc.	181874326.44	557378268.95	1478505	3321829
5	I&T	62297332.63	88610736.69	301816	1764185
4	I&T	263644001.50	1213150695.78	2953589	24302170
3	4000 SpaceLiner Passenger Cabin/Emergency Rescue Capsule	2340538833.87	7003813482.98	18692462	36655304
4	4200 Cabin Propulsion	48306065.99	306793589	710199	1716585
5	Two RCS engines	5613389.09	306793588.65	44126	130820
5	Retro rockets	7505944.15	38512213.78	58821	174125
5	Pitch motor	2248651.47	51315290.87	34051	87945
5	Separation System	30379475.72	14776960.55	87195	319623
5	I&T	2559210.34	15152926	35424	328734
4	4300 Cabin Structure	336439399.08	1142112698.24	2957104	5822045
5	Body Structure	66615021.02	209293564	551817	1245401
5	Body Flap	11668029.14	31894536	87125	190641
5	Crew Compartment	228102358.70	844046986	2144299	4386003
5	I&T	30080256.08	56360719	172882	1108262
4	4400 Cabin TPC/TC	256646258.87	909375633	2332044	5167024
4	4600 Cabin Avionics	182955133.46	325931014	1017772	1810555
5	Mechanical	13596158.82	62670783	152534	374415
5	Electronic	161207723.77	243679436	809774	1436140
5	I&T	8190275.22	19580806	55542	436107

4	4700 Cabin Power & Electrical	205227037.96	341718758	1093892	1722009
5	Power & ECS	159577848.47	227838758	774833	1166471
5	Cabling etc.	33114572.81	93174191	252578	555539
5	I&T	12529492.03	20509392	66078	409196
4	4800 Cabin Life Support	1200015350.36	3804109869	10008251	20417144
4	I&T	110924922.38	173771922	569394	3516675
3	Software				
4	SpaceLiner in flight				
4	Booster				
4	Ground				
4	I&T				
3	I&T	233161083.78	480826206	1427975	9697110

APPENDIX I – PRICE TOOL KEY INPUTS & OUTPUTS

Table 127: PRICE key hardware inputs for development cost calculation as discussed in Chapter 4.9.4

Index	Elements Title	PROTOS	PLTFM	WS	WT	MCPLXS	MCPLXE	ECMPLX	NEWST	NEWEL
0	SpaceLiner - Phase C/D	5	2	0	0	0	0	1.5	1	0
1	Orbiter (2000)	5	2	0	0	0	0	1.5	1	0
2	Propulsion (2200)	5	2	0	0	0	0	1.5	1	0
3	Engine Equipment	5	2	450	450	6.36	0	1.5	1	0
4	GOX Tank Pressurisation	5	2	1000	1000	6.36	0	1.5	1	0
5	LH2 Pressurisation	5	2	155	155	6.36	0	1.5	1	0
6	LOX Tank Pressurisation	5	2	195	195	6.36	0	1.5	1	0
7	LH2 Tank Pressurisation	5	2	150	150	6.36	0	1.5	1	0
8	Rocket Engines (2 per Orbiter)	10	2	3300	3300	8.034	0	2.7	1	0
9	RCS Engines	15	2	200	200	6.36	0	1.5	1	0
10	LOX/LH2 Feed Lines	5	2	1800	1800	6.36	0	1.5	1	0
11	Orbiter Propulsion Integration	5	2	0	0	0	0	1.5	0	0
12	Structure & Mechanisms (2300)	5	2	0	0	6.5	0	1.5	1	0
13	Hypersonic Vehicle Body	5	2	14500	14500	7.902	0	1.5	1	0
14	LOX Tank (WAATS)	5	2	3300	3300	7.696	0	1.5	1	0
15	LH2 Tank	5	2	4400	4400	7.696	0	1.5	1	0
16	Wing Structure	5	2	19000	19000	7.772	0	1.5	1	0
17	Fins/Vertical Stabiliser	5	2	4000	4000	7.772	0	1.5	1	0
18	Wing Control Flaps	5	2	1900	1900	7.772	0	1.5	1	0
19	Body Flap (Protected	5	2	300	300	7.492	0	1.5	1	0

	Structure)									
20	Thrust Frame	5	2	1000	1000	7.419	0	1.5	1	0
21	Launch Table Support	5	2	885	885	6.871	0	1.5	1	0
22	Separation Motor	5	2	3070	3070	7.83	0	1.5	1	0
23	Hydraulics	5	2	300	300	6.86	0	1.5	1	0
24	Water Tanks	5	2	460	460	7.019	0	1.5	1	0
25	Main Landing Gear	5	2	3300	3300	7.94	0	1.5	1	0
26	Nose Landing Gear	5	2	585	585	7.94	0	1.5	1	0
27	Orbiter Structure & Mechanisms I&T	5	2	0	0	6.5	0	1.5	0	0
28	TPC/TC (2400)	5	2	0	0	0	0	1.5	0	0
29	Cryogenic Insulation	5	2	810	810	6	0	1.5	1	0
30	Active TPS	5	2	800	970	6.57	9.497	1.5	1	1
31	Passive TPS	5	2	25470	25470	6.4	0	1.5	1	0
32	Orbiter TPC/TC Integration	5	2	0	0	0	0	1.5	0	0
33	Power & Housekeeping (2700)	5	2	0	0	0	0	1.5	1	0
34	Power and ECS	5	2	390	400	6	8.422	1.5	1	1
35	Cabling	5	2	2300	2300	7.3	0	1.5	1	0
36	Orbiter Power & Housekeeping I&T	5	2	0	0	0	0	1.5	0	0
37	Orbiter I&T	5	2	0	0	0	0	1.5	0	0
38	Booster (3000)	5	2	0	0	0	0	1.5	1	1
39	Propulsion (3200)	5	2	0	0	0	0	1.5	0.01	1
40	GOX/LH2/LOX Tank Pressurisation	5	2	7300	7300	6.36	0	1.5	0.01	0
41	Main Rocket Engine (9 per Booster)	45	2	2944.44	2944.44	8.034	0	1.5	0.01	0
42	LOX/LH2 Feed Lines	5	2	5100	5100	6.36	0	1.5	0.01	0
43	RCS Engines	15	2	200	200	6.36	0	1.5	0.01	0
44	Booster Propulsion I&T	5	2	0	0	0	0	1.5	0	0

45	Structure & Mechanisms (3300)	5	2	0	0	0	0	1.5	1	1
46	Nose	5	2	1800	1800	7.9	0	1.5	1	0
47	Hypersonic Vehicle Body (HASA)	5	2	7000	7000	6.29	0	1.5	1	0
48	Body Flap	5	2	350	350	7.419	0	1.5	1	0
49	LOX Tank (WAATS)	5	2	17750	17750	7.65	0	1.5	1	0
50	LH2 Tank	5	2	24000	24000	7.65	0	1.5	1	0
51	Landing Wing Structure	5	2	15700	15700	7.65	0	1.5	1	0
52	Fins/Vertical Stabiliser	5	2	1500	1500	7.65	0	1.5	1	0
53	Wing Control Flaps	5	2	2100	2100	7.65	0	1.5	1	0
54	Thrust Frame Rocket Engine	5	2	4700	4700	6.36	0	1.5	1	0
55	Launch Table Support	5	2	2500	2500	6.36	0	1.5	1	0
56	Fwd Stage Attachment	5	2	1400	1400	7.94	0	1.5	1	0
57	Aft Stage Attachment	5	2	1100	1100	7.94	0	1.5	1	0
58	Fwd/Aft Crossfeed Fairing	5	2	500	500	6.3	0	1.5	1	0
59	Separation Mechanism	5	2	2150	2150	7.94	0	1.5	1	0
60	Hydraulics	5	2	400	400	6.83	0	1.5	1	0
61	Landing Gear	5	2	5550	5550	7.94	0	1.5	1	0
62	Booster Structure & Mechanisms I&T	5	2	0	0	0	0	1.5	0	0
63	Thermal Protection (Active Elements) (3400)	5	2	0	0	0	0	1.5	0	0
64	Cryogenic Insulation	5	2	2850	2850	8.116	0	1.5	1	0
65	TPS	5	2	17150	17150	7.784	0	1.5	0	0
66	Booster Thermal Protection I&T	5	2	0	0	0	0	1.5	0	0
67	Avionics (3600)	5	2	0	0	0	0	1.5	1	1
68	OBC	5	2	130	150	6.57	9.036	1.5	1	0.8
69	ADCS	5	2	110	120	6.57	9.271	1.5	1	0.8

70	Communications	5	2	40	50	6.57	9.397	1.5	1	0.8
71	Health Monitoring	5	2	40	50	6.57	9.397	1.5	1	0.8
72	Booster Avionics I&T	5	2	0	0	0	0	1.5	0	0
73	Power & Electrical (3700)	5	2	0	0	0	0	1.5	1	1
74	Power & ECS	5	2	100	600	6.57	8.096	1.5	1	1
75	Cabling	5	2	2700	2700	7.3	0	1.5	1	0
76	Booster Power & Electrical I&T	5	2	0	0	0	0	1.5	0	0
77	Booster I&T	5	2	0	0	0	0	1.5	0	0
78	Capsule (4000)	5	2	0	0	0	0	1.5	0	0
79	Propulsion (4200)	5	2	0	0	0	0	1.5	0	0
80	RCS Engines	10	2	140	140	6.36	0	1.5	1	0
81	Retro Rockets	10	2	200	200	6.36	0	1.5	1	0
82	Pitch Motor	5	2	90	90	6.36	0	1.5	1	0
83	Separation System	5	2	430	430	6.36	0	1.5	1	0
84	Capsule Propulsion I&T	5	2	0	0	0	0	1	0	0
85	Cabin Structure (4300)	5	2	0	0	0	0	1.5	0	0
86	Body Structure	5	2	1400	1400	6.4	0	1.5	1	0
87	Body Flap	5	2	140	140	6.4	0	1.5	1	0
88	Crew Compartment	5	2	6560	6560	6.4	0	1.5	1	0
89	Cabin Structure I&T	5	2	0	0	0	0	1.5	0	0
90	Cabin TPC/TC (4400)	5	2	0	0	0	0	0	0	0
91	Top AFRSI	5	2	210	210	7.9	0	1.5	1	0
92	Top TABI	5	2	1610	1610	6.3	0	1.5	1	0
93	Bottom TABI	5	2	150	150	6.8	0	1.5	1	0
94	Bottom	5	2	1220	1220	6.8	0	1.5	1	0
95	Nose	5	2	1350	1350	6.8	0	1.5	1	0
96	Body Flap TPS	5	2	60	60	6.8	0	1.5	1	0

97	Cabin TPC/TC I&T	5	2	0	0	0	0	1.5	0	0
98	Cabin Avionics (4600)	5	2	0	0	0	0	0	0	0
99	Cabin Avionics	5	2	270	300	6.57	8.268	1.5	1	1
100	Cabin Avionics I&T	5	2	0	0	0	0	1.5	0	0
101	Cabin Power & Electrical (4700)	5	2	0	0	0	0	1.5	0	0
102	Power & ECS	5	2	195	200	6.57	8.422	1.5	1	0.8
103	Cabling	5	2	520	520	7.3	0	1.5	1	0
104	Cabin Power & Electrical I&T	5	2	0	0	0	0	1.5	0	0
105	Cabin Life Support (4800)	5	2	0	0	0	0	1.5	0	0
106	Cabin Life Support	5	2	7800	7800	7.94	0	1.5	1	0
107	Cabin Life Support I&T	5	2	0	0	0	0	1.5	0	0
108	Cabin I&T	5	2	0	0	0	0	1.5	0	0
109	Orbiter/Booster/Capsule I&T	5	2	0	0	0	0	1.5	0	0

Table 128: PRICE key hardware outputs for development cost calculation as discussed in Chapter 4.9.4

Index	Elements Title	TOTAL_DEV Total	ENGINEERING_DEV Total	MANUFACTURING_DEV Total	PROTOTYPE_DEV Total	PROGMGMT_DEV Total
0	SpaceLiner - Phase C/D	22176.76	13495.71	8681.05	7884.47	2364.59
1	**Orbiter (2000)**	**9547.33**	**5982.44**	**3564.89**	**3274.42**	**1021.30**
2	Propulsion (2200)	2151.56	1193.69	957.87	896.20	283.15
3	Engine Equipment	33.49	27.59	5.90	5.41	3.83
4	GOX Tank Pressurisation	60.08	48.60	11.49	10.57	6.86
5	LH2 Pressurisation	15.39	12.97	2.43	2.22	1.77
6	LOX Tank Pressurisation	18.20	15.26	2.94	2.69	2.09
7	LH2 Tank Pressurisation	15.03	12.67	2.36	2.16	1.73

8	Rocket Engines (2 per Orbiter)	1793.25	912.30	880.95	825.29	243.13
9	RCS Engines	25.46	17.61	7.85	7.32	3.06
10	LOX/LH2 Feed Lines	92.54	73.72	18.82	17.34	10.55
11	Orbiter Propulsion Integration	98.11	72.97	25.14	23.19	10.13
12	Structure & Mechanisms (2300)	5736.68	3562.85	2173.84	1983.39	567.75
13	Hypersonic Vehicle Body	1322.05	762.05	560.00	510.32	128.08
14	LOX Tank (WAATS)	363.11	237.62	125.49	114.52	36.32
15	LH2 Tank	453.61	291.85	161.75	147.66	45.26
16	Wing Structure	1496.34	865.64	630.70	576.07	146.43
17	Fins/Vertical Stabiliser	442.73	283.43	159.30	145.22	43.90
18	Wing Control Flaps	249.10	166.54	82.55	75.18	24.85
19	Body Flap (Protected Structure)	51.58	38.78	12.80	11.68	5.33
20	Thrust Frame	122.26	87.90	34.36	31.41	12.64
21	Launch Table Support	77.61	59.83	17.78	16.32	8.45
22	Separation Motor	374.47	241.60	132.87	120.99	37.02
23	Hydraulics	34.64	27.60	7.03	6.44	3.79
24	Water Tanks	52.72	40.83	11.90	10.90	5.68
25	Main Landing Gear	425.38	268.90	156.48	142.23	41.60
26	Nose Landing Gear	112.22	78.24	33.98	30.82	11.12
27	Orbiter Structure & Mechanisms I&T	158.86	112.02	46.84	43.63	17.28
28	TPC/TC (2400)	1116.71	852.99	263.72	241.17	117.66
29	Cryogenic Insulation	40.26	33.68	6.58	6.04	4.76
30	Active TPS	302.84	247.58	55.26	48.55	27.81
31	Passive TPS	678.51	495.30	183.21	169.95	76.13
32	Orbiter TPC/TC Integration	95.09	76.42	18.67	16.62	8.96
33	Power & Housekeeping (2700)	273.23	200.46	72.76	66.54	28.31
34	Power and ECS	42.38	37.20	5.18	4.57	4.22

35	Cabling	212.60	149.32	63.28	58.00	22.12
36	Orbiter Power & Housekeeping I&T	18.25	13.95	4.30	3.97	1.97
37	Orbiter I&T	269.15	172.44	96.71	87.11	24.43
38	**Booster (3000)**	**10467.48**	**6111.69**	**4355.78**	**3915.79**	**1122.98**
39	Propulsion (3200)	850.25	313.81	536.45	426.75	169.05
40	GOX/LH2/LOX Tank Pressurisation	71.32	10.52	60.80	56.25	7.36
41	Main Rocket Engine (9 per Booster)	502.37	159.83	342.55	247.47	133.71
42	LOX/LH2 Feed Lines	52.84	7.86	44.98	41.56	5.46
43	RCS Engines	9.23	1.41	7.82	7.30	1.07
44	Booster Propulsion I&T	214.49	134.19	80.30	74.18	21.45
45	Structure & Mechanisms (3300)	7266.98	4538.51	2728.47	2495.41	728.09
46	Nose	259.20	170.92	88.28	80.23	25.57
47	Hypersonic Vehicle Body (HASA)	239.93	185.34	54.59	50.50	27.38
48	Body Flap	55.41	41.66	13.75	12.55	5.76
49	LOX Tank (WAATS)	1304.58	773.84	530.74	485.59	129.23
50	LH2 Tank	1653.37	960.95	692.41	633.78	163.36
51	Landing Wing Structure	1184.88	708.61	476.26	435.73	117.50
52	Fins/Vertical Stabiliser	192.33	132.22	60.11	54.82	19.43
53	Wing Control Flaps	248.95	168.08	80.86	73.78	25.09
54	Thrust Frame Rocket Engine	187.84	145.65	42.19	38.99	21.32
55	Launch Table Support	117.87	93.07	24.80	22.88	13.42
56	Fwd Stage Attachment	218.98	145.73	73.24	66.51	21.57
57	Aft Stage Attachment	181.91	122.70	59.21	53.76	17.95
58	Fwd/Aft Crossfeed Fairing	34.74	28.70	6.05	5.55	4.00
59	Separation Mechanism	305.05	197.96	107.09	97.29	29.94
60	Hydraulics	41.98	33.29	8.70	7.97	4.60
61	Landing Gear	638.02	390.11	247.91	225.49	62.12

62	Booster Structure & Mechanisms I&T	401.94	239.67	162.27	150.01	39.86
63	Thermal Protection (Active Elements) (3400)	1212.24	422.22	790.02	719.13	112.82
64	Cryogenic Insulation	425.48	264.30	161.18	146.07	40.99
65	TPS	649.44	69.76	579.68	527.72	58.10
66	Booster Thermal Protection I&T	137.32	88.17	49.15	45.34	13.73
67	Avionics (3600)	144.79	122.45	22.34	19.64	13.62
68	OBC	42.74	35.84	6.90	6.08	4.06
69	ADCS	32.15	27.03	5.12	4.48	3.01
70	Communications	26.12	21.98	4.14	3.63	2.42
71	Health Monitoring	26.12	21.98	4.14	3.63	2.42
72	Booster Avionics I&T	17.67	15.62	2.05	1.82	1.71
73	Power & Electrical (3700)	576.19	459.74	116.45	106.17	59.24
74	Power & ECS	277.39	242.50	34.89	31.43	28.19
75	Cabling	240.04	167.37	72.67	66.62	24.94
76	Booster Power & Electrical I&T	58.76	49.87	8.90	8.11	6.11
77	Booster I&T	417.02	254.96	162.05	148.68	40.16
78	**Capsule (4000)**	**1977.00**	**1383.62**	**593.38**	**542.17**	**205.33**
79	Propulsion (4200)	85.55	67.94	17.61	16.26	9.82
80	RCS Engines	17.10	13.02	4.07	3.78	2.02
81	Retro Rockets	22.27	16.78	5.49	5.09	2.63
82	Pitch Motor	10.37	8.82	1.55	1.41	1.19
83	Separation System	32.40	26.72	5.68	5.21	3.71
84	Capsule Propulsion I&T	3.41	2.59	0.82	0.77	0.26
85	Cabin Structure (4300)	364.47	283.06	81.41	75.22	41.29
86	Body Structure	79.04	63.16	15.88	14.63	8.98
87	Body Flap	14.67	12.35	2.32	2.12	1.68
88	Crew Compartment	247.34	188.96	58.38	53.99	27.93

89	Cabin Structure I&T	23.41	18.59	4.82	4.47	2.70
90	Cabin TPC/TC (4400)	379.73	294.54	85.19	78.19	41.56
91	Top AFRSI	50.36	37.00	13.35	12.11	5.03
92	Top TABI	81.80	65.74	16.06	14.80	9.38
93	Bottom TABI	20.01	16.33	3.68	3.37	2.21
94	Bottom	93.85	72.20	21.66	19.91	10.28
95	Nose	101.18	77.58	23.60	21.70	11.08
96	Body Flap TPS	10.24	8.53	1.70	1.56	1.13
97	Cabin TPC/TC I&T	22.30	17.17	5.13	4.75	2.46
98	Cabin Avionics (4600)	72.19	63.30	8.88	7.93	7.28
99	Cabin Avionics	64.43	56.26	8.17	7.29	6.47
100	Cabin Avionics I&T	7.75	7.04	0.71	0.64	0.81
101	Cabin Power & Electrical (4700)	106.26	82.73	23.52	21.38	10.94
102	Power & ECS	28.36	23.84	4.52	4.01	2.80
103	Cabling	69.37	51.86	17.51	16.02	7.28
104	Cabin Power & Electrical I&T	8.52	7.03	1.49	1.35	0.86
105	Cabin Life Support (4800)	901.61	544.16	357.46	325.55	87.76
106	Cabin Life Support	832.87	497.86	335.01	304.88	80.85
107	Cabin Life Support I&T	68.74	46.29	22.45	20.67	6.91
108	Cabin I&T	67.19	47.89	19.30	17.65	6.68
109	Orbiter/Booster/Capsule I&T	184.95	17.96	166.99	152.09	14.98

Table 129: PRICE key hardware inputs for production cost calculation as discussed in Chapter 4.10.4

Index	Elements Title	PSTART	QTY	PLTFM	WS	WT	MCPLXS	MCPLXE	Labor/ Material Learning Curve	YRTECH
0	SpaceLiner - Phase C/D	132	500	1.8	0	0	0	0	85	2025
1	Orbiter (2000)	132	500	1.8	0	0	0	0	85	2025
2	Propulsion (2200)	132	500	2	0	0	0	0	85	2025
3	Engine Equipment	132	500	2	450	450	6.36	0	85	2025
4	GOX Tank Pressurisation	132	500	2	1000	1000	6.36	0	85	2025
5	LH2 Pressurisation	132	500	2	155	155	6.36	0	85	2025
6	LOX Tank Pressurisation	132	500	2	195	195	6.36	0	85	2025
7	LH2 Tank Pressurisation	132	500	2	150	150	6.36	0	85	2025
8	Rocket Engines (2 per Orbiter)	132	1000	2	3300	3300	8.034	0	85	2025
9	RCS Engines	132	1500	2	200	200	6.36	0	85	2025
10	LOX/LH2 Feed Lines	132	500	2	1800	1800	6.36	0	85	2025
11	Orbiter Propulsion Integration	132	500	2	0	0	0	0	85	2025
12	Structure & Mechanisms (2300)	132	500	1.8	0	0	5.873	0	85	2025
13	Hypersonic Vehicle Body	132	500	1.8	14500	14500	7.14	0	85	2025
14	LOX Tank (WAATS)	132	500	1.8	3300	3300	6.954	0	85	2025
15	LH2 Tank	132	500	1.8	4400	4400	6.954	0	85	2025
16	Wing Structure	132	500	1.8	19000	19000	7.023	0	85	2025
17	Fins/Vertical Stabiliser	132	500	1.8	4000	4000	7.023	0	85	2025
18	Wing Control Flaps	132	500	1.8	1900	1900	7.023	0	85	2025
19	Body Flap (Protected Structure)	132	500	1.8	300	300	6.77	0	85	2025
20	Thrust Frame	132	500	1.8	1000	1000	6.704	0	85	2025
21	Launch Table Support	132	500	1.8	885	885	6.209	0	85	2025

22	Separation Motor	132	500	1.8	3070	3070	7.075	0	85	2025
23	Hydraulics	132	500	1.8	300	300	6.199	0	85	2025
24	Water Tanks	132	500	1.8	460	460	6.342	0	85	2025
25	Main Landing Gear	132	500	1.8	3300	3300	7.175	0	85	2025
26	Nose Landing Gear	132	500	1.8	585	585	7.175	0	85	2025
27	Orbiter Structure & Mechanisms I&T	132	500	1.8	0	0	5.873	0	85	2025
28	TPC/TC (2400)	132	500	1.8	0	0	0	0	85	2025
29	Cryogenic Insulation	132	500	1.8	810	810	5.422	0	85	2025
30	Active TPS	132	500	1.8	800	970	5.937	9.497	85	2025
31	Passive TPS	132	500	1.8	25470	25470	5.783	0	85	2025
32	Orbiter TPC/TC Integration	132	500	1.8	0	0	0	0	85	2025
33	Power & Housekeeping (2700)	132	500	1.8	0	0	0	0	85	2025
34	Power and ECS	132	500	1.8	390	400	5.422	8.422	85	2025
35	Cabling	132	500	1.8	2300	2300	6.596	0	85	2025
36	Orbiter Power & Housekeeping I&T	132	500	1.8	0	0	0	0	85	2025
37	Orbiter I&T	132	500	1.8	0	0	0	0	85	2025
38	Booster (3000)	132	500	1.8	0	0	0	0	85	2025
39	Propulsion (3200)	132	500	2	0	0	0	0	85	2025
40	GOX/LH2/LOX Tank Pressurisation	132	500	2	7300	7300	6.36	0	85	2025
41	Main Rocket Engine (9 per Booster)	132	4500	2	2944.44	2944.44	8.034	0	85	2025
42	LOX/LH2 Feed Lines	132	500	2	5100	5100	6.36	0	85	2025
43	RCS Engines	132	1500	2	200	200	6.36	0	85	2025
44	Booster Propulsion I&T	132	500	2	0	0	0	0	85	2025
45	Structure & Mechanisms (3300)	132	500	1.8	0	0	0	0	85	2025
46	Nose	132	500	1.8	1800	1800	7.138	0	85	2025

47	Hypersonic Vehicle Body (HASA)	132	500	1.8	7000	7000	5.684	0	85	2025
48	Body Flap	132	500	1.8	350	350	6.704	0	85	2025
49	LOX Tank (WAATS)	132	500	1.8	17750	17750	6.913	0	85	2025
50	LH2 Tank	132	500	1.8	24000	24000	6.913	0	85	2025
51	Landing Wing Structure	132	500	1.8	15700	15700	6.913	0	85	2025
52	Fins/Vertical Stabiliser	132	500	1.8	1500	1500	6.913	0	85	2025
53	Wing Control Flaps	132	500	1.8	2100	2100	6.913	0	85	2025
54	Thrust Frame Rocket Engine	132	500	1.8	4700	4700	5.747	0	85	2025
55	Launch Table Support	132	500	1.8	2500	2500	5.747	0	85	2025
56	Fwd Stage Attachment	132	500	1.8	1400	1400	7.175	0	85	2025
57	Aft Stage Attachment	132	500	1.8	1100	1100	7.175	0	85	2025
58	Fwd/Aft Crossfeed Fairing	132	500	1.8	500	500	5.693	0	85	2025
59	Separation Mechanism	132	500	1.8	2150	2150	7.175	0	85	2025
60	Hydraulics	132	500	1.8	400	400	6.172	0	85	2025
61	Landing Gear	132	500	1.8	5550	5550	7.175	0	85	2025
62	Booster Structure & Mechanisms I&T	132	500	1.8	0	0	0	0	85	2025
63	Thermal Protection (Active Elements) (3400)	132	500	1.8	0	0	0	0	85	2025
64	Cryogenic Insulation	132	500	1.8	2850	2850	7.334	0	85	2025
65	TPS	132	500	1.8	17150	17150	7.034	0	85	2025
66	Booster Thermal Protection I&T	132	500	1.8	0	0	0	0	85	2025
67	Avionics (3600)	132	500	1.8	0	0	0	0	85	2025
68	OBC	132	500	1.8	130	150	5.937	9.036	85	2025
69	ADCS	132	500	1.8	110	120	5.937	9.271	85	2025
70	Communications	132	500	1.8	40	50	5.937	9.397	85	2025
71	Health Monitoring	132	500	1.8	40	50	5.937	9.397	85	2025
72	Booster Avionics I&T	132	500	1.8	0	0	0	0	85	2025

73	Power & Electrical (3700)	132	500	1.8	0	0	0	0	85	2025
74	Power & ECS	132	500	1.8	100	600	5.937	8.096	85	2025
75	Cabling	132	500	1.8	2700	2700	6.596	0	85	2025
76	Booster Power & Electrical I&T	132	500	1.8	0	0	0	0	85	2025
77	Booster I&T	132	500	1.8	0	0	0	0	85	2025
78	Capsule (4000)	132	500	1.8	0	0	0	0	85	2025
79	Propulsion (4200)	132	500	1.8	0	0	0	0	85	2025
80	RCS Engines	132	1000	1.8	140	140	5.747	0	85	2025
81	Retro Rockets	132	1000	1.8	200	200	5.747	0	85	2025
82	Pitch Motor	132	500	1.8	90	90	5.747	0	85	2025
83	Separation System	132	500	1.8	430	430	5.747	0	85	2025
84	Capsule Propulsion I&T	132	500	1.8	0	0	0	0	85	2025
85	Cabin Structure (4300)	132	500	1.8	0	0	0	0	85	2025
86	Body Structure	132	500	1.8	1400	1400	5.783	0	85	2025
87	Body Flap	132	500	1.8	140	140	5.783	0	85	2025
88	Crew Compartment	132	500	1.8	6560	6560	5.783	0	85	2025
89	Cabin Structure I&T	132	500	1.8	0	0	0	0	85	2025
90	Cabin TPC/TC (4400)	132	500	1.8	0	0	0	0	85	2025
91	Top AFRSI	132	500	1.8	210	210	7.138	0	85	2025
92	Top TABI	132	500	1.8	1610	1610	5.693	0	85	2025
93	Bottom TABI	132	500	1.8	150	150	6.144	0	85	2025
94	Bottom	132	500	1.8	1220	1220	6.144	0	85	2025
95	Nose	132	500	1.8	1350	1350	6.144	0	85	2025
96	Body Flap TPS	132	500	1.8	60	60	6.144	0	85	2025
97	Cabin TPC/TC I&T	132	500	1.8	0	0	0	0	85	2025
98	Cabin Avionics (4600)	132	500	1.8	0	0	0	0	85	2025
99	Cabin Avionics	132	500	1.8	270	300	5.937	8.268	85	2025

100	Cabin Avionics I&T	132	500	1.8	0	0	0	0	85	2025
101	Cabin Power & Electrical (4700)	132	500	1.8	0	0	0	0	85	2025
102	Power & ECS	132	500	1.8	195	200	5.937	8.422	85	2025
103	Cabling	132	500	1.8	520	520	6.596	0	85	2025
104	Cabin Power & Electrical I&T	132	500	1.8	0	0	0	0	85	2025
105	Cabin Life Support (4800)	132	500	1.8	0	0	0	0	85	2025
106	Cabin Life Support	132	500	1.8	7800	7800	7.175	0	85	2025
107	Cabin Life Support I&T	132	500	1.8	0	0	0	0	85	2025
108	Cabin I&T	132	500	1.8	0	0	0	0	85	2025
109	Orbiter/Booster/Capsule I&T	132	500	1.8	0	0	0	0	85	2025

Table 130: PRICE key hardware outputs for production cost calculation as discussed in Chapter 4.10.4

Index	Elements Title	T1_COST	UPC	AMORTIZED_ UNIT_COST	TOTAL_ PROD Total	AMORTIZED_UNIT _COST_TOT*	ENGINEERING _PROD Total	MANUFACTURING _PROD Total	PROGMGMT_ PROD Total
0	**SpaceLiner - Phase C/D**	**456.52**	**186.49**	**218.54**	**197991.61**	**395.98**	**14401.99**	**183589.62**	**10161.05**
1	**Orbiter (2000)**	**170.73**	**62.17**	**72.70**	**53857.46**	**107.7149**	**4140.55**	**49716.91**	**2940.45**
2	Propulsion (2200)	28.37	8.91	10.67	22842.61	45.68521	1428.49	21414.12	978.76
3	Engine Equipment	0.64	0.24	0.28	142.27	0.284536	13.35	128.92	8.88
4	GOX Tank Pressurisation	1.26	0.48	0.56	278.19	0.556383	26.11	252.08	17.43
5	LH2 Pressurisation	0.26	0.10	0.12	58.23	0.116451	5.45	52.78	3.62
6	LOX Tank Pressurisation	0.32	0.12	0.14	70.57	0.141136	6.61	63.96	4.39
7	LH2 Tank Pressurisation	0.26	0.10	0.11	56.65	0.113298	5.30	51.35	3.52
8	Rocket Engines (2 per Orbiter)	20.65	2.88	3.50	21010.48	42.02095	1262.03	19748.44	867.82
9	RCS Engines	0.33	0.10	0.11	164.14	0.32828	13.75	150.39	9.29

10	LOX/LH2 Feed Lines	2.07	0.78	0.91	456.14	0.912285	42.88	413.26	28.64
11	Orbiter Propulsion Integration	2.58	1.03	1.21	605.95	1.21189	53.01	552.94	35.17
12	Structure & Mechanisms (2300)	114.08	42.53	49.60	24800.95	49.60191	2169.11	22631.84	1577.39
13	Hypersonic Vehicle Body	29.18	10.84	12.71	6356.54	12.71309	556.48	5800.07	404.10
14	LOX Tank (WAATS)	6.69	2.50	2.90	1449.64	2.899271	126.58	1323.05	92.17
15	LH2 Tank	8.56	3.19	3.71	1854.02	3.708036	162.15	1691.87	118.04
16	Wing Structure	32.34	12.00	14.05	7026.42	14.05284	617.57	6408.85	448.64
17	Fins/Vertical Stabiliser	8.50	3.17	3.69	1843.51	3.687026	160.91	1682.61	117.09
18	Wing Control Flaps	4.49	1.68	1.94	972.11	1.944218	84.69	887.42	61.68
19	Body Flap (Protected Structure)	0.71	0.27	0.31	153.15	0.306306	13.41	139.74	9.77
20	Thrust Frame	1.85	0.69	0.79	396.53	0.793065	34.88	361.66	25.48
21	Launch Table Support	0.98	0.36	0.42	208.60	0.417208	18.69	189.91	13.67
22	Separation Motor	7.16	2.68	3.11	1555.41	3.110823	135.40	1420.01	98.52
23	Hydraulics	0.39	0.15	0.17	83.68	0.167365	7.48	76.20	5.46
24	Water Tanks	0.65	0.24	0.28	139.34	0.278683	12.41	126.93	9.06
25	Main Landing Gear	8.48	3.17	3.69	1845.74	3.691475	160.40	1685.34	116.62
26	Nose Landing Gear	1.91	0.72	0.83	414.91	0.829813	35.92	378.99	26.16
27	Orbiter Structure & Mechanisms I&T	2.19	0.88	1.00	501.34	1.002688	42.13	459.21	30.94
28	TPC/TC (2400)	18.68	6.99	8.15	4075.32	8.150642	364.39	3710.94	256.19
29	Cryogenic Insulation	0.38	0.14	0.16	80.67	0.161346	7.45	73.22	5.47
30	Active TPS	7.04	2.65	3.15	1575.24	3.150471	139.56	1435.67	92.76
31	Passive TPS	9.89	3.66	4.22	2109.15	4.218297	191.50	1917.65	140.32
32	Orbiter TPC/TC Integration	1.36	0.55	0.62	310.26	0.620528	25.88	284.39	17.65
33	Power & Housekeeping (2700)	3.94	1.48	1.70	849.80	1.6996	74.88	774.92	54.34
34	Power and ECS	0.39	0.15	0.17	84.30	0.168602	7.51	76.79	5.14
35	Cabling	3.34	1.24	1.43	716.63	1.43325	63.26	653.36	46.21

36	Orbiter Power & Housekeeping I&T	0.21	0.09	0.10	48.87	0.097747	4.11	44.77	2.99
37	Orbiter I&T	5.65	2.26	2.58	1288.78	2.577551	103.68	1185.09	73.76
38	**Booster (3000)**	**243.39**	**108.10**	**127.09**	**134757.02**	**269.514**	**9455.21**	**125301.80**	**6636.69**
39	Propulsion (3200)	39.02	31.49	37.89	90156.34	180.3127	5559.81	84596.52	3813.56
40	GOX/LH2/LOX Tank Pressurisation	6.75	2.53	2.97	1487.03	2.974052	140.41	1346.62	93.60
41	Main Rocket Engine (9 per Booster)	18.68	2.61	3.16	85452.88	170.9058	5130.89	80321.99	3528.18
42	LOX/LH2 Feed Lines	4.99	1.87	2.20	1097.65	2.195295	103.60	994.05	69.10
43	RCS Engines	0.33	0.10	0.11	164.14	0.32828	13.75	150.39	9.29
44	Booster Propulsion I&T	8.27	3.31	3.91	1954.64	3.909279	171.16	1783.48	113.40
45	Structure & Mechanisms (3300)	141.25	52.72	61.39	30693.95	61.3879	2690.50	28003.45	1957.67
46	Nose	4.84	1.81	2.10	1051.41	2.102828	91.29	960.13	66.43
47	Hypersonic Vehicle Body (HASA)	3.03	1.12	1.28	642.46	1.28491	58.48	583.98	42.97
48	Body Flap	0.76	0.28	0.33	162.77	0.325549	14.29	148.48	10.42
49	LOX Tank (WAATS)	26.99	10.01	11.69	5846.83	11.69365	515.21	5331.61	374.56
50	LH2 Tank	34.93	12.95	15.15	7573.22	15.14644	668.10	6905.12	485.54
51	Landing Wing Structure	24.30	9.02	10.53	5262.97	10.52595	463.54	4799.44	337.04
52	Fins/Vertical Stabiliser	3.26	1.22	1.41	703.80	1.407599	61.51	642.28	44.85
53	Wing Control Flaps	4.35	1.62	1.88	939.62	1.879232	82.14	857.48	59.86
54	Thrust Frame Rocket Engine	2.34	0.87	1.00	497.84	0.995675	45.21	452.63	33.22
55	Launch Table Support	1.39	0.51	0.59	295.30	0.590597	26.86	268.44	19.71
56	Fwd Stage Attachment	4.06	1.52	1.76	880.71	1.761415	76.38	804.33	55.58
57	Aft Stage Attachment	3.30	1.23	1.43	714.95	1.429909	62.00	652.96	45.13
58	Fwd/Aft Crossfeed Fairing	0.35	0.13	0.15	73.72	0.147435	6.73	66.99	4.93
59	Separation Mechanism	5.87	2.20	2.55	1276.33	2.552666	110.70	1165.63	80.52
60	Hydraulics	0.48	0.18	0.21	103.30	0.206591	9.26	94.04	6.76
61	Landing Gear	13.27	4.95	5.78	2887.85	5.775701	251.61	2636.24	182.85
62	Booster Structure & Mechanisms	7.75	3.11	3.56	1780.88	3.561756	147.21	1633.67	107.33

	I&T								
63	Thermal Protection (Active Elements) (3400)	41.16	15.37	17.96	8980.76	17.96153	783.46	8197.30	569.34
64	Cryogenic Insulation	8.86	3.31	3.87	1933.96	3.86793	167.35	1766.61	121.58
65	TPS	29.98	11.13	13.03	6514.64	13.02927	572.21	5942.42	415.71
66	Booster Thermal Protection I&T	2.32	0.93	1.06	532.16	1.064323	43.90	488.26	32.06
67	Avionics (3600)	2.56	0.98	1.15	572.75	1.145491	50.44	522.30	33.38
68	OBC	0.75	0.29	0.33	166.21	0.332427	14.67	151.55	9.82
69	ADCS	0.54	0.21	0.24	119.17	0.238343	10.48	108.69	6.97
70	Communications	0.52	0.20	0.23	115.70	0.231402	10.19	105.51	6.70
71	Health Monitoring	0.52	0.20	0.23	115.70	0.231402	10.19	105.51	6.70
72	Booster Avionics I&T	0.24	0.10	0.11	55.96	0.111917	4.91	51.04	3.18
73	Power & Electrical (3700)	8.78	3.28	3.82	1910.11	3.820224	171.93	1738.19	119.67
74	Power & ECS	4.26	1.58	1.86	930.13	1.860259	85.74	844.39	57.40
75	Cabling	3.82	1.42	1.64	821.44	1.64289	72.52	748.92	52.96
76	Booster Power & Electrical I&T	0.69	0.28	0.32	158.54	0.317075	13.66	144.87	9.31
77	Booster I&T	10.62	4.25	4.89	2443.11	4.886215	199.06	2244.05	143.08
78	**Capsule (4000)**	**31.91**	**12.03**	**13.94**	**6971.39**	**13.94278**	**611.22**	**6360.17**	**444.45**
79	Propulsion (4200)	0.77	0.37	0.42	209.23	0.418462	18.28	190.95	13.43
80	RCS Engines	0.13	0.04	0.05	46.20	0.092407	3.91	42.29	2.89
81	Retro Rockets	0.17	0.05	0.06	61.88	0.123762	5.25	56.63	3.88
82	Pitch Motor	0.09	0.03	0.04	19.20	0.038407	1.73	17.47	1.27
83	Separation System	0.33	0.12	0.14	69.14	0.138272	6.29	62.84	4.61
84	Capsule Propulsion I&T	0.06	0.02	0.03	12.81	0.025614	1.09	11.72	0.80
85	Cabin Structure (4300)	4.50	1.67	1.92	960.44	1.92089	86.85	873.59	63.73
86	Body Structure	0.90	0.33	0.38	190.41	0.380825	17.33	173.09	12.70
87	Body Flap	0.13	0.05	0.06	28.64	0.057283	2.59	26.05	1.89

88	Crew Compartment	3.22	1.19	1.37	684.60	1.3692	62.10	622.50	45.60
89	Cabin Structure I&T	0.25	0.10	0.11	56.79	0.113582	4.84	51.95	3.55
90	Cabin TPC/TC (4400)	4.73	1.77	2.03	1015.45	2.030908	90.47	924.98	66.17
91	Top AFRSI	0.76	0.29	0.33	166.00	0.331991	14.32	151.67	10.42
92	Top TABI	0.91	0.34	0.39	192.97	0.385935	17.61	175.35	12.92
93	Bottom TABI	0.21	0.08	0.09	44.37	0.088731	3.96	40.40	2.89
94	Bottom	1.19	0.44	0.51	254.24	0.508489	22.82	231.43	16.71
95	Nose	1.30	0.48	0.55	276.78	0.553551	24.83	251.95	18.18
96	Body Flap TPS	0.10	0.04	0.04	20.74	0.041485	1.84	18.90	1.34
97	Cabin TPC/TC I&T	0.26	0.11	0.12	60.36	0.120725	5.09	55.28	3.72
98	Cabin Avionics (4600)	0.75	0.28	0.33	162.66	0.325313	14.55	148.11	9.90
99	Cabin Avionics	0.69	0.26	0.30	148.13	0.296263	13.26	134.87	9.05
100	Cabin Avionics I&T	0.06	0.03	0.03	14.53	0.02905	1.28	13.24	0.85
101	Cabin Power & Electrical (4700)	1.33	0.50	0.57	286.93	0.573855	25.21	261.72	18.13
102	Power & ECS	0.31	0.12	0.13	65.73	0.131451	5.78	59.94	4.00
103	Cabling	0.95	0.35	0.41	202.76	0.405515	17.89	184.87	13.06
104	Cabin Power & Electrical I&T	0.08	0.03	0.04	18.44	0.036889	1.53	16.91	1.08
105	Cabin Life Support (4800)	18.86	7.05	8.24	4119.15	8.238305	358.24	3760.91	260.32
106	Cabin Life Support	17.79	6.62	7.74	3872.45	7.744903	337.89	3534.56	245.47
107	Cabin Life Support I&T	1.08	0.43	0.49	246.70	0.493402	20.35	226.35	14.85
108	Cabin I&T	0.96	0.38	0.44	217.52	0.435047	17.62	199.90	12.75
109	Orbiter/Booster/Capsule I&T	10.48	4.19	4.81	2405.74	4.81149	195.01	2210.73	139.46

APPENDIX J – PRELIMINARY CASE-STUDY OPERATIONS CONCEPT

These two excerpt tables of preliminary Space-Liner case-study Operational cost categories and figures is taken from a Final Year Thesis work entitled "*Innovation Appraisal for Complex Space Transportation Projects*" [111] written by Ms. Sarah Lipp conducted at the DLR, SART Department, and supervised by the author and within context and compilation and based on inputs resulting from this PhD Thesis.

Table 131: Assumptions underlying calculation of preliminary operations scenario [111]

SpaceLiner Fleet (Quantity)	500
Number of Spaceports	5
Launches per Day	2
Launch per Annum	730
Duration of Operation (years)	20
Ticket Price (€)	200000
PAX Number/SpaceLiner	50
LOX per Launch (kg)	1266000
LH2 per Launch (kg)	254000

Table 132: Preliminary breakdown and estimate of DOC & IOC categories [111]

ANNUAL (OPERATIONS) COSTS (€): 6,155,521,804							
Indirect Operating Costs (IOC)							3,066,573,078
ITEM	CATEGORY		UNIT	QUANTITY	DESCRIPTION	COST (€)	∑COST PER ANNUM (€)
Power			kWh/ Year	568000000	Price / kWh	0.1586	90,084,800
Water			m³/ Year	1000560	Price/ m³	1.813	1,821,045
Wastewater			m³/ Year	30017	Price/ m³	2.307	76,279
Communication			Months / Year	12	Costs/ Month	15,000	180,000
Management							7,500,000
	CEO		# of Employees	1	Costs/ Employee	300,000	300,000
	Overall Management		# of Employees	1	Costs/ Employee	300,000	300,000
	Spares Management		# of Employees	2	Costs/ Employee	300,000	600,000
	PAX Management		# of Employees	2	Costs/ Employee	300,000	600,000
	Refurbishment Management		# of Employees	2	Costs/ Employee	300,000	600,000
	Risk Management		# of Employees	4	Costs/ Employee	300,000	1,200,000
	Precipitation Management		# of Employees	3	Costs/ Employee	300,000	900,000
	Human Research Management		# of Employees	4	Costs/ Employee	300,000	1,200,000
	Financial Management		# of Employees	3	Costs/ Employee	300,000	900,000
	Quality Management		# of Employees	3	Costs/ Employee	300,000	900,000
Service Terminal							7,029,344
	Staff						5,569,344
		Check-in	# of Employees	3	Costs/ Employee	300,000	900,000
		PAX Support	# of Employees	8	Costs/ Employee	8064	64,512
		Security Check	# of Employees	4	Costs/ Employee	8,064	32,256

		Toll	# of Employees	4	Costs/ Employee	8,064	32,256
		Boarding	# of Employees	1	Costs/ Employee	300,000	300,000
		Cleaning	# of Employees	5	Costs/ Employee	300,000	1,500,000
		Technician	# of Employees	2	Costs/ Employee	300,000	600,000
		Security	# of Employees	5	Costs/ Employee	300,000	1,500,000
		Information	# of Employees	2	Costs/ Employee	300,000	600,000
		Luggage	# of Employees	5	Costs/ Employee	8,064	40,320
	Expenses		# of PAX	36500	Expenses/ PAX	40	1,460,000
Distribution							903,600
	Staff		# of Employees	3	Costs/ Employee	300,000	900,000
	(Office) Material		# of Employees	3	Annual Material Costs/ Employee	1,200	3,600
Media/ Marketing							1,168,000
	Staff		# of Employees	3	Costs/ Employee	300,000	900,000
	(Office) Material		# of Employees	3	Annual Material Costs/ Employee	6,000	18,000
	Extern Media Costs						250,000
Administration							3,614,400
	Staff						3,600,000
		Organisation	# of Employees	10	Costs/ Employee	300,000	3,000,000
		Purchasing Department	# of Employees	2	Costs/ Employee	300,000	600,000
	(Office) Material		# of Employees	12	Annual Material Costs/ Employee	1,200	14,400
Launch Site Support & Maintenance							10,975,610
	Staff		# of Employees	30	Costs/ Employee	300,000	9,000,000
	Supplies		Ratio Supplies/ Staff	0.22			1,975,610
Range Costs							50,000,000

Other Staff							9,900,000
	Waste Disposal		# of Employees	3	Costs/ Employee	300,000	900,000
	Area Cleaning		# of Employees	7	Costs/ Employee	300,000	2,100,000
	Gardener		# of Employees	2	Costs/ Employee	300,000	600,000
	Paramedic		# of Employees	4	Costs/ Employee	300,000	1,200,000
	Fire Department		# of Employees	15	Costs/ Employee	300,000	4,500,000
	Company Doctor		# of Employees	2	Costs/ Employee	300,000	600,000
door-to-door-Service							55,182,500
	Staff						24,000,000
		Pilot Helicopter (2x)	# of Employees	24	Costs/ Employee	300,000	7,200,000
		Jet crew (2x Pilot.1x Steward)	# of Employees	36	Costs/ Employee	300,000	10,800,000
		Driver	# of Employees	20	Costs/ Employee	300,000	6,000,000
	Vehicles						30,968,000
		Limousine (leasing)	Number	20	Monthly Leasing Rate	700	168,000
		Helicopter	Number	11	Price-Resale Price after a1	800,000	8,800,000
		Jet	Number	11	Price-Resale Price after a1	2,000,000	22,000,000
	Maintenance Helicopter. Jet		Number	22	Maintenance Costs Heli+Jet	9,750	214,500
Jumbo jet + Maintenance			Number	2	Annual Depreciation+Maint.	10,000,000	20,000,000
Annual Charges			Months / Year	12	Monthly Charges	1,000,000	12,000,000
Reserves for Crash without PAX			Crash without PAX/ Year	0.73	Production Costs for 1 SL	440,000,000	321,200,000
Reserves for Crash with PAX			Crash with PAX/ Year	0.0073	Reserves/ Launch	100,000	3,744,900
Depreciation							2,521,192,600
	(Running Costs) Production						2,200,000,000

	Depreciation Develop. Booster		Rate of Interest	0.07			107,085,600
	Depreciation Develop. Orbiter		Rate of Interest	0.07			90,832,300
	Depreciation Develop. Rest		Rate of Interest	0.07			123,274,700
DIRECT OPERATING COSTS (DOC)							3,088,948,726
Water during Launch			m^2/ Year	2448000	Price/ m^3	1.813	4,445,254
Vehicles							6,220,000
	Transportation Platform B & O		Number	2	Price/ Number	30,000,000	3,000,000
	Transportation Platform Capsule		Number	2	Price/ Number	10,000,000	1,000,000
	Big Cranes		Number	5	Price/ Number	6,500,000	1,625,000
	Small Cranes		Number	10	Price/ Number	500,000	500,000
	Working Platform		Number	10	Price/ Number	20,000	20,000
	Tug for SL		Number	2	Price/ Number	250,000	25,000
	Other SP Vehicles						50,000
Maintenance Vehicles & Equipment			Factor of Maintenance	0.0025			15,550
Ground Operations							763,576,146
Flight Control							176,315,957
Mission Costs							30,742,167
Charges per Launch					Charges/ Launch	100,000	73,000,000
Propellants							1,624,165,652
	LOX		Boil-off Loss in 4h	0.2	Price/ kg	0.18	199,622,880
	LH2		Boil-off Loss in 4h	0.2	Price/ kg	6.25	1,390,650.000
	Kerosene			64265800	Price/ kg	0.5	32,132,900
	Diesel			1366560	Price/ l	1.2	1,639,872

	Other fuel						120,000
Refurbishment after Landing							404,420,000
	Refurbishment Booster		Factor of Maintenance	0.0004	Maintenance Costs/ Flight	104,000	75,920,000
	Refurbishment Orbiter & Capsule		Factor of Maintenance	0.0025	Maintenance Costs/ Flight	450,000	328,500,000
Launch Delay			Boil-off Loss in 0.5h	0.025	Delays	73	2,774,000
Forced Landing							2,774,000
	Return O & B with in-air-capturing		Forced Landings/ Year	0.73	B & O in-air-capturing	100,000	73,000
	Transport PAX & Luggage		Refund	0.3	Airplane for PAX	700,000	2,701,000
Transport from Manufacture to SP					B & O in-air-capturing	100,000	500,000

References

[1] 4cost GmbH, "4cost-suite V3 Help Manual," instructional manual computer file.

[2] 4cost GmbH. (Accessed 14 September, 2010). *4cost GmbH website*. Available: http://www.4cost.de

[3] 4cost GmbH, "4cost=Interactive and Integrated Management Method for Software and Product Costing," Berlin, Germany.

[4] 4cost GmbH, "General Overview of the aces Cost Estimation Model, Advanced Cost Estimating System," 4cost GmbH, Berlin, Germany, 2011.

[5] Abitzsch, S., "Prospects of Space Tourism," presented at the 9th European Aerospace Congress - Visions and Limits of Long-term Aerospace Developments, Berlin, Germany, 1996.

[6] Adebola, S., Antifaev, J., Curran, C., Desportes, C., Rovira, O. G., Kelly, C., *et al.*, "Great Expectations: An Assessment of the Potential for Suborbital Transportation," Masters, International Space University (ISU), Illkirch-Graffenstaden, France, 2008.

[7] Aerospace Corporation. (Accessed 7 December, 2010). *Small Satellite Cost Model (SSCM) website*. Available: http://www.aero.org/capabilities/sscm/index.html

[8] Air Force Systems, "Cost Estimating Procedures," Headquarters Air Force System Command, USA, AFSCM-173-1, 1972.

[9] AIRBUS S.A.S. (Accessed 12 December, 2014). *A380*. Available: www.airbus.com

[10] AIRBUS website. (Accessed 19 August, 2014). *How is an aircraft built? Test Programme and Certification*. Available: http://www.airbus.com/company/aircraft-manufacture/how-is-an-aircraft-built/test-programme-and-certification/

[11] American Society of Professional Estimators (ASPE). (Accessed 1 October, 2010). *ASPE website*. Available: http://www.aspenational.org/

[12] Apgar, H., "A Tribute to Frank Frieman," presented at the ISPA Parametric World, A Newsletter to the International Society of Parametric Estimators, 2010.

[13] Arena, M. V., Younossi, O., Galway, L. A., Fox, B., Graser, J. C., Sollinger, J. M., *et al.*, "Impossible Certainty - Cost Risk Analysis for Air Force Systems," RAND Corporation, 2006.

[14] Armadillo Aerospace website. (Accessed 21 March, 2011). Available: http://www.armadilloaerospace.com

[15] Ashford, D., "An aviation approach to space transportation (A strategy for increasing space exploration within existing budget streams)," *The Aeronautical Journal* vol. 113, pp. 499-514, August, 2009.

[16] Association for the Advancement of Cost Engineering through Total Cost Management International (AACE). (Accessed 1 October, 2010). *AACE website*. Available: http://aacei.org/

[17] "Astra Hopper - System Concept Data Book," EADS Space Transportation, 27 June, 2003.

[18] Augustine, N. R., *Augustine's Laws and Major System Development Programs*. New York: American Institute of Aeronautics and Astronautics, 1980.

[19] Barrett, O. ([1999], Accessed 4 February, 2014). *An evaluation of the potential demand for space tourism within the United Kingdom*. Available: http://www.spacefuture.com/archive/an_evaluation_of_the_potential_demand_for_space_tourism_within_the_united_kingdom.shtml

[20] Batey, A. (23 April, 2014). *Your flight is now departing from space terminal 1: the amazing story behind Branson's Virgin Galactic project* Available: https://markosun.wordpress.com/2010/06/08/your-flight-is-now-departing-from-space-terminal-1-the-amazing-story-behind-bransons-virgin-galactic-project/

[21] Bauer, C., Garbers, N., Johannsson, M., and Lentsch, A., "Investigations of the SpaceLiner Passenger Capsule and Various Abort Scenarios," presented at the Deutscher Luft- und Raumfahrtkongress (DGLR), Berlin, Germany, 2012.

[22] Bauer, C., Garbers, N., and Sippel, M., "The SpaceLiner7 - Vehicle and Rescue Capsule," presented at the 29th International Symposium on Space Technology and Science (ISTS), Nagoya, Japan, 2013.

[23] Beard, S. S., Starzyk, J., "Space Tourism Market Study - orbital space travel & destinations with suborbital space travel," Futron Corporation, 2002.

[24] Benkard, C. L., "Learning and Forgetting: The Dynamics of Aircraft Production," *American Economic Review,* vol. 90, pp. 1034-1054, 4 September, 2000.

[25] Blanchard, B. S., *Design and Manage to Life Cycle Cost*. USA: M/A Press, 1978.

[26] Blum, C., Jones, P., and Meinders, B., "Dual Liquid Flyback Booster for the Space Shuttle," Lockheed Martin Michoud Space Systems, New Orleans, LA, 1998.

[27] Boehm, B. W., "Software Engineering Economics," *IEEE Transactions on Software Engineering,* vol. SE-10, pp. 4-21, 1984.

[28] Boehm, B. W., "Understanding and Controlling Software Costs " *Journal of Parametrics,* vol. 8, 1988.

[29] Boehm, B. W., Reifer, J. D., and Valerdi, R., "COSYSMO: A Systems Engineering Cost Model," University of Southern California, USA.

[30] Boeing. (Accessed 12 December, 2014). *777 Family - Orders and Deliveries*. Available: http://active.boeing.com/commercial/orders/index.cfm

[31] Butts, G., Linton, K., "The Joint Confidence Level Paradox: A History of Denial," National Aeronautics and Space Administration, 28 April, 2009.

[32] Christensen, P., Dysert, L. R., "Cost Estimate Classification System - As Applied in Engineering, Procurement, and Construction for the Process Industries," AACE International - the Authority for Total Cost Management, 29 November, 2011.

[33] Collins, P., Isozaki, K., "The Japanese Rocket Society's Space Tourism Research," presented at the International Symposium of Space Tourism, Bremen, 1997.

[34] Collins, P., Iwasaki, Y., Kanayama, H., and Ohnuki, M., "Commercial implications of market research on space tourism," *Journal of Space Technology and Science: Special Issue on Space Tourism, part 2,* vol. 10, No. 2, pp. 3-11, 1994.

[35] Collins, P., Stockmans, R., and Maita, M., "Demand for space tourism in America and Japan, and its implications for future space activities," *Advances in Astronautical Sciences,* vol. 91, pp. 601-610, 1995.

[36] *Commercial Space Transportation Study*. ([1997], Accessed 24 June, 2011). Available: http://www.hq.nasa.gov/webaccess/CommSpaceTrans/

[37] Crouch, G. I., "Researching the Space Tourism Market," in *Annual Conference of the Travel and Tourism Research Association*, 2001.

[38] Crouch, G. I., Devinney, T. M., Louviere, J. J., and Towhidul, I., "Modelling consumer choice behaviour in space tourism," *Tourism Management,* vol. 30, pp. 441-454, 2009.

[39] Crouch, G. I., Laing, J. H., "Australian public interest in space tourism and a cross-cultural comparison," *The Journal of Tourism Studies,* vol. 15, December, 2004.

[40] Curran, R., Raghunathan, S., and Price, M., "Review of aerospace engineering cost modeling: the genetic causal approach," *Progress in Aerospace Sciences,* vol. 40, pp. 487-534, 2004.

[41] *Currency Converter* (Accessed 13 June, 2014). Available: http://fxtop.com/

[42] Department of Defense (DoD). ([1995], Accessed 13 September, 2010). *DoD Parametric Cost Estimating Handbook (2nd ed.)*. Available: http://www.cost.jsc.nasa.gov/pceh.htm

[43] deSelding, P. B. (4 December, 2009) ESA Determined to Learn from the Mistakes of BepiColombo. *Space News International*.

[44] deSelding, P. B. (20 October, 2003) Europe's ATV Program Facing Launch Delay, Cost Overruns. *Space News International*.

[45] DLR-SART, "Space Transportation Systems Manual (STSM)," DLR - SART, Volume 1.2, Bremen, Germany, 2014.

[46] DLR Institute für Raumfahrtsysteme. (Accessed 13 September, 2011). *Astra Concept: semi-reusable launch vehicle with Ariane 5 cost stage and two attached reusable fly-back boosters (LFBB)* Available: http://www.dlr.de/irs/DesktopDefault.aspx/tabid-7629/12934_read-32489/gallery-1/gallery_read-Image.46.20496/

[47] Dryden, J. A., Large, J. P., "A Critique of Spacecraft Models, R-2196-1-AF," 1977.

[48] EADS Astrium, "ASSC 1 Life Cycle Cost - Issue 3," Excel spreadsheet, 22 March, 2001.

[49] EADS Astrium, "ASSC 1 Life Cycle Cost - Issue 6," Excel spreadsheet, 12 January, 2004.

[50] EADS Astrium, "ASSC 2Y Life Cycle Cost Calculation- Issue 4," Excel spreadsheet, 13 January, 2004.

[51] Eilingsfeld, F., "Technical Appendix - Parametrics," International Space University (ISU), 27 October, 2010.

[52] Eilingsfeld, F., "Estimating the Development Cost of an Orbital Passenger Spaceplane - Case Study for the International Space University," PRICE Systems Deutschland Ruesselsheim, Germany, 2006.

[53] Eilingsfeld, F., "Hardware Cost Modeling," International Space University (ISU), Illkirch-Graffenstaden, Lecture Series, 2014.

[54] *Encyclopedia Astronautica*. (Accessed 16 November, 2011). Available: www.astronautix.com

[55] ESA Requirements and Standards Division (ESTEC), "Space engineering - Testing " The Netherlands, European Cooperation for Space Standardization ECSS-E-10-03A, 15 February, 2002.

[56] ESA Requirements and Standards Division (ESTEC), "Space project management - Cost and schedule management," The Netherlands, European Cooperation for Space Standardization ECSS-M-ST-60C, 31 July, 2008.

[57] ESA Requirements and Standards Division (ESTEC), "Space project management - Project planning and implementation," European Cooperation for Space Standardization, The Netherlands ECSS-M-ST-10C Revision 1, 6 March, 2009.

[58] Evans, A., Bond, A., "The Commercial Case (2010) for the SKYLON Spaceplane Satellite Launcher," Reaction Engines Ltd., Abingdon, UK, July, 2010.

[59] *Federal Acquisition Regulation website*. (Accessed 22 October, 2010). Available: http://www.acquisition.gov/Far/

[60] Federal Aviation Administration (FAA), "FAA Life Cycle Cost Estimating Handbook: Parametric, Analogy, Engineering Estimation Risk Analysis Modeling and Simulation, Version 2.0," FAA Investment Cost Analysis Branch ASD-410, June, 2002.

[61] Floreani, D., Wood, L., "Internet to Orbit - Exploring the Potential of IP Networking Technologies in Space," 2005.

[62] Flottau, J. (10 June, 2013) Readying for Take Off. *Aviation Week & Space Technology*.

[63] Flottau, J. (17 June, 2013) Testing Times. *Aviation Week & Space Technology*

[64] Foussier, P., *From Product Descrpition to Cost: A Practical Approach* vol. 1: The Parametric Approach. France: Springer Publishing, 2006.

[65] Fox, B., Brancato, K., and Alkire, B., "Guidelines and Metrics for Assessing Space System Cost Estimates," The RAND Corporation, 2008.

[66] Futron Corporation, "Suborbital Space Tourism Demand Revisited," Bethesda, Maryland, August, 2006.

[67] Futron Corporation, "Innovative Strategies for Space Competitiveness," Bethesda, Maryland, 1 February, 2011.

[68] German Bureau of Statistics. (Accessed 20 October, 2014). *Weekly Hours Worked*. Available: https://www.destatis.de/EN/FactsFigures/Indicators/QualityEmployment/Dimension3/3_1_WeeklyHoursWorked.html

[69] Gerosa, S., Nasini, F., "Project Financing and Risk Management: a new challenge for program manahement in the space industry of the third millennium," presented at the Fourth European Project Management Conference (PMI), London, UK, 2001.

[70] Giacalone, J. A., "The evolving private spaceflight industry: space tourism and cargo transport," in *ASBBS Annual Conference*, Las Vegas, USA, 2013.

[71] Goehlich, R. A., Rücker, U., "Low-cost management aspects for developing, producing and operating future space transportation systems," *Acta Astronautica,* vol. 56, pp. 337-346, 2005.

[72] Greves, D., Schreiber, B. ([1995], Accessed 12 September, 2011). *Engineering Costing Techniques in ESA*. Available: http://www.esa.int/esapub/bulletin/bullet81/greve81.htm

[73] Haas, R., Maixner, O., "An Illustrated Guide to the Analytic Hierarchy Process," Institute of Natural Resource and Applied Life Sciences, Vienna, presentation slides.

[74] Habib-Agahi, H., Kwan, E., "NASA Instrument Cost Model (NICM) Presented to the NASA Cost Symposium " 13 April, 2005.

[75] Hamaker, J., "NASA Cost Estimating with emphasis on the Exploration Systems Architecture Study," in *NIA/SACD Distinguished Lecture Series in Systems Analysis*, NASA Headquarters, Washington D.C., 2006.

[76] Hammond, W. E., *Space Transportation: A Systems Approach to Analysis and Design* Virginia, USA: American Institute of Aeronautics and Astronautics Inc., 1999.

[77] Hart, K. ([2007], Accessed 21 March, 2011). *Travel Agency launches tourists on out-of-this-world adventures*. Available: http://seattletimes.nwsource.com/html/businesstechnology/

[78] Hartley, K., "The Learning Curve and its Application to the Aircraft Industry," *Journal of Industrial Economics,* vol. 13, pp. 122-128, 1965.

[79] Havranek, T. J., *Modern Project Management Techniques for the Environmental Remediation Industry*. Florida, USA: CRC Press LCC, 1999.

[80] Hendrickx, v. B., Vis, B., *Energiya-Buran: The Soviet Space Shuttle* Checheser, UK: Praxis Publishing Ltd., 2007.

[81] Hess, R. W., Romanoff, H. P., "Aircraft Airframe Cost Estimating Relationships - Study Approach and Conclusions," Santa Monica, USA R-3255-AF, December, 1987.

[82] Hochschule für Angewandte Wissenschaften Hamburg (HAW), IDS Hamburg GmbH, "Vision of the SpaceLiner concept in gliding flight," Graphic.

[83] Hughes, R. T., "Expert judgement as an estimating method," *Information & Software Technology,* vol. 38, pp. 67-75, 1996.

[84] Humphreys, K., Wellman, P., "Basic Cost Engineering," New York, USA, 1996.

[85] Hunt, C. D., van Pelt, M. O., "Comparing NASA and ESA Cost Estimating Methods for Human Missions to Mars," NASA MSFC, Huntsville, USA, ESA-ESTEC, Noordwijk, The Netherlands, March, 2004.

[86] Interesting Engineering. (Accessed 27 November, 2014). *Kansai International Airport*. Available: http://interestingengineering.com/kansai-international-airport/

[87] International Cost Engineering Council (ICOSTE). (Accessed 5 October, 2010). *ICOSTE website*. Available: http://www.icoste.org/

[88] International Cost Estimating and Analysis Association (ICEAA). (Accessed 2 December, 2014). *ICEAA website* Available: http://www.iceaaonline.com/

[89] International Society of Parametric Analysts (ISPA), Society of Cost Estimating and Analysis (SCEA), "ISPA and SCEA Parametric Estimating Handbook," 4th Edition, Vienna, VA.

[90] International Society of Parametric Analysts (ISPA). (Accessed 1 October, 2010). *ISPA website*. Available: http://www.ispa-cost.org/

[91] Jenkins, D. R., *Space Shuttle - The History of the National Space Transportation System, The First 100 Missions*: Elsevier Publishing, 2010.

[92] Johnson, J. P., Gaier, E. M., "Air Cargo Operations Cost Database," NASA, Virginia, USA, April, 1998.

[93] Johnson, R. F., Smith, P. L., "Future spacelift projections," *Space Policy,* vol. 14, pp. 145-151, 1998.

[94] Jonas, V., "Five steps to Enterprise Risk Management " Risk Decisions Group, January, 2011.

[95] Kasperczyk, N., Knickel, K. ([2006], 16 March, 2011). *The Analytic Hierarchy Process (AHP)* Available: www.ivm.vu.nl/en/Images/MCA3_tcm53-161529.pdf

[96] Keiderling, D., "SART TN-002/2010: Aufstiegssimulation des Space Transportation Systems," DLR Systemanalyse Raumtransport (SART), Bremen, 2010.

[97] Kitchenham, B., *Making Process Predictions*. New York Chapman & Hall, 1997.

[98] Klepper, S., "Industry Life Cycles," *Industrial and Corporate Change,* vol. 6, 1997.

[99] Koelle, D. E., "Cost Engineering, the new paradigm for space launch vehicle design," *Journal of Reducing Space Mission Cost,* vol. 1, pp. 73-86, 1998.

[100] Koelle, D. E., "Handbook of Cost Engineering for Space Transportation Systems including TransCost 7.3, Revision 3," TransCostSystems, 2010.

[101] Koelle, D. E., "Handbook of Cost Engineering for Space Transportation Systems including TransCost 8.1, Revision 3a," TransCostSystems, 2010.

[102] Koelle, D. E., "Handbook of Cost Engineering for Space Transportation Systems including TransCost 8.2, Revision 4," TransCostSystems, 2012.

[103] Koelle, D. E., "Two TransCost Questions re. Shuttle ET & WYr," E-mail communication, 27 November, 2012.

[104] Kothari, A. P., Webber, D., "Potential Demand for Orbital Space Tourism Opportunities Made Available via Reusable Rocket and Hypersonic Architectures " presented at the AIAA SPACE 2010 Conference & Exposition, Anaheim, California, USA, 2010.

[105] *Kurshistorie EUR/USD Currency Converter*. (Accessed 9 November, 2013). Available: http://www.boerse.de/historische-kurse/Euro-Dollar/EU0009652759

[106] Laing, J., Crouch, G. I., *Chapter 2: Vacationing in Space: Tourism Seeks "New Skies"*. Oxfordshire, UK: CABI Publishing, 2004.

[107] Liebers, A., "An architecture for cost control, the use of cost information in order-related decisions," Ph.D. Thesis, University of Twente, 1998.

[108] "Life Cycle Cost Estimations for FESTIP Concepts - FESTIP CONFIDENTIAL, FSS-SCT-RP-0060 Report," Germany.

[109] Lillie, C. F., Thompson, B. E., "Parametric cost estimation for space science missions," presented at the International Society for Optical Engineering (SPIE), Congress of Advanced Optical and Mechanical Technologies in Telescopes and Instrumentation, Marseille, France, 2008.

[110] Lipp, S., "Spaceport Concepts and Locations for the SpaceLiner," Deustsches Zentrum für Luft- und Raumfahrt, Bremen, Germany, November, 2014.

[111] Lipp, S., "Innovationsbewertung bei komplexen Raumtransportprojekten," Wirtschaftsingenieurwesen Produktionstechnik, Schwerpunkt Luft- und Raumfahrt Bachelor Thesis, Universität Bremen, Germany, 2015.

[112] Madauss, B., "Management Advantages of the Standard Work Breakdown Structure Proposed by the European Space Agency for Space Satelitte Projects," Pacific States University, Los Angeles, USA, 1980.

[113] Madauss, B., *Planung und Überwaching von Forschungs- und Entwicklungsprojekten - mit Beiträgen aus der Raumfahrttechnik (Planning and Monitoring of Research and Development projects - with contributions from Space Technology)*. Ottobrunn: AIB Fachliteratur, 1982.

[114] Madauss, B., *Handbuch Projektmanagement (Project Management Handbook)*. Stuttgart: 5th Edition, Schäffer-Poeschel, 1994.

[115] Madauss, B., *Handbuch Projektmanagement (Project Management Handbook)*. Stuttgart: 6th Edition, Schäffer-Poeschel, 2000.

[116] Madauss, B., "Training for Satelitte Engineering and Management - XIII.6 Risk Evaluation and Mitigation Plan," International Space University (ISU), Illkirchen-Graffenstanden, France, Lecture Series, 2010.

[117] Madauss, B., "Hourly Rates for SPO," E-mail communication, 20 October, 2014.

[118] Madauss, B., "SpaceLiner - Additional SPO Information," International Space University (ISU), Illkirch-Graffenstaden, France, official ISU letter, 28 November, 2014.

[119] Madauss, B., "SpaceLiner - SPO Information," International Space University (ISU), Illkirch-Graffenstaden, France, official ISU letter, 18 October, 2014.

[120] Madauss, B., "SpaceLiner - Model Philosophy," International Space University (ISU), Illkirch-Graffenstaden, France, official ISU letter, 5 January, 2015.

[121] Madauss, B., "SpaceLiner - Model Philosophy (revised)," International Space University (ISU), Illkirch-Graffenstaden, France, official ISU letter, 12 January, 2015.

[122] Madauss, B., Trivailo, O., "Important Programmatic Aspects," in *SpaceLiner Workshop*, power point presentation slides, Bremen, Germany, 2013.

[123] *Make or Break: Why Accurate Cost Estimation Is Key*. ([2008], Accessed 9 November, 2012). Available: http://www.projectsmart.co.uk/make-or-break-why-accurate-cost-estimation-is-key.html

[124] Maryniak, G. E., "When will we see a golden age of spaceflight?," *Space Policy,* vol. 21, pp. 111-119, 2005.

[125] Mealey, A. (Accessed 8 June, 2011). *Space Tourism Survey*. Available: http://www.spacetourismnow.com/blog/index.php/space-tourism/space-tourism-survey/

[126] Mediavilla, J. I. ([2011], Accessed 20 November, 2014). *Learning Curves: Boeing 787 case in 2013*. Available: http://theblogbyjavier.com/2014/03/05/learning-curves-boeing-787-case-in-2013/

[127] Mediavilla, J. I. ([2011], Accessed 20 November, 2014). *Will Boeing 787 ever break-even?* Available: http://theblogbyjavier.com/2011/10/28/will-boeing-787-ever-break-even/

[128] Meisl, C. J., "Techniques for cost estimating in early program phases," *Engineering Costs and Production Economics,* vol. 14, pp. 95-106, 1988.

[129] Merlin, P. W., *Design and Development of the Blackbird*. California, USA: American Institute of Aeronautics and Astronautics, Inc., 2008.

[130] Meyer, M. A., Booker, J. M., *Eliciting and Analyzing Expert Judgement - A Practical Guide* London: Academic Press Ltd., 2001.

[131] Mikheev, A., Lukashevich, V. ([2000], Accessed 19 August, 2013). *Buran Schematic*. Available: http://airwingmedia.com/news/2013/buran-soviet-space-shuttle/

[132] Miller, D. W., Keesee, K., and Jilla, C., "Space System Cost Modeling," MIT Aeronautics and Astronautics Course, 2003.

[133] Möller, T., *Projekte erfolgreich managen*. Köln, Germany: TÜV Media, 2014.

[134] *NASA/Jet Propulsion Laboratories Cost Estimation website*. (Accessed 13 September, 2010). Available: http://cost.jsc.nasa.gov/

[135] National Aeronautics and Space Administration, *2002 NASA Cost Estimating Handbook*. Washington D.C., 2002.

[136] National Aeronautics and Space Administration, *2004 NASA Cost Estimating Handbook*. Washington D.C., 2004.

[137] National Aeronautics and Space Administration, *2008 NASA Cost Estimating Handbook*. Washington D.C., 2008.

[138] National Aeronautics and Space Administration, "NASA's Challenges to Meeting Cost, Schedule, and Performance Goals," National Aeronautics and Space Administration, IG-12-021, 27 September, 2012.

[139] National Aeronautics and Space Administration, "Understanding Joint Confidence Level (JCL) at NASA," Office of Evaluation, Cost Analysis Division, JCL Analysis Primer, 2012.

[140] National Aeronautics and Space Administration, "Structural Design and Test Factors of Safety for Spaceflight Hardware," Washington D.C. NASA-STD-5001B, 6 August, 2014.

[141] National Research Council of the National Academies, *Reusable Booster System: Review and Assessment*. Washington, DC: The National Academies Press, 2012.

[142] O'Leary, B., "The Space Shuttle - NASA's White Elephant in the Sky " *Science and Public Affairs - Bulletin of the Atomic Scientists,* vol. XXIX, pp. 36-43, February, 1973.

[143] O'Neil, D., Bekey, I., Mankins, J., Rogers, T. F., and Stallmen, E. W., "General Public Space Travel and Tourism," March, 1998.

[144] *Operating and Support Cost-Estimating Guide*. ([1992], Accessed 25 April, 2014). Available: http://www.dtic.mil/pae/

[145] Orlebar, C., *The Concorde Story*: 6th Edition, Osprey Publishing Ltd., 2004.

[146] Papathanassis, A., Klemm, G., and Markkanen, S., "Space tourism: The Long Tail of Tourism - Holiday Niches and their Impact on Mainstream Tourism," Germany, 2011.

[147] Pataki, G. E., Dillon, J. T., and McCormack, M., "Project Management Lifecycle," New York State Office for Technology, 2003.

[148] Peeters, W., *Space Marketing*. El Segundo, USA and Dordrechts, The Netherlands: Microcosm Inc. and Kluwer Publishers, 2000.

[149] Peeters, W., "From suborbital space tourism to commercial personal spaceflight," *Acta Astronautica,* vol. 66, pp. 1625-1632, 2010.

[150] Penn, J. P., Lindley, C. A., "Requirements and approach for a space tourism launch system," *Acta Astronautica* vol. 52, pp. 49-75, 2003.

[151] Perrault, J. W. D., Cannon, J., and McArthy, E. J., *Essentials of Marketing*: 12th Edition, McGraw-Hill, 2009.

[152] PRICE Systems. (Accessed 11 October, 2011). *PRICE Systems website*. Available: http://www.pricesystems.com

[153] PRICE Systems, "PRICE H - Hardware Model for Estimation of Acquisition Costs," PRICE information pamphlet, Mt. Laurel, New Jersey, USA, 2005.

[154] PRICE Systems, "PRICE H User Manual - Estimating Cost and Schedule of Hardware Development and Production," PRICE Systems, Mt. Laurel, New Jersey, USA, 2005.

[155] PRICE Systems, "Guidelines for ESA cost estimating projects," Rüsselsheim, Germany, iternal report, 2012.

[156] Project Management Institute Inc., "A Guide to the Project Management Body of Knowledge (PMBOK Guide)," Project Management Institute Inc., 4th Edition, Pennsylvania, USA, 2008.

[157] *Reaction Engines Limited website* (Accessed 15 May, 2014). Available: http://www.reactionengines.co.uk/

[158] Reinbold, G., "Life Cycle Cost Assessments - ASTRA System Study Slice 2," EADS Astrium, technical note, 2004.

[159] Remer, D. S., Buchanan, H. R., "A Model for the Cost of Doing a Cost Estimate, TDA Progress Report 42-110," Jet Propulsion Laboratory, Pasadena, California, 15 August, 1992.

[160] Roxburgh, G. (Accessed 7 August, 2013). *Concorde History, Early History- The End of the Beginning* Available: http://www.concordesst.com/history/eh5.html#n

[161] Roy, R., "Cost Engineering: Why, What and How?," Cranfield University, UK, July, 2008.

[162] Roy, R., Kelvesjo, S., Forsberg, S., and Rush, C., "Quantitative and qualitative cost estimating for engineering design," *Journal of Engineering Design,* vol. 12, 1 June, 2001.

[163] Rush, C., Roy, R., "Analysis of cost estimating processes used within a concurrent engineering environment throuhgout a product life cycle," in *Concurrent Engineering 2000 (CE2) Conference*, Lyon, France, 2000.

[164] Saaty, T. L., *The Analytic Hierarchy Process: Planning, Priority Setting, Resource Allocation*. New York: McGraw-Hill, 1980.

[165] Saaty, T. L., "Decision making with the analytical hierarchy process," *International Journal of Services Science,* vol. 1, pp. 83-89, 2008.

[166] Sabre Airline Solutions. Airport Data Intelligence (ADI) Database [Online]. Available: http://www.sabreairlinesolutions.com/home/software_solutions/airports

[167] Savino, R., Russo, G., Carandente, V., and D'oriano, V., "Hyplane: Challenges for Space Tourism and Business Transportation," *Journal of Aeronautics & Aerospace Engineering,* vol. 2, 2013.

[168] Schwanekamp, T., Bauer, C., and Kopp, A., "The Development of the SpaceLiner Concept and its Latest Progress," presented at the 4th CSA-IAA Conference on Advanced Space Technology, Shanghai, China, 2011.

[169] Schwanekamp, T., Bütünley, J., and Sippel, M., "Preliminary Multidisciplinary Design Studies on an Upgraded 100 Passenger SpaceLiner Derivative," presented at the 18th AIAA/3AF International Space Planes and Hypersonic Systems and Technologies Conference, Tours, France, 2012.

[170] Science Applications International Corporation (SAIC), "Recent NAFCOM Extensions and Improvements, powerpoint presentation," 14 April, 2005.

[171] Science Applications International Corporation (SAIC), "NASA/Air Force Cost Model NAFCOM," powerpoint presentation, 15 May, 2002.

[172] Seventh Framework Programme Theme 7, "FAST20XX/233816 Seventh Framework Programme Theme 7 Transport Aeronautics - Annex 1," January, 2009.

[173] Shermon, D., *Systems Cost Engineering - Program Affordability, Management and Cost Control*. UK Gower Publising Ltd., 2009.

[174] Shishko, R., "Model for Estimating Space Station Operations Costs (MESSOC)," presentation slides, Jet Propulsion Laboratory, National Aeronautics and Space Administration, Pasadena, California, February, 2004.

[175] Shishko, R., Chamberlain, R. G., Bilardo, V., Forsberg, K., Mooz, H., Polaski, L*., et al.*, "Management Issues in Systems Engineering," 1993.

[176] Sippel, M., "Introducing the SpaceLiner Vision," presented at the 7th International Symposium on Launcher technologies, Barcelona, Spain, 2007.

[177] Sippel, M., Klevanski, J., "Progress in Simulating the Advanced In-Air-Capturing Method," presented at the 5th International Conference on Launcher Technology, Madrid, Spain, 2003.

[178] Sippel, M., Klevanski, J., and Kauffmann, J., "Innovative Method for Return to the Launch Site of Reusable Winged Stages," presented at the 52nd International Astronautical Congress, Toulouse, France, 2001.

[179] Sippel, M., Klevanski, J., and Steelant, J., "Comparative Study on Options for High-Speed Intercontinental Passenger Transports: Air-Breathing- vs Rocket Propelled," presented at the 56th International Astronautical Congress, Fukuoka, Japan, 2005.

[180] Sippel, M., Klevanski, J., and Van Foreest, A., "The SpaceLiner Concept and its Aerothermodynamic Challenges," presented at the 1st ARA-Days, Arachon, France, 2006.

[181] Sippel, M., Manfletti, C., Burkhardt, H., and Eggers, T., "Technical Development Perspective of Reusable Booster Stages," presented at the 12th International Space Planes and Hypersonic Systems and Technologies, , Norfolk, Virginia, 2003.

[182] Sippel, M., Schwanekamp, T., Bauer, C., Garbers, N., van Foreest, A., Tengzelius, U.*, et al.*, "Technical Maturation of the SpaceLiner Concept," presented at the 18th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, Tours, France, 2012.

[183] Sippel, M., Schwanekamp, T., Trivailo, O., and Lentsch, A., "Progress of SpaceLiner Rocket-Powered High-Speed Concept," presented at the 64th International Astronautical Congress (IAC), Beijing, China, 2013.

[184] Sippel, M., van Foreest, A., "Latest Progress in Research on the SpaceLiner High-Speed Passenger Transportation Concept," presented at the 58th International Astronautical Congress, India, 2007.

[185] Sippel, M., van Foreest, A., "SpaceLiner Rocket-Powered High-Speed Passenger Transportation Concept Evolving in FAST20XX," presented at the 61st International Astronautical Congress (IAC) Prague, Czech Republic, 2010.

[186] Sippel, M., van Foreest, A., and Bauer, C., "System Investigations of the SpaceLiner Concept in FAST20XX," presented at the 17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, San Francisco, USA, 2011.

[187] Sippel, M., van Foreest, A., Dietlein, I., Schwanekamp, T., Kopp, A., and Neeb, D., "System Analyses Driving Improved Aerothermodynamic Lay-out of the SpaceLiner Configuration," presented at the 1st ESA Aerothermodynamic Conference, Brugge, Belgium, 2011.

[188] Smith, K., "NASA/Air Force Cost Model NAFCOM," in *2002 SCEA National Conference*, Scottsdale, Arizona, 2002.

[189] Society of Cost Estimating and Analysis (SCEA). (Accessed 4 October, 2010). *SCEA website*. Available: http://sceaonline.org/

[190] *Soyuz spaceship makes harmonious docking with ISS*. ([2012], Accessed 16 November, 2013). Available: http://rt.com/news/soyuz-iss-docking-space-salaries-585/

[191] Space Foundation, "The Space Report - The Authoritative Guide to Global Space Activity," Colorado Springs, USA, 2012.

[192] Space News International, "Suborbital Price Drop Foreseen by 2014," 23 July, 2003.

[193] Space News International, "Old Model Doesn't Apply to SpaceX's Expenditure," letter to the editor, 7 February, 2011.

[194] "Space Operations Cost Model, SOCM, Final Report for Option 2 Contract Year," SAIC December, 2007.

[195] *Space Shuttle graphics*. ([2007], Accessed 24 October, 2014). Available: http://www.columbiassacrifice.com/&0_shttlovrvw.htm

[196] Space Systems Cost Analysis Group (SSCAG). (Accessed 1 October, 2010). *SSCAG website*. Available: http://sscag.saic.com/

[197] SPACECAST2020. ([1994], Accessed August 8, 2013). *SPACECAST2020, The World of 2020 and Alternative Futures* Available: http://www.fas.org/spp/military/docops/usaf/2020/alt-futr.htm

[198] *SpaceX website*. (Accessed 21 February, 2011). Available: http://www.spacex.com

[199] Spies, J., "ASTRA System Requirements, Design Standards, and Technology Assumptions," 2000.

[200] Srivastava, M., Srivastava, S., "Space Tourism: The Future Tourism," *Management Insight,* vol. 6, 2010.

[201] Stevenson, W., Hojati, M., "Supplement to Chapter 7: Learning Curves," McGraw-Hill Higher Education, 2004.

[202] Stewart, R. D., Wyskida, R. M., and Johannes, J. D., "Cost Estimator's Reference Manual," 2nd Edition, Wiley-Interscience, 1995.

[203] tenBrinke, E., "Costing support and cost control in manufacturing - a cost estimation tool applied to the sheet metal domain," Ph.D. Thesis, University of Twente, Enschede, The Netherlands, 2002.

[204] The Association of Cost Engineers (ACOSTE). (Accessed 4 October, 2010). *ACOSTE website*. Available: http://www.acoste.org.uk/

[205] The White House Office of the Press Secretary, "Remarks by the President of Space Exploration in the 21st Century," John F. Kennedy Space Center, Merrit Island, Florida, 2010.

[206] The World Bank's International Trade Department, "Air Freight: A Market Study with Implications for Landlocked Countries, TP-26," Chapter 4, The World Bank Group, Washington D.C.August, 2009.

[207] Trivailo, O., "Calibration of TransCost for Launcher Development Cost Calculations, SART TN-001/2012," Deutsches Zentrum für Luft- und Raumfahrt, Bremen, Germany, December, 2012.

[208] Trivailo, O., Sippel, M., Lentsch, A., and Sekercioglu, A., "Cost Modeling Considerations & Challenges of the SpaceLiner - An Advanced Hypersonic, Suborbital Spaceplane," presented at the AIAA SPACE 2013 Conference & Exposition, San Diego, USA, 2013.

[209] Trivailo, O., Sippel, M., and Sekercioglu, A., "Review of hardware cost estimation methods, models and tools applied to early phases of space mission planning," *Progress in Aerospace Sciences,* vol. 53, pp. 1-17, August, 2012.

[210] United States Governement Accountability Office (GAO), "NASA Lack of Disciplined Cost-Estimating Processes Hinders Effective Program Management," GAO, Virginia, May, 2004.

[211] United States Governement Accountability Office (GAO), "GAO Cost Assessment Guide - Best Practices for Estimating and Managing Program Costs," GAO-07-1134SP, GAO, Virginia, July, 2007.

[212] United States Governement Accountability Office (GAO), "GAO Cost Estimating and Assessment Guide - Best Practices for Developing and Managing Capital Program Costs," GAO-09-3SP, GAO, Virginia, March, 2009.

[213] United States Government Accountability Office (GAO), "James Webb Space Telescope - Actions Needed to Improve Cost Esimtate and Oversight of Test and Integration " GAO-13-4, GAODecember, 2012.

[214] "Unmanned Space Vehicle Cost Model (USCM)," software tool, 8th Edition, California, USA, 2002.

[215] van Foreest, A., Bauer, C., and Sippel, M., "The Development of the SpaceLiner in the FAST20XX Program," presented at the 2nd International IAA Conference on Private Human Access to Space, Arachon, France, 2011.

[216] van Foreest, A., Sippel, M., "The Logistical Challenges of the SpaceLiner," presented at the 1st International Academy of Astronautics Symposium on Private Human Access to Space, Arachon, France, 2008.

[217] Velden, A. V. d., *New Design Concepts for High Speet Air Transport*. New York: Springer Wien, 1997.

[218] *Virgin Galactic website* (Accessed 29 August, 2011). Available: www.virgingalactic.com

[219] Wade, M. ([1993], Accessed 19 November, 2012). *Yeltsin cancels Buran Project*. Available: http://www.astronautix.com/details/yelt5401.htm

[220] Washington, A. B., "Clashing Calculations - Cost per flying hour proves a thorny subject for F-35 overseers," *Aviation Week & Space Technology,* 6 May, 2013.

[221] Watkins, T. (Accessed 21 March, 2013). *The Concorde Supersonic Transport*. Available: http://www.applet-magic.com/concorde.htm

[222] Wertz, J. R., Larson, W. J., *Reducing Space Mission Cost*. California, USA: Microcosm Press and Kluwer Academic Publishers, 1996.

[223] Wideman, R. M., Havranek, T. J., *Modern Project Management Techniques for the Environmental Remediation Industry, General Project Management Concepts, Chapter 3: A Framework for Project and Program Management Integration*, 1999.

[224] Woolley, P. K., "A Cost-Benefit Analysis of the Concorde Project," *Journal of Transport Economics and Policy,* vol. 6, pp. 225-239, 1972.

[225] Yamashiro, R., Sippel, M., "Preliminary Design Study of Staged Combustion Cycle Rocket Engine for SpaceLiner High-Speed Passenger Transport Concept," presented at the 63rd International Astronautical Congress (IAC) Naples, Italy, 2012.

[226] Young, M., Markley, T., "A Better Cost-Estimating Tool: The Key to Not Going Over Budget," *Defense AT&L,* pp. 23-26, July, 2008.

[227] Younossi, O., Lorell, M. A., Brancato, K., Cook, C. R., Eisman, M., Fox, B.*, et al.*, "Improving the Cost Estimation of Space Systems," The RAND Corporation, 2008.

[228] Zak, A. (Accessed 13 June, 2014). *Spacecraft Manned: Buran*. Available: http://www.russianspaceweb.com/buran.html

[229] Zapata, E., "Air Force Reusable Booster System A Quick-look, Design Focused Modeling and Cost Analysis Study," NASA, Kennedy Space Center, Florida, 2011.