Doctoral Dissertation
Doctoral Program in Aerospace Engineering (34th Cycle)

Cost-effective and sustainable scenarios for future reusable space transportation and re-entry systems

By

Valeria Vercella

******

Supervisor:
Prof. Nicole Viola, PhD, Supervisor

Doctoral Examination Committee:
Dr. Björn Nagel, PhD, Referee, German Aerospace Center
Dr. Bayindir Saracoglu, PhD, Referee, Von Karman Institute for Fluid Dynamics
Dr. Marco Marini, PhD, Board Member, Centro Italiano Ricerche Aerospaziali
Dr. Victor Fernandez Villace, PhD, Board Member, European Space Agency
Prof. Alfonso Pagani, PhD, Board Member, Politecnico di Torino

Politecnico di Torino
2023

Declaration

I hereby declare that, the contents and organization of this dissertation constitute my own original work and does not compromise in any way the rights of third parties, including those relating to the security of personal data.

Valeria Vercella

2023

* This dissertation is presented in partial fulfillment of the requirements for **Ph.D. degree** in the Graduate School of Politecnico di Torino (ScuDo). This Dissertation has been carried out in the framework of the Stratospheric Flying Opportunities for High-Speed Propulsion Concepts (STRATOFLY) Project, funded by the European Union's Horizon 2020 research and innovation programme under grant agreement No 769246. All data and results reported in the manuscript are updated to the submission date.

To Anella

Acknowledgment

PhD is certainly an immersive journey, full of challenges, excitement, and… people. Many people are involved in this tremendous experience, but some of them play a key role in the success of the overall endeavor. The moment has come to thank them all, one by one, and to acknowledge their contribution to this work.

Thank you, Prof. Viola, for your continuous technical and moral support during these years. Thank you, for suggesting me to undertake this trip and for believing in me from the beginning and all along the PhD (up to the very last intense days of writing this Thesis);
Thank you, Dr. Fusaro. For all. You have been my "hidden" co-supervisor all the time and, most importantly, a precious friend;
Thank you, Dr. Ferretto, for our fundamental psychological morning sessions before work. I miss them, a lot;
Thank you, Dr. Stesina, for all your advices, support, life tips and, most of all, your unconditional friendship;
Thank you, Oscar, for your technical help in performing simulation analyses;
Thank you, Marco, for being my rock in the last decade;
Thank you to my parents, for their lovely support, and to my sister, for her delicious meals.
And last, but certainly not least, thanks to my grandma, to which this work is dedicated. I hope that you are proud of me, wherever you are.

Abstract

This Dissertation proposes a comprehensive methodology aimed at supporting preliminary and conceptual design activities by determining the Cost-Effectiveness and the technological sustainability of advanced Reusable Launch Vehicle (RLV) concepts. This is performed through the development of three key Modules specifically tailored for future RLVs analysis, i.e., a Cost Model (Module 1), an Effectiveness Model (Module 2) and a Methodology for Technology Roadmapping (Module 3). Results from Module 1 and Module 2 are properly merged to suggest the most cost-effective solution among competing options. Moreover, the integration of Module 1 and Module 3 is extensively studied with the purpose to exploit the outcomes from cost estimation to determine the technological sustainability of future reusable concepts. Selected Case Studies are also introduced to verify and test each Module. At the beginning, a through literature review on previous efforts on RLVs development is presented, highlighting the major technological challenges encountered in past activities. Then, benefitting of the historical overview, a discussion about the most promising design options is provided, selecting proper Case Studies to be used to test developed models. Subsequently, a Cost Model is proposed basing on main identified gaps of state-of-the-art cost methodologies. In this context, special attention is devoted in developing a dedicated set of Cost Estimation Relationships (CERs) for the most promising RLV configurations previously identified, suggesting a structured mathematical approach to be followed for new CERs derivation. The proposed Cost Model is also tested with the selected Case

Studies, comparing obtained results with previous estimations from independent sources. Moreover, in support of technological sustainability assessment, an enhanced version of a state-of-the-art methodology for Technology Roadmapping (called TRIS) is presented. The enhanced TRIS is applied to a noteworthy Case Study among those previously identified, providing a practical example of technological sustainability assessment. To support the roadmapping process, a thorough revision of an already existing database (HyDat) able to store data required for Technology Roadmapping is also performed. Then, after introducing suitable approaches to perform Cost-Effectiveness assessment, an Effectiveness Model specific for RLVs and based on trade-off analysis is proposed, providing guidelines towards Cost-Effectiveness assessment and results evaluation. Ultimately, the Cost-Effectiveness comparison of Case Studies is provided, suggesting the most cost-effective option.

Contents

1. Background and aim of the work 1

1.1 The Quest for Cost-Effective and Sustainable Reusable Launchers 1

1.2 Historical Overview 3

1.2.1 Main High-Speed Activities in the US 5

1.2.2 Main High-Speed Activities in Europe 12

1.3 Research Outlook 18

1.4 Chapter 1 Abbreviations 22

2. Future reusable space transportation and re-entry concepts 24

2.1 Vehicle and Mission Concept Overview 25

2.1.1 Promising Design Options for future RLVs 25

2.1.2 Preliminary Requirements Definition 27

2.2 Case Studies 30

2.2.1 Case Study 1: STRATOFLY MR3 evolution as a Two Stage to Orbit 31

2.2.2 Case Study 2: SpaceX Starship TSTO 47

2.3 Chapter 2 Abbreviations 50

3. Parametric Cost Model for Future Reusable Space Transportation and Re-Entry Systems 51

3.1 Literature Review 52

3.1.1 Introduction to Life-Cycle Cost analysis and Parametric Estimating 52

3.1.2 Existing parametric cost models for space vehicles 58

3.2 Cost Model Overview 93

3.2.1 Development Cost......95
3.2.2 Production Cost......118
3.2.3 Operating Cost......136
3.2.4 CpF, PpF, cost per unit mass of payload and Final LCC Assessment......142
3.2.5 Uncertainty in cost estimation......147
3.3 Software implementation......149
3.4 Application to the Case Studies......153
3.4.1 Case Study 1......153
3.4.2 Case Study 2......171
3.5 Chapter 3 Abbreviations......186
4. Technology Roadmap for Future Reusable Space Transportation and Re-Entry Systems......188
4.1 Literature Review......189
4.1.1 Introduction to Technology Roadmapping......189
4.1.2 SoA TRIS Methodology Summary......192
4.1.3 Final comments on SoA TRIS Methodology......202
4.2 TRL, Project Phases and Technology Development Cost......207
4.2.1 Mapping of LCC onto Project Phases and TRL Milestones......207
4.2.2 Vehicle CaC breakdown onto TRL Transits for RLVs......212
4.2.3 Technology Development Cost Assessment......215
4.3 Enhanced TRIS Methodology Overview......221
4.3.1 Stakeholders' Analysis......222
4.3.2 Elements' Definition......223
4.3.3 Prioritization Studies......231
4.3.4 Planning......236
4.3.5 Results Evaluation......241
4.4 Software implementation......241

4.5 Application to the Case Studies..246
4.5.1 Case Study 1 246
4.5.2 Case Study 2 (Planning update)...274
4.6 Chapter 4 Abbreviations...277
5. Cost-Effectiveness 279
5.1 Introduction 280
5.2 System Effectiveness: Key Definitions 280
5.3 Literature Review 282
5.3.1 WSEIAC-related Methodologies (ARINC Research Corporation, 1971; Pecht, 2009; WSEIAC, 1966) 282
5.3.2 Cost-Effectiveness analysis based on Trade-Off (Hammond, 1999; Mroczek, 2014)...285
5.3.3 NASA RMAT (Ebeling, 1993a) 291
5.4 Effectiveness Model and Cost-Effectiveness Assessment 293
5.5 Application to the Case Studies..298
5.6 Chapter 5 Abbreviations...301
6. Conclusions and Future Works...302
7. Annexes 306
7.1 Work-Year (WYr) Conversion Factors 306
7.2 Summary of New RDTE and TFU Production CERs (HyCost) 308
7.3 Database Architecture Formalization (HyDat Back-end) 309
7.3.1 Elements' Tables Definition 309
7.3.2 Relationships between Elements' Tables 316
7.4 Complete List of ACs and MCs for Case Study 1..............................321
7.5 Ordered List of ACs and MCs for Case Study 1 341
7.6 NASA RMAT (Ebeling, 1993a)...346
8. References..348

List of Figures

Figure 1: HST and RLV Studies, Ground Tests and Flight Tests (adapted from (Tang & Chase, 2008))....................4

Figure 2: X-15 launch from B-52 in 1959 (Credits: NASA Photo (NASA, 2017)....................5

Figure 3: Artist illustration of the NASP (Courtesy of NASA) (Snead, 2006).7

Figure 4: (a) X-43 flight testing through modified Pegasus booster carried aloft by the NASA NB-52B (Credits: NASA Photo (NASA, 2009)); (b) X-43 vehicle after release (Credits: NASA Photo (NASA, 2009))....................8

Figure 5: (a) DC-X (Credits: NASA Photo (NASA, 2012)); (b) X-33 (Credits: Lockheed Martin Image (NASA, 2014)); (c) X-34 (Credits: Lockheed Martin Image (NASA, 2016b)....................9

Figure 6: (a) Artist concept of X-37 vehicle (Credits: NASA Photo (NASA, 2001)); (b) X-40 (Credits: NASA Photo (NASA, 2022a)); (c) X-51A, artist's concept (Credits: NASA (NASA, 2010))....................10

Figure 7: (a) SpaceX vehicles comparison (adapted from (Musk, 2017c)), (b) SpaceShipTwo rocket mated to the mothership WhiteKnightTwo before take-off (Credits: Virgin Galactic (Virgin Galactic, 2021b))....................11

Figure 8: (a) HOTOL Configuration (Burns, 1990); (b) SKYLON C1 Internal Layout (Hempsell et al., 2009)....................12

Figure 9: New SKYLON TSTO concepts (Brevault et al., 2020)....................13

Figure 10: (a) ESA-proposed Ariane 5 configurations without Hermes (left) and with Hermes (right) (Feustel-Buechel & Wamsteker, 1990); (b) RLV concepts studied during FESTIP (Kuczera & Johnson, 1999)....................14

Figure 11: Artist's view of IXV reentry phase (ESA Image (ESA, 2011)); (a) Artist's view of Themis (ESA Image (ESA, 2021))....................16

Figure 12: Sänger hypersonic first stage vehicle configuration with the two upper stage options (Koelle & Kuczera, 1989)....................17

Figure 13: (a) LAPCAT MR2.4 (Steelant & Langener, 2014); (b) STRATOFLY MR3 (Viola et al., 2021)....................18

Figure 14: Overview of PhD Activities....................19

Figure 15: RLV High-Level Requirements derivation from Mission Statement 28

Figure 16: LAPCAT MR2.4 Mass Breakdown (Steelant, Varvill, et al., 2015) 34

Figure 17: Lockheed L-1011 Stargazer with Pegasus-XL (Northrop Grumman, 2022) 36

Figure 18: Sänger II EHTV Mission Profile as RLV (Koelle, 1988) 37

Figure 19: CARGUS Upper Stage key design features 38

Figure 20: STRATOFLY TSTO First Stage Mission Profile –Propellant vs. Total Mass 40

Figure 21: STRATOFLY TSTO First Stage Mission Profile – Altitude and Mach 42

Figure 22: STRATOFLY TSTO First Stage Mission Profile – Satellite View 43

Figure 23: Drag Coefficient as a function of Mach (Balesdent, 2011) 46

Figure 24: (a) Artist's impression of satellite payload release from Starship payload bay in LEO (Musk, 2017a); (b) Starship crew (left) and uncrewed (right) configurations (SpaceX, 2020) 47

Figure 25: Key characteristics of the Raptor engine (Musk, 2017b) 48

Figure 26: Life-Cycle Cost Impacts from Early Phase Decision-Making (Hirshorn et al., 2017) 52

Figure 27: Typical CER Development Process (ISPA, 2008) 54

Figure 28: Graphical representation of "Learning" (GAO, 2020) 56

Figure 29: (a) Estimated production cost of space vehicles with reference Saturn S-I cost per lb highlighted; (b) Correction factor for vehicle production cost (Koelle & Huber, 1961) 60

Figure 30: TransCost Model Overview 65

Figure 31: (a) RDTE CER for Winged Orbital Rocket Vehicles from TC; (b) TC chart to be used to determine NMF for Winged Orbital Rocket Vehicle (Koelle, 2013) 72

Figure 32:RDTE CER for Winged Orbital Rocket Vehicles from TC Revised vs Original TC CER for RDTE Cost of Fly-back Boosters (Trivailo, 2015) 74

Figure 33: Liquid Propellant Rocket Engine RDTE CER - TC Versions Comparison 76

Figure 34: TC CER for TFU Production Cost of Winged Orbital Rocket Vehicles (Koelle, 2013) 79

Figure 35: Detail of Ground and Flight Operations Cost Model from TC 81

Figure 36: Values for $f5$ correction factor suggested by TC 85

Figure 37: Commercialization Cost vs LpA from TC 86

Figure 38: Summary of Liquid Hydrogen Cost (Fusaro, Vercella, et al., 2020) 88

Figure 39: Proposed Cost Model Overview (HyCost) 94

Figure 40: Approach for new Vehicle Systems RDTE and TFU Production CERs derivation 98

Figure 41: Example of implementation of MPE-ZPB technique in MS Excel to derive Vehicle System RDTE 103

Figure 42: New CER for Vehicle System RDTE Cost of HTHL Liquid Propellant Rocket 1st Stage 105

Figure 43: New CER for Vehicle System RDTE Cost of HTHL Airbreathing First Stage and Advanced Aircraft Vehicle System RDTE 106

Figure 44: New CER for Vehicle System RDTE Cost of HTHL Airbreathing First Stages 108

Figure 45: New CER for Vehicle System RDTE Cost of Rocket Second Stage with HL (with Staging Mach dependency) 111

Figure 46: New CER for Vehicle System RDTE Cost of VTHL and HTHL Rocket SSTO 113

Figure 47: New CER for Vehicle System RDTE Cost of VTVL Rocket SSTO 114

Figure 48: New CER for Vehicle System RDTE Cost of VTVL Rocket SSTO 115

Figure 49: Turbojet, Ramjet and Scramjet Engines RDTE Cost Comparison 116

Figure 50: New CER for Vehicle System TFU Production Cost of HTHL Liquid Propellant Rocket 1st Stage 124

Figure 51: New CER for Vehicle System TFU Production Cost of VTHL Liquid Propellant Rocket 1st Stage 128

Figure 52: New CER for Vehicle System TFU Production Cost of HTHL Airbreathing First Stage..130

Figure 53: Available TFU Production Cost data for VTHL, VTVL, HTHL Rocket SSTO and comparison with TC CERs 131

Figure 54: New CER for Vehicle System TFU Production Cost of HTHL, VTHL and VTVL Rocket SSTO with comparison with TC CERs....................133

Figure 55: New CER for Vehicle System TFU Production Cost of Liquid Propellant Rocket Second Stage with HL..134

Figure 56: New CER for Vehicle System TFU Production Cost of VTVL Liquid Propellant Rocket First Stage..136

Figure 57: Reference Data used to derive correlation between Launch Mass and Total Insurance Coverage 139

Figure 58: Reference Data used to derive correlation between Total Insurance Coverage and Insurance Cost per Flight as a % of Total Insurance Coverage....140

Figure 59: Flowchart for the estimation of Insurance Cost per Flight for a Launch Vehicle with known Launch Mass...142

Figure 60: RDTE Cost Amortization Charge per launch as a function of total launches (Koelle, 2013)...145

Figure 61:Charge per launch as a function of total Launch cost per kilogram to LEO versus first launch date (Jones, 2018)..146

Figure 62: Cost Items variations due to uncertainties on Cost Drivers and on Cost Parameters (Fusaro, Viola, et al., 2020)...148

Figure 63: HyCost Tool (1)..150

Figure 64:: HyCost Tool (2)...152

Figure 65: HyCost Tool (3)..153

Figure 66: RDTE results comparison with reference for STRATOFLY TSTO First Stage 158

Figure 67: RDTE results comparison with reference for STRATOFLY TSTO Second Stage...159

Figure 68: TFU Production results comparison with reference for STRATOFLY TSTO First Stage 162

Figure 69:(a) Space vehicle unit production cost model; (b) Liquid propellant rocket engine cost model (Koelle, 1989) 162

Figure 70: Production cost reduction due to learning curve effect for STRATOFLY TSTO Vehicle System 164

Figure 71: Production cost reduction due to learning curve effect for (a) ATR Engines and (b) DMR and Rocket Engines 165

Figure 72: Reference CpF breakdown for ELVs and RLVs suggested by (Koelle, 2013) 170

Figure 73:Reference Mars Mission for Space X Starship TSTO (Musk, 2017b) 175

Figure 74: Current trend of SpaceX LpA 179

Figure 75: Estimated cost of SpaceX Starship for the Mission to Mars (Musk, 2017b) 183

Figure 76: SpaceX Starship TSTO Fabrication Cost Comparison 184

Figure 77: SpaceX Starship TSTO Average Maintenance Cost per use Comparison 184

Figure 78: SpaceX Starship TSTO Total Cost per One Mars Trip Comparison 185

Figure 79: ESA Definitions for TRL Scale 190

Figure 80: SoA TRIS methodology Flowchart from (Viola et al., 2020) 193

Figure 81:Example of HyDat Excel files filling using the GUI (Fusaro et al., 2017) 195

Figure 82: Activity flow diagram for HyDat filling through Matlab® described in (Fusaro et al., 2017) 195

Figure 83: Stakeholders Grid (Cresto Aleina, 2018) 196

Figure 84: Example of Applicability analysis between OCs and Technologies (Cresto Aleina, 2018) 197

Figure 85: CaC distribution on TRL Transits in SoA TRIS (Cresto Aleina, 2018) 200

Figure 86: SoA TRIS Planning algorithm (Viola et al., 2020) 201

Figure 87: TaC distribution on TRL Transits in SoA TRIS (Cresto Aleina, 2018) 202

Figure 88: Phases of project life cycle according to ESA and NASA (Cotterman, H. et al., 2005) 207

Figure 89: ESA Project Phases and related Activities (ECSS (European Cooperation for Space Standardization), 2017) 208

Figure 90: Typical LCC distribution over time for aircraft (Roskam, 1990) 210

Figure 91: Location of TRL Milestones on Project Phases for hypersonic derived from original ESA subdivision (Viola et al., 2022) 212

Figure 92: Space Shuttle Program History, Early Events and Program Phases (Mandell, 1983) 213

Figure 93: Space Shuttle Program History, Early Events and Program Phases (Mandell, 1983) 214

Figure 94: Newly derived Vehicle CaC distribution on TRL transits for RLVs 215

Figure 95: Vehicle RDTE distribution on TRL Transits 218

Figure 96: Cumulative Vehicle RDTE distribution on TRL Transits 218

Figure 97: Enhanced TRIS Methodology Flowchart 222

Figure 98: Structure of the ESA Technology Tree (ESA, 2020a) 224

Figure 99: Overview of ESA Product Tree 227

Figure 100: BBs Hierarchy based on ESA Product Tree 228

Figure 101: Performance Types and Mission Features related to Take-off functions from (Cresto Aleina, 2018) 230

Figure 102: New Planning algorithm (Viola et al., 2022) 237

Figure 103: FESTIP envisaged timeline with TRL Milestones added (Kuczera & Johnson, 1999) 239

Figure 104: Newly derived TaC distribution on TRL transits for RLVs 240

Figure 105: TRIS Tool (1) 243

Figure 106: TRIS Tool (2) 244

Figure 107: TRIS Tool (3) 245

Figure 108: (a) STRATOFLY MR3 PBS from (Ferretto, 2020); (b) Modified STRATOFLY MR3 PBS derived in this work 249

Figure 109: Development cost allocation onto PBS elements for STRATOFLY MR3 vehicle (Ferretto, 2020) 253

Figure 110: Portion of ESA Product Tree of interest for this study (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011) 262

Figure 111: BBs Hierarchy for STRATOFLY MR3 267

Figure 112: Proposed MCs' Planning for Case Study 1 272

Figure 113: Proposed Techs Planning for Case Study 1 (STRATOFLY MR3 Technology Roadmap)..273

Figure 114: Comparison with SpaceX Planning (Musk, 2017b) using TRIS TaC Breakdown 276

Figure 115: System Effectiveness Definition Process (adapted from (INCOSE, 2015; NASA, 2016a)...281

Figure 116: Example of MOE, KPP, MOP, TPM definition for a generic data system (NASA, 2016a) 282

Figure 117: Major components of Product/System Effectiveness according to (Pecht, 2009)..283

Figure 118: Examples of Cost-Effectiveness Curves from (ARINC Research Corporation, 1971)..285

Figure 119: Example of Objectives Hierarchy for a Naval Space Mission used to derive MOEs (Source: (Mroczek, 2014)) 287

Figure 120: Raw Swing Weight Matrix assumed by (Mroczek, 2014) 289

Figure 121: Trade-Off Approach based Raw Swing Weight Matrix (Mroczek, 2014) 290

Figure 122: Environmental Monitoring Scenario Cost Effectiveness Results (Mroczek, 2014)..291

Figure 123: RMAT Summary 292

Figure 124: TPMs Derivation for RLVs starting from Mission Statement definition 295

Figure 125: Cost-Effectiveness (C-E) Comparison: Case Study 1 vs. Case Study 2 300

Figure 126: Results Summary for the Case Studies 301

Figure 127: *technologies* Table 310

Figure 128: Overview of major HyDat Tables....310

Figure 129: Techs Tables in HyDat 311

Figure 130: BBs Tables in HyDat 312

Figure 131: ACs and MCs Tables 314

Figure 132: Programmes Tables 315

Figure 133: Projects Tables....315

Figure 134: New HyDat back-end filling process....317

Figure 135: Direct links between elements in HyDat back-end....318

Figure 136: New HyDat back-end Structure....320

Figure 137: NASA RMAT Graphical Overview 346

Figure 138: Mission Profile from NASA RMAT (Ebeling, 1993b) 347

List of Tables

Table 1: List of High-Level Mission Requirements for a Space Transportation System....29

Table 2: Comparison of EHTV and STRATOFLY MR3 main characteristics 33

Table 3: SpaceX Starship TSTO design characteristics from (Musk, 2017b) 49

Table 4: CER Categories and Algebraic Forms considering multiple cost drivers derived from (ISPA, 2008) 56

Table 5: Engine CERs availability in TC....65

Table 6: Vehicle System (without engines) CERs availability in TC....66

Table 7: List of correction factors (fi) for TransCost core CERs 68

Table 8: Values suggested for fv correction factor (Koelle, 2013)....82

Table 9: Values suggested for fc, correction factor (Koelle, 2013) 83

Table 10: List of Vehicle Systems (without Engines) to be handled in HyCost and RDTE CERs availability (Case 1,2 or 3) 95

Table 11: List of Engine Types to be handled in HyCost and RDTE CERs availability (Case 1 or 3)...97

Table 12: Updated Vehicle System RDTE Database used for CERs derivation (original TC cost data not included) 100

Table 13: HTHL Rocket First Stage RDTE CERs – Dry Mass (without Engines) dependency 103

Table 14: HTHL Rocket First Stage RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency 104

Table 15: HTHL Airbreathing First Stage and Advanced Aircraft RDTE CERs – Dry Mass (without Engines) dependency..106

Table 16: HTHL Airbreathing First Stage RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency 107

Table 17: Rocket Second Stage with HL RDTE CERs – Dry Mass (without Engines) dependency 109

Table 18: Rocket Second Stage with HL RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency 110

Table 19: VTHL or HTHL Rocket SSTO RDTE CERs – Dry Mass (without Engines) dependency 112

Table 20: VTVL Rocket SSTO RDTE CERs – Dry Mass (without Engines) dependency 113

Table 21: VTVL Liquid Propellant Rocket First Stage RDTE CERs – Dry Mass (without Engines) dependency 115

Table 22: List of Vehicle Systems to be handled in HyCost and Production CERs availability (Case 1,2 or 3) 119

Table 23: Updated Airframe TFU Production Database used for CERs derivation (TransCost cost data not included) 122

Table 24: ROT – Rocket (1st Stage) Data..125

Table 25: HTHL Rocket First Stage TFU production CERs – Dry Mass (without Engines) dependency..127

Table 26: VTHL First Stage TFU Production CERs – Dry Mass (without Engines) dependency 128

Table 27: VTHL First Stage TFU Production CERs – Dry Mass (without Engines) and Staging Mach dependency 128

Table 28: HTHL Airbreathing First Stage TFU Production CERs – Dry Mass (without Engines) dependency 129

Table 29: HTHL Airbreathing First Stage TFU Production CERs – Dry Mass (without Engines) and Staging Mach dependency 129

Table 30: VTVL, VTHL and HTHL Rocket SSTO TFU Production CERs – Dry Mass (without Engines) dependency 132

Table 31: Liquid Propellant Rocket Second Stage with HL TFU Production CERs – Dry Mass (without Engines) dependency 134

Table 32: VTVL Liquid Propellant Rocket First Stage TFU Production CERs – Dry Mass (without Engines) dependency 135

Table 33: Typical Launch Site User Fees (Low vs High values) at Commercial Florida Spaceport (Futron, 2005) 138

Table 34: Refence data for Public Damage Insurance (Koelle, 2013) 139

Table 35: Initial estimation of missing data for Public Damage Insurance Cost Model 140

Table 36: Final estimation of missing data for Public Damage Insurance Cost Model 141

Table 37: CpF scheme based on (Koelle, 2013) 144

Table 38: Summary of RDTE CERs for STRATOFLY TSTO 154

Table 39: Inputs for Vehicle System RDTE CERs - STRATOFLY TSTO.. 155

Table 40: Inputs for ATR and DMR Engines 156

Table 41: Inputs for total RDTE cost 156

Table 42: RDTE cost results for STRATOFLY TSTO 157

Table 43: Summary of TFU Production CERs for STRATOFLY TSTO 159

Table 44: Additional inputs required for TFU Production CERs 160

Table 45: TFU Production cost results for STRATOFLY TSTO 160

Table 46: Total Production costs summary for STRATOFLY TSTO 163

Table 47: Average Production costs summary for STRATOFLY TSTO.....164

Table 48: Summary of Operating CERs for STRATOFLY TSTO...............166

Table 49: Inputs for Operating Cost assessment for STRATOFLY TSTO ..167

Table 50: Results – CpF Scheme for STRATOFLY TSTO..........................168

Table 51: CpF Summary and cost per kilo for STRATOFLY TSTO...........170

Table 52: LCC Summary for STRATOFLY TSTO 171

Table 53: Summary of RDTE CERs for SpaceX Starship TSTO.................172

Table 54: Inputs for Vehicle System RDTE CERs – SpaceX Starship TSTO 173

Table 55: RDTE cost results for SpaceX Starship TSTO 173

Table 56: Summary of TFU Production CERs for SpaceX Starship TSTO .174

Table 57: TFU Production cost results for SpaceX Starship TSTO 174

Table 58: Learning Factors assumed for SpaceX Starship TSTO 176

Table 59: Total Production costs summary for SpaceX Starship TSTO.......176

Table 60: Average Production costs summary for SpaceX Starship TSTO .177

Table 61: Summary of Operating CERs for SpaceX Starship TSTO 178

Table 62: Inputs for Operating Cost assessment for SpaceX Starship..........178

Table 63: Results – CpF Scheme for SpaceX Starship TSTO.......................180

Table 64: CpF Summary and cost per kilo for SpaceX Starship TSTO 182

Table 65: LCC Summary for SpaceX Starship TSTO..................................182

Table 66: Commonly-used models for TRL progression (ECSS (European Cooperation for Space Standardization), 2017)..209

Table 67: Example of TD, TS and TGs according to ESA Technology Tree (ESA, 2020a) 225

Table 68: Generical summary of input data for Prioritization Studies from Stakeholders' Analysis 232

Table 69: Generical summary of input data for Prioritization Studies from Elements' Definition..233

Table 70: Generical overview of sub-lists of ACs/MCs linked to Techs and referred to specific TRL Transits. 235

Table 71: Generical overview of inputs for MCs Prioritization...................235

Table 72: List of technologies considered for the roadmapping exercise (Case Study 1) 251

Table 73: KTech iTDPropulsion estimation for Technologies TDPropulsion 256

Table 74: HyDat *technologies* Table filling with available technology data 257

Table 75: HyDat *trl_plan* Table filling with available technology data 258

Table 76: HyDat *activities* Table filling with available AC data..................260

Table 77: HyDat *missionconcepts* Table filling with available MC data 260

Table 78: HyDat *bb_system_category* Table filling 263

Table 79: HyDat *bb_system* Table filling 263

Table 80: HyDat *bb_equipment_category* Table filling 264

Table 81: HyDat *bb_equipment* Table filling 264

Table 82: HyDat *bb_component_category* Table filling..............................265

Table 83: HyDat *bb_component_category* Table filling..............................266

Table 84: HyDat *operationalcapabilities* Table filling................................268

Table 85: Normalized technology data required for trade-off analysis 269

Table 86: Ranked list of technologies for Case Study 1 270

Table 87: Generic example of trade-off analysis from (Hammond, 1999)...286

Table 88: Environmental Monitoring Scenario Effectiveness Model (Option 1) (adapted from (Mroczek, 2014)) 287

Table 89: Template for Effectiveness Analysis 296

Table 90: Effectiveness Analysis for the Case Studies................................299

Table 91: Details of Raw Ratings Values 299

Table 92: Work-Year (WYr) Conversion Factors..307

Table 93: New RDTE CERs 308

Table 94: New TFU Production CERs..308

1

Chapter 1

Background and aim of the work

1.1 The Quest for Cost-Effective and Sustainable Reusable Launchers

Since the successful mastering of access to space capability through Expendable Launch Vehicles (ELVs), the reduction of the cost to orbit has been the ultimate target of worldwide government and private initiatives in the space sector, thus enhancing competitiveness within the launch market (Heald, 1995). Systems reusability has been by far the most attractive means for achieving this goal. Along with the continuous pursuit towards performance increase, a growing emphasis has also been put in maximizing characteristics related to system effectiveness such as reliability, maintainability and supportability (RM&S) (Hammond, 1999). According to (Pecht, 2009), reliability is "*a measure of the product's ability to avoid failure*", availability "*represents the likelihood of having the product in a usable state*", while maintainability "*addresses the ease and economy with which the maintenance actions necessary to restore a failed product to a satisfactory state can be taken*". In addition, logistic supportability deals with "*the planning, acquisition, and positioning of the resources necessary to effect the repair or replacement of a product*" such as spare parts, support equipment, and maintenance personnel. For future reusable access to space and re-entry systems (also referred as Reusable Launch Vehicles (RLVs) in this Dissertation) "*system effectiveness is largely driven by continual (or continuous) operations at some level of output over a number of years*" (Hammond, 1999). As discussed by (Nix, 2005), higher reliability implies fewer failures with consequent reduction in maintenance down time and increase availability. Moreover, higher maintainability results in a faster return to service after an interruption, increasing availability and reducing the maintenance effort, while higher supportability decreases the "logistics footprint", i.e., spares and materials required to support maintenance activities. By incorporating RM&S requirements since early design stages it is possible to fully understand their implications onto system operations and, most importantly, provide the means of potential operational costs savings (Hammond, 1999; Nix, 2005). In this context, a concrete example can be traced in the Space Shuttle experience, in which the lack of accessibility of the Orbiter negatively impacted onto the maintainability of the system, causing an unforeseen increase in time required to perform maintenance actions and, consequently, of operations cost (Nix, 2005). It is also worth mentioning that improvement in RM&S characteristics may imply higher developmental, production and acquisition costs due to the increase in overall system complexity (Nix, 2005). This strict relationship between costs and effectiveness helps in justifying the interest in RM&S issues in RLVs design mentioned at the beginning of this Section. Indeed, the goal to attain costs reduction in space access cannot disregard the influence of the high effectiveness targeted for these systems. At this purpose, proper Cost-Effectiveness (C-E) analyses should be carried out in the framework of conceptual design activities with the aim "*to find designs that provide a better combination of the various dimensions of cost and effectiveness*" (Hammond, 1999). This implies the need of dedicated methodologies for cost estimation and effectiveness analysis. Results of such studies for selected case studies should be then properly merged to obtain a C-E assessment for each alternative and thus select the most suitable option.

The ambitious goal of cost-effective reusable space access requires the establishment of a solid technological know-how to enable all the capabilities needed by future RLVs. In the past decades, several RLV efforts suffered abrupt cancellations due to the huge budgetary resources needed to sustain both development and qualification of substantially immature technologies. To prevent the recurrence of such unsuccessful attempts in the future, it is of utmost importance to guarantee the sustainability of proposed technological solutions. For sake of clarity, the term sustainability is here intended as technological sustainability as discussed in (Vacchi et al., 2021). Basing on (Purvis et al., 2019) a sustainable development can be characterized by three pillars, 1) environmental sustainability ("*the ability to protect the environment and preserve the resources offered by the planet*"); 2) economic sustainability ("*continuous ability to* *generate profit, welfare, and wealth while respecting what surrounds us*"), and 3) social sustainability ("*ability to ensure social welfare to every individual in the world in an equitable manner*") (Vacchi et al., 2021). This definition stresses the importance of "sustainability of technologies" from an environmental point-of-view with less emphasis on the socio-economic aspects of sustainability (Vacchi et al., 2021). Therefore, a fourth dimension of sustainability, i.e., "technological sustainability", shall be considered, taking into account the key role of technology feasibility from a technical point of view. Indeed, "*a process or a product, as well as minimizing the impact on the environment and society and being economically viable, must also be a technically feasible solution and have technological performance that complies with applicable standards degree of sustainability of technological solutions*" (Vacchi et al., 2021). As anticipated, the fourth pillar of sustainability is specifically targeted in this Dissertation. At this purpose, basing on the rationale discussed in (Petrick & Echols, 2004), technology roadmapping can be by far a central tool to assess the sustainability of innovative technologies and it can help avoiding new failing attempts in RLVs development. Indeed, "*a technology roadmap is nothing less than a graphical representation of technologies, often relating objects like products or competencies and the connections that have evolved between them in the course of time. The activities required in generating and updating this kind of representation are referred to as technology roadmapping*" (Moehrle et al., 2013).

Starting from this introduction, Section 1.2 summarizes the key research efforts towards cost-effective reusable launchers performed in the past decades. The survey has the purpose to highlight the technological challenges encountered during previous studies mainly related to a lack in technological sustainability. Subsequently, Section 1.3 clearly states the Research Outlook of this Dissertation, focusing on the key objectives of the present study and summarizing the main contents of each Chapter. Eventually, the list of abbreviations used within the text is provided in Section 1.4.

1.2 Historical Overview

Since the 1960s, several studies explored available system options to achieve cost-effective RLV solutions. Complementary, many technology development programs were financed to pursue the maturation of required technologies and enable the exploitation of such complex systems in the near future. In account of this, with the aim to resume the key milestones of RLVs development, the historical overview provided by (Tang & Chase, 2008) and collecting "*the major* *past achievements in air breathing powered hypersonic aircraft and launch vehicles*” in the US up to the 2010s is taken as baseline and the historical overview summarized in Figure 1 extends the original timeframe considered by (Tang & Chase, 2008) up to the period in which this Dissertation is prepared.

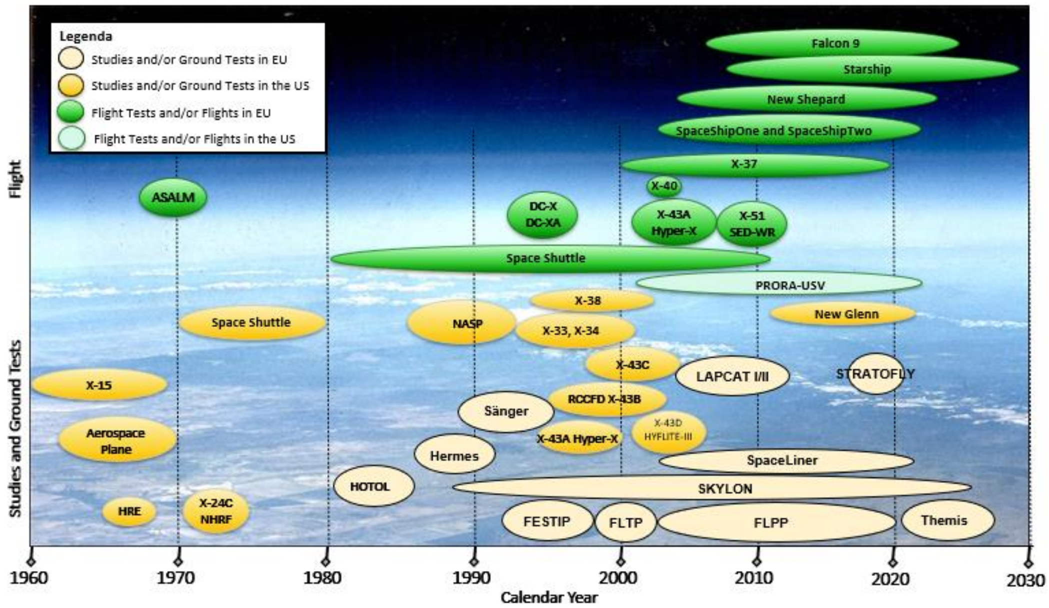


Figure 1: HST and RLV Studies, Ground Tests and Flight Tests (adapted from (Tang & Chase, 2008))

All the meaningful activities and programs related to hypersonic vehicles carried out in the past or still on-going in Europe and in the US are included in Figure 1. Details about US activities are provided in Section 1.2.1, while European efforts are described in Section 1.2.2. Please, notice that the proposed survey pertains two different applications of hypersonic flight, i.e., RLVs and High-Speed Transportation (HST), including both airbreathers and rocket-based systems. For sake of clarity, HST vehicles are sub-orbital civil passenger aircraft performing a hypersonic cruise with the potential to substantially reduce travel time for long-haul routes in the future (Noor & Venneri, 1997). These concepts are also referred as hypersonic cruisers in literature (Steelant, 2011). Despite being two distinct applications of hypersonic flight, HST vehicles and RLVs are often treated together (Hunt et al., 1999; Hunt & Wagner, 1997; Sziroczak & Smith, 2016) since they share the same technical issues within the design, with major technological challenges envisaged in the fields of aerothermodynamics, structures, and propulsion. However, propulsion “*is probably the most critical factor that limits efficient and routines space access*” and “*the success of a* *hypersonic transport [...] depends greatly on its propulsion system*" (Sziroczak & Smith, 2016). As it will be clarified by some examples reported in Section 1.2.2, the HST potential of great interest for this Dissertation lies in the possibility to convert them into RLVs, thus exploiting the same vehicle (with associated development costs and technological expertise) for several purposes.

1.2.1 Main High-Speed Activities in the US

From a chronological perspective, the first hypersonic flight was achieved in the US through the X-15 vehicle back in the 1960s. This rocket airplane was air-launched by a modified B-52 aircraft (Figure 2) with the aim to assess the feasibility of reusable concepts in an environment similar to that expected for future RLVs (Love & Young, 1966).

Figure 2: X-15 launch from B-52 in 1959 (Credits: NASA Photo (NASA, 2017)

During the program, almost 200 test flights were performed using three X-15 vehicles, which were recovered and reused several times. As additional but fundamental achievement, the X-15 experience proved the advantage of reuse in terms of refurbishment cost, "*which has been 3 percent of the cost of a new X-15 for each flight*" (Love & Young, 1966). However, several challenges related to reusability were encountered, such as the consistent turnaround delays mainly related to the accomplishment of routine maintenance and pre-flight preparation. Notably, the mean turnaround time experienced during the program was around 30 days in opposition to the 3 to 7 days targeted for RLVs at that time. In addition, prohibitive costs were incurred during flight testing, i.e., more than $602,000 per flight in Fiscal Year (FY) 1966, equal to almost 7.5 M$ in FY2021. As commented by (Love & Young, 1966), both turnaround time and costs "*are greater than estimates for a reusable booster, because of the research nature of* *the X-15 program and because the X-15 airplane is equivalent to a prototype vehicle*".

In parallel to the X-15 flight testing campaign, as shown in Figure 1, preliminary studies on scramjet propulsion were performed within the Aerospace Plane research project by the US Air Force. Such analyses inspired early airbreathing Space Shuttle concepts which were soon discarded due the technical immaturity of the proposed propulsive strategies (Hammond, 1999; Rupert, 1961). However, the idea to achieve scramjet propulsion capability was not abandoned and, by the end of the 1970s, several activities were carried out in the US to specifically advance scramjet propulsion technology exploiting the know-how obtained through the X-15 experience (Figure 1). In particular, the Hypersonic Research Engine (HRE) Project (Andrews, 1994) aimed at demonstrating the "*high internal thrust performance for a scramjet engine over a Mach number range of 4 to 8*" with the (unrealized) purpose to perform flight testing on the X-15 platform. Moreover, analyses on a X-24C concept similar to the X-15 but mounting ramjet/scramjet propulsion was performed at the National Hypersonic Flight Research Facility (NHRF) (Neumann et al., 1978). Nevertheless, the study was suspended for budgetary reasons and no flight tests were performed. Conversely, successful flight testing of the Advanced Strategic Air-Launched Missile (ASALM) was pursued in the same period (Tang & Chase, 2008). ASALM was a hydrocarbon fuelled air-launched cruise missile equipped with a ramjet propulsion system. Subsequently, as clearly shown by Figure 1, with the aim "*to provide a low-cost, reliable space transportation to low-Earth orbit [...] NASA concentrated on developing a reusable system with the level of technology available at the time*" (Hammond, 1999)., i.e. the Space Shuttle. However, in the 1980s, research efforts on airbreathing high-speed vehicles were resumed with the National AeroSpace Plane (NASP) Program (Augenstein & Harris, 1993; Hammond, 1999; Noor & Venneri, 1997; Tang & Chase, 2008). NASP contributed to the development of major technologies required for high-speed airbreathing applications, i.e., propulsion, materials and structures, thermal protection system (TPS), and aerodynamics. Notably, it focused on the design of an experimental liquid-hydrogen fueled Single Stage to Orbit (SSTO) vehicle, i.e., the X-30 in Figure 3 with Horizontal Take-Off Horizontal Landing (HTHL) capability.

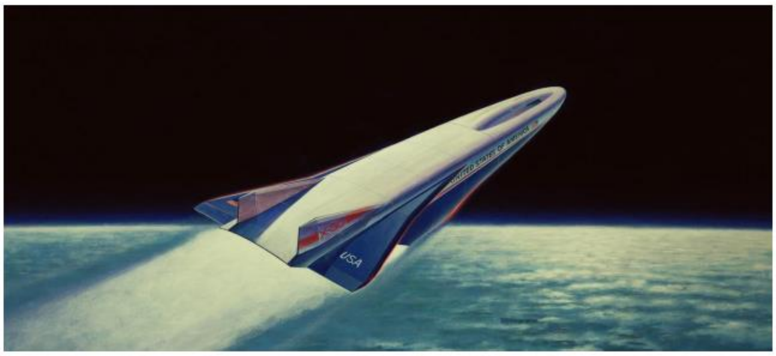


Figure 3: Artist illustration of the NASP (Courtesy of NASA) (Snead, 2006)

Despite the $2.5 billion expenditure over a period of 8 years (Tang & Chase, 2008), the ambitious goal of the NASP was not met due to the enormous technological challenges encountered and the program was cancelled in 1994 before the X-30 flight testing. The NASP experience substantially proved that "*the feasibility of airbreathing SSTO is critically dependent on the performance of the scramjet engine at high Mach numbers*" (Noor & Venneri, 1997). This paved the way for the subsequent activities related to airbreathing hypersonic aircraft performed in the US during the 1990s. In this context, it is worth mentioning the Hyper-X program, in which three prototypes of the X-43A research vehicle were developed and two of them were successfully flight tested in 2004 (Voland et al., 2006). The X-43A was a small-scale, low-cost, and non-recoverable flight demonstrator with airframe integrated scramjet engine. For flight testing, as shown in Figure 4(a), it was mounted on-top a modified Pegasus booster carried aloft by the NASA NB-52B carrier aircraft (Jenkins et al., 2003). After separation from the carrier aircraft, the Pegasus booster accelerated the X-43 up to Mach 7 and released it (Figure 4(b)). Subsequently, the scramjet engine on the prototype vehicle was ignited to allow powered flight for about 10 s. At the end of the test, the vehicle glided in free flight and splashed into the Pacific Ocean (Voland et al., 2006). Besides demonstrating scramjet propulsion, through the X-43A flights, measurements of surface pressures, temperatures, strains, and accelerations experienced during hypersonic flight were collected thanks to proper instrumentation installed on test vehicles. The great amount of data gathered allowed to validate experimental, analytical, and design methods exploited in the analysis of scramjet vehicles (Voland et al., 2006), thus contributing to a better understanding of the complex factors that come into play during hypersonic flight.

(a) (b)

Figure 4: (a) X-43 flight testing through modified Pegasus booster carried aloft by the NASA NB-52B (Credits: NASA Photo (NASA, 2009)); (b) X-43 vehicle after release (Credits: NASA Photo (NASA, 2009))

As shown in Figure 1, other X-43-related activities during the same period were 1) the Reusable Combined Cycle Flight Demonstrator (RCCFD) X-43B Project aimed at validating the performance of a rocket-based combined cycle (RBCC), turbine-based combined cycle (TBCC), or a combined RBCC/TBCC propulsion system in the same Mach range of the X-43A (Cook & Hueter, 2003; Jenkins et al., 2003); 2) the X-43C Project, to demonstrate through powered flight a dual-mode scramjet propulsion system with hydrocarbon fuel from Mach 5 to Mach 7 (Jenkins et al., 2003; Moses, 2003) and 3) the X-43D Project, focused towards a Mach 15 flight test vehicle with hydrogen-fueled scramjet engine (Johnson & Robinson, 2005). Basing on literature information, these concepts were explored only at conceptual stage and no flight test campaigns are documented. However, building on the heritage of the X-43 research, successful flight test activities were pursued within the X-51A Program (Lane, 2007) by means of the hydrocarbon fueled Scramjet Engine Demonstrator – WaveRider (SED-WR). Thanks to the high Lift-to-Drag ratio provided by the waverider configuration, the X-51 SED-WR was able to set a new record in the duration of a scramjet burn (i.e. up to 200 s) at Mach 5 (NASA, 2010).

Complementary to the activities on X-43 vehicles, in the mid 1990s and 2000s NASA was also involved in the RLV Program, in which a fully reusable rocket SSTO was targeted (Freeman et al., 1997; Freeman & Talay, 1996). As a result, design and test activities on rocket propulsion concepts were conducted in parallel to the already discussed scramjet technology development program. This might be interpreted as evidence that a decision between airbreathing and rocket concepts was still to be made at NASA. Indeed, available high-speed technologies were not sufficiently mature to allow the selection of the most feasible RLV solution in the near term. As far as NASA RLV Program is concerned, three major concepts were investigated, Delta Clipper Experimental (DC-X) (Figure 5(a)), X-33 (Figure 5(b)), and X-34 (Figure 5(c)). The DC-X was a Vertical Take-off Vertical Landing (VTVL) vehicle which evolved into the Delta Clipper Experimental Advanced (DC-XA). Both DC-X and DC-XA were flight tested, demonstrating VTVL capability, rapid vehicle turnaround and, for the first time, key RLV technologies such as composite liquid hydrogen tanks. However, the program was terminated for a landing accident caused by a failure in landing gear deployment. In that occasion, most of the vehicle was destroyed for the explosion of the propellant tanks (Freeman et al., 1997). This clearly revealed a substantial lack in reliability of the system substantially due to "*an immature technology base*" (Erbland, 2004). Furthermore, the X-33 was conceived as a subscale version of the future Vertical Take-off Horizontal Landing (VTHL) Venture Star SSTO (Hammond, 1999), while the X-34 effort was initiated with the objective to "*provide a pathfinder for the more advanced X-33 program*" (Freeman et al., 1997). However, both X-33 and X-34 programs ended in early 2001 due to technical problems and rising costs (Erbland, 2004).

(a) (b) (c)

Figure 5: (a) DC-X (Credits: NASA Photo (NASA, 2012)); (b) X-33 (Credits: Lockheed Martin Image (NASA, 2014)); (c) X-34 (Credits: Lockheed Martin Image (NASA, 2016b)

In parallel to the RLV Program, in mid 1990s NASA was also pursuing the development of the X-38. This lifting body Crew Return Vehicle (CRV) with pure re-entry capability aimed at returning seven crew members from the International Space Station (ISS) in case of unavailability of the Space Shuttle. As reported in (Machin et al., 1999), the CRV exploitation would occur in case of crew member illness or injury, catastrophe a board the ISS or inability to resupply it. The X-38 program, which also saw the participation of the European Space Agency (ESA), was cancelled in 2002 for budgetary reasons. In the framework of the X-Vehicles studied by NASA, it is also worth mentioning the flight test activities on the X-37, whose development started in 1999 and is still on-going. Notably, the X-37 (Figure 6(a)) aims at testing orbital and reentry capabilities of future RLVs. It is based on a scaled-up version of the X-40 demonstrator (Figure 6(b)), which in turn was successfully flight tested until 2001 (Erbland, 2004).

(a) (b) (c)

Figure 6: (a) Artist concept of X-37 vehicle (Credits: NASA Photo (NASA, 2001)); (b) X-40 (Credits: NASA Photo (NASA, 2022a)); (c) X-51A, artist's concept (Credits: NASA (NASA, 2010))

More recently, the advent of commercial spaceflight activities has provided a new pursuit for the development of RLVs. In this context, the SpaceX company is certainly playing a key role in the development of required technologies (Dreyer et al., 2011). Figure 7(a) summarizes the current SpaceX launcher vehicles, i.e., Falcon 9, Falcon Heavy, and Starship. Notably, the already operational Falcon 9 is the only US rocket fully certified by NASA for transporting crew to the ISS (NASA, 2020a). In addition, it is able to land vertically and, after refurbishment, it can be reused for payload delivery. Therefore, it is the first partially reusable launcher operated after the Space Shuttle retirement, thus setting a new key milestone in the journey towards full reusability. As far as Starship is concerned, it is an under development fully reusable space transportation system with the projected capability to carry both crew and cargo up to Mars and beyond (Musk, 2017a). Further details about this concept are provided in Section 2.2.2, where Starship is presented as a case study of interest in the present Dissertation.

(a)

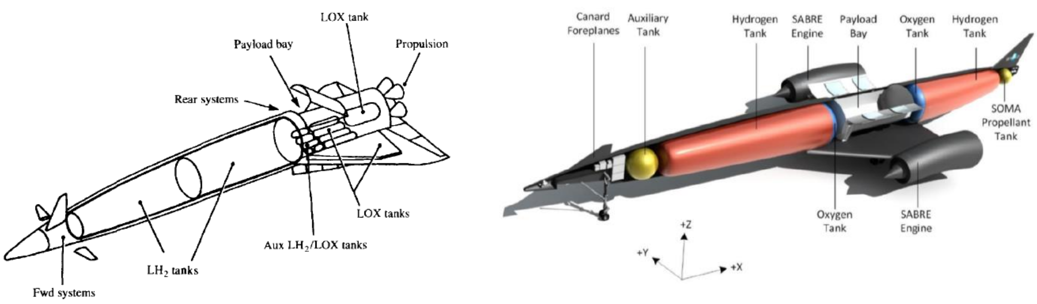
(b)

Figure 7: (a) SpaceX vehicles comparison (adapted from (Musk, 2017c)), (b) SpaceShipTwo rocket mated to the mothership WhiteKnightTwo before take-off (Credits: Virgin Galactic (Virgin Galactic, 2021b))

Before concluding this overview of current RLV efforts in the US, some additional commercial space activities also reported in Figure 1 are worth citing. In particular, Virgin Galactic is targeting to provide suborbital space tourism services (Seedhouse, 2015). Indeed, after the success of the SpaceShipOne in 2004, flight testing is ongoing for the new SpaceShipTwo vehicle (Figure 7(b)) which achieved the first fully crewed spaceflight in 2021 (Virgin Galactic, 2021a). The reusable SpaceShipTwo rocket is air-launched by the airbreathing mothership WhiteKnightTwo at an altitude of 15 km. After separation, the crewed SpaceShipTwo reaches an altitude of 100 km, while the mothership glides back performing horizontal landing on a conventional runway (Seedhouse, 2015). Despite its characteristics as suborbital passengers' transport, the SpaceShipTwo development is undoubtedly contributing to achieve RLV capabilities in the near future. Similar remarks apply to Blue Origin, which through the suborbital New Shepard (already proved to take astronauts and research payloads beyond the Kármán line (Blue Origin, 2022b)) is testing the technology required for the New Glenn. The latter is a heavy-lift launch vehicle with reusable first stage aimed at carrying people and payloads routinely to Low Earth Orbit (LEO) and beyond (Blue Origin, 2022a).

1.2.2 Main High-Speed Activities in Europe

In the European context, the first noteworthy RLV effort was initiated by British Aerospace in early 1980s with the study of the HTHL fully reusable SSTO concept in Figure 8(a), i.e. the HOTOL (Burns, 1990; Hammond, 1999; Noor & Venneri, 1997). This unpiloted vehicle, aimed at delivering up to 7 tons payload to LEO, was equipped with a combined airbreathing/rocket cycle engine (called RB 545) operating in airbreathing mode up to Mach 5.5 and then switching to rocket mode up to orbit. An important target was also the possibility to exploit conventional runways for take-off and landing phases. Despite the end of the HOTOL project for lack of funding in 1989, the work was continued at Reaction Engines Ltd (REL) to improve the performance of the RB 545 engine. These efforts culminated in the development of the Synergetic Air-Breathing Rocket Engine (SABRE). The envisaged application of SABRE technology was on the SKYLON vehicle, which was a substantial redesign the HOTOL (Davis et al., 1999; Hempsell & Longstaff, 2010; Longstaff & Bond, 2011).



(a) (b)

Figure 8: (a) HOTOL Configuration (Burns, 1990); (b) SKYLON C1 Internal Layout (Hempsell et al., 2009)

As shown in Figure 1, the development of SABRE and SKYLON, started in the 1990s, is still ongoing at REL. As far as SABRE is concerned, ground testing focuses onto the "*three core building blocks [...] (i.e.) the precooler, the engine core and the thrust chamber*" (REL (Reaction Engines Ltd.), 2022). In 2013 a thorough technology validation programme for SABRE demonstrated the pre-cooler heat exchanger with a successful test of a full scale section of this component (Davis et al., 2015; Hempsell, 2013). Moreover, "*the high temperature test of the precooler took place in 2019*" and "*testing of the core engine components and pre-burner have taken place during 2020 and 2021*" (REL (Reaction Engines Ltd.), 2022). For SKYLON, the SSTO configuration inspired by the HOTOL has undergone several design iterations through the years, leading to the C1 version depicted in Figure 8(b). The vehicle is able to deliver up to 15 ton of payload to LEO, with the possibility to carry a rocket-powered upper stage (the so-called SKYLON Upper Stage (SUS)) reaching higher orbits (up to 600 km) (Davis et al., 2015). Current studies focus on the improvement of the C1 version up to the final SKYLON D1 (Hempsell & Longstaff, 2010). More recently, a Two Stage To Orbit (TSTO) concept exploiting SKYLON as first stage and a small expendable rocket as second stage is under analysis by the French Space Agency (CNES), the UK Space Agency (UKSA), REL, and the French Aerospace Lab (ONERA) (Brevault et al., 2020). In this context, it is interesting to highlight that, according to (Brevault et al., 2020), "*reusable first stages combined with expendable upper stages are a promising first step towards fully reusable launch vehicles*". As depicted in Figure 9, both a payload-bay and an in-front configuration are under evaluation.

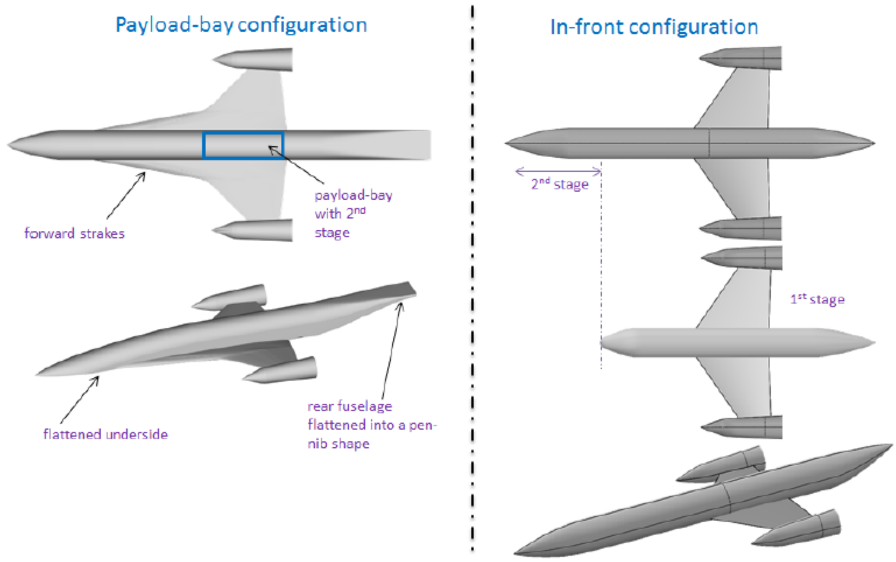
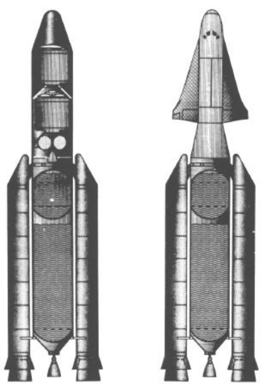


Figure 9: New SKYLON TSTO concepts (Brevault et al., 2020)

In parallel to HOTOL and SKYLON activities, in the early 1990s ESA decided to benefit of the success of the ARIANE 4 launcher by starting the development of the heavy-lift Ariane 5. The combination of this expendable launcher with the HERMES reusable rocket spaceplane (Figure 10(a)) was expected to allow "*Europe to master the technology required for manned space flight*" (Feustel-Buechel & Wamsteker, 1990). HERMES aimed at servicing the European Columbus orbital facility (subsequently attached to the ISS in 1998) by transporting crew, equipment and payload (Feustel-Buechel & Wamsteker, 1990; Hammond, 1999). However, the program was cancelled in mid 1990s due to lack of funding. Subsequently, the ESA RLV effort restarted at conceptual design level with the Future European Space Transportation Investigations Programme (FESTIP), which identified "*which launcher concepts are most likely to become the first reusable or semi-reusable systems to be technically feasible and economically viable for Europe*" (Dujarric et al., 1997). A summary of the concepts explored within FESTIP in shown in (Figure 10 (b)). As it can be noticed, FESTIP system studies enabled trade-offs for key RLV key design features (Dujarric et al., 1997):

- Number of stages: SSTO, TSTO or "Quasi SSTO";
- Propulsion Type: all-Rocket and airbreathing plus rocket propulsion (for TSTO concepts);
- Take-off and Landing Mode: vertical versus horizontal ascent and horizontal versus vertical landing.
- Vehicle configuration: Winged Vehicles versus Lifting Body or ballistic configurations;
- Flight Profile: orbital versus suborbital trajectory.

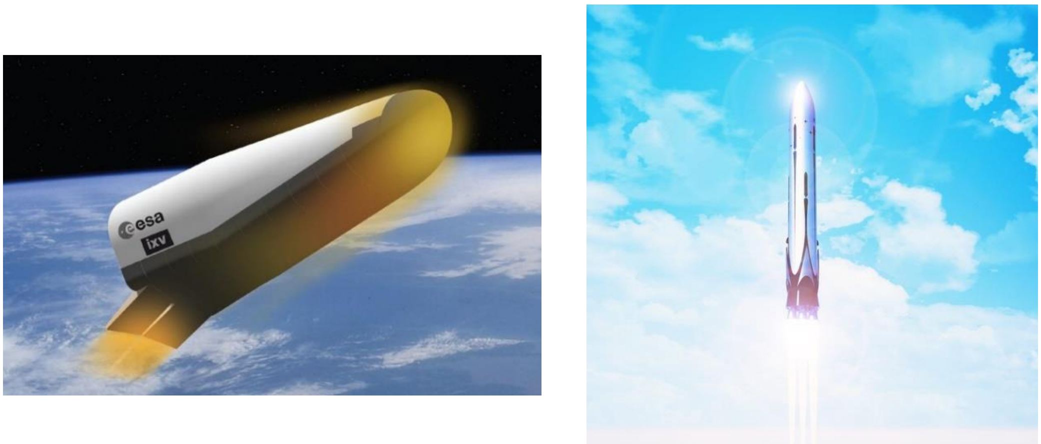


FSSC-01	VTO-HL SSTO, 8 x 150 bar rocket engines
FSSC-01HPE	VTO-HL SSTO, 5 x 244 bar rocket engines
FSSC-02TRIPROP	VTO-HL SSTO, 8 x 245/103 bar tri-propellant rocket engines
FSSC-03	VTO-VL SSTO, 4 x 244 bar ascent & 6 x 40 bar landing engines
FSSC-04	HTO-HL SSTO, sled launched, 3 x 244 bar rocket engines
FSSC-05AEROSPIKE	VTO-HL SSTO, lifting body, aerospike engine
FSSC-05HPE	VTO-HL SSTO, lifting body, 7 x 244 bar rocket engines
FSSC-09	VTO-HL TSTO, 4 x 244 + 1 x 244 bar rocket engines
FSSC-09e0-TT	VTO-HL TSTO, semi-reusable, AR 5 core, booster TT
FSSC-09e1-FT	VTO-HL TSTO, semi-reusable, AR 5 core, booster FT
FSSC-12T	HTO-HL TSTO, A/B propulsion in first stage/trapezoidal config.
FSSC-12D	HTO-HL TSTO, A/B propulsion in first stage/delta configuration
FSSC-15SOH-TT	Suborbital Hopper HTO-HL, sled launched, Vulcain II
FSSC-15SOH-FT	Suborbital Hopper HTO-HL, sled launched, HPE
FSSC-15OAE	Suborbital Once-Around-Earth, HTO-HL, sled launched, HPE
FSSC-16SR	VTO-HL TSTO, semi-reusable, AR 5 core, booster with Vulcain II
FSSC-16ASR	VTO-HL TSTO, semi-reusable, AR 5 core, booster with HPE
FSSC-16FR	VTO-HL TSTO, fully reusable, siamese config., HPE

(a) (b)

Figure 10: (a) ESA-proposed Ariane 5 configurations without Hermes (left) and with Hermes (right) (Feustel-Buechel & Wamsteker, 1990); (b) RLV concepts studied during FESTIP (Kuczera & Johnson, 1999)

As outcome of FESTIP analyses, two preferred concepts were selected and considered achievable in the near-term from a technological perspective, i.e. FSSC-16 and FSSC-15 "Hopper" (Kuczera & Johnson, 1999). The former was intended as an evolution of the Ariane-5 core stage with fly-back capability, while the latter was expected to carry an expendable second stage reaching up to 160 km (Erbland, 2004). Preferred FESTIP concepts were used as starting point for the subsequent Future Launchers Technologies Programme (FLTP), which aimed at 1) identifying, developing and validating the technologies required to establish a new generation of cost-effective launchers; 2) elaborating a plan to demonstrate technologies on ground and in-flight to achieve a sufficient degree of confidence before proceeding with actual vehicle development; 3) supporting a possible programmatic decision about the initiation of a European development program for next generation RLVs (Bonnal & Caporicci, 2000). Within these main FLTP objectives it is interesting to notice the role of planning activities for the definition of a clear path towards RLV technologies. This is a signal of the continuous growing importance of technology roadmapping in support of strategic decisions since the late 1990s. Few information is available in literature about the completion of FLTP. Basing on (Erbland, 2004), FLTP activities were suspended for review of their relevance in 2001. However, the path initiated with FLTP has been pursued in the subsequent Future Launchers Preparatory Programme (FLPP), which started in 2003 and it is still ongoing (ESA, 2022). A key milestone within FLPP was achieved in February 2015, when the Intermediate eXperimental Vehicle (IXV) was flown under realistic flight conditions (Figure 11(a)). The IXV was a lifting-body re-entry demonstrator equipped with system-integrated advanced TPS and hot structures and implementing advanced guidance navigation and control techniques (Tumino & Gerard, 2006). Basing on ESA plans (ESA, 2022), current activities under FLPP Period 3 and New Economic Opportunities (NEO) should focus on developing a portfolio of demonstrators and associated technologies to guarantee the shortest time to market of price-competitive innovative solutions. Moreover, ESA just started the work on a prototype reusable rocket first stage called Themis (Figure 11(b)) which is intended to "*assess the economic value of reusability for Europe*" (ESA, 2021).



(a) (b)

Figure 11: Artist's view of IXV reentry phase (ESA Image (ESA, 2011)); (a) Artist's view of Themis (ESA Image (ESA, 2021))

As mentioned in Section 1.2, it is worth including HST studies when dealing with the RLVs research efforts considering their commonalities in terms of design issues and technological challenges to be faced. At this purpose, from a chronological perspective, the Sänger Program carried out in the framework of the German Hypersonics Technology Program studied the Sänger II, in which for the first time HST and RLV capabilities were combined together in a unique concept (Koelle & Kuczera, 1989; Koelle, 1988). Notably, the Sänger II was equipped with dual-purpose airbreathing first stage called European Hypersonic Transport Vehicle (EHTV). As HST, the EHTV was supposed to carry up to 250 passengers in business class configuration over a range of 10,000 km, while as RLV and with minor modifications, EHTV was able to host a second stage delivering up to 15 tons of payload to LEO. For the second stage, two options were envisaged, i.e., the manned winged HORUS and the unmanned ballistic CARGUS, thus leading to the alternative Sänger II vehicle configurations depicted in Figure 12. However, like most of the RLV activities performed in that period, Sänger Program was cancelled in late 1990s for funding difficulties (Hammond, 1999).

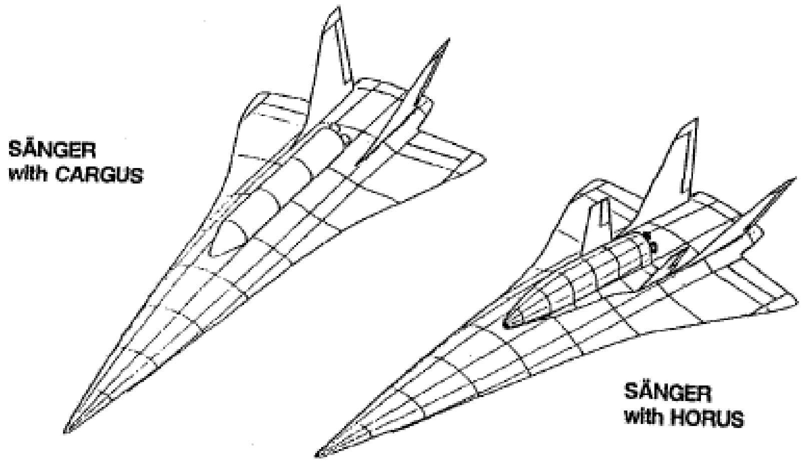


Figure 12: Sänger hypersonic first stage vehicle configuration with the two upper stage options (Koelle & Kuczera, 1989)

More recently, several noteworthy activities have been performed in Europe to analyze the potential of HST in the future. In this context, the Long-Term Advanced Propulsion Concepts and Technologies (LAPCAT I/II) performed by ESA with European Commission (EC) co-funding aimed at reducing antipodal passenger flights to less than 2 to 4 hours (Steelant, 2008b, 2009; Steelant, Varvill, et al., 2015). Notably, the LAPCAT II Project focused on the design of the Mach 8 airbreathing cruise passenger vehicle called LAPCAT MR2 (Figure 13(a)). Key achievements of the MR2 design effort for the progress of HST technologies included the accomplishment of dedicated aerodynamic and propulsive experiments for the different components as well as for the complete vehicle with the verification of wind tunnels (Steelant, Varvill, et al., 2015). LAPCAT studies along with other European Projects (i.e. ATLLAS I/II (Steelant, 2008a), HIKARI (Blanvillain & Gallic, 2015), HEXAFLY (Steelant, Langener, et al., 2015) and HEXAFLY Int. (Favaloro et al., 2015)) paved the way for the Horizon 2020 (H2020) Stratospheric Flying Opportunities for High-Speed Propulsion Concepts (STRATOFLY) funded by the EC. Carried out in the timeframe 2018-2021, STRATOFLY aimed at assessing the potential of an airbreathing high-speed transport vehicle to reach Technology Readiness Level (TRL) 6 by 2035, with respect to key technological, societal and economical aspects (Viola et al., 2021). Key concept analyzed during the Project was the STRATOFLY MR3 Cruiser (Figure 13(b)) based on the design of LAPCAT MR2.4.

(a) (b)

Figure 13: (a) LAPCAT MR2.4 (Steelant & Langener, 2014); (b) STRATOFLY MR3 (Viola et al., 2021)

In this context, it is worth highlighting that the H2020 STRATOFLY Project was coordinated by Politecnico di Torino and involved several partners in Europe among universities and research centers, i.e., VKI, CIRA, DLR, FICG, ONERA, CNRS, NLR, FOI, TUHH and LUND University. Considering the direct involvement of the Author within the activities performed during the Project in parallel to the PhD activities, the expertise gained during that experience has been fundamental to complete a substantial part of the work described in this Dissertation. In account of this, a STRATOFLY derivative concept with RLV features is proposed as case study in Section 2.2.1, where additional information regarding the STRATOFLY MR3 is also provided. For completeness, to conclude this survey on current HST studies, it is also mentioned the SpaceLiner concept, an "*ultrafast intercontinental passenger transport based on a rocket powered two-stage reusable vehicle*" (Sippel, 2007) proposed by DLR in 2005. Recently, building on the heritage from Sänger study, an evolution of SpaceLiner as TSTO vehicle is under evaluation (Sippel et al., 2016, 2019).

1.3 Research Outlook

Starting from the quest for cost-effective and sustainable RLVs discussed in Section 1.1, it is of utmost importance to evaluate future concepts feasibility since the very early design stages. On one side, this implies the need for a Cost-Effectiveness (C-E) approach made up of dedicated cost and effectiveness models properly merged to provide a C-E assessment. On the other side, taking into account the possibility to assess sustainability through a technology roadmap, the set-up of an appropriate technology roadmapping methodology is required. In account of this, after a thorough literature review of available C-E and technology roadmapping approaches, the flowchart in Figure 14 has been established. It summarizes the major activities performed along the PhD and described within this Dissertation.

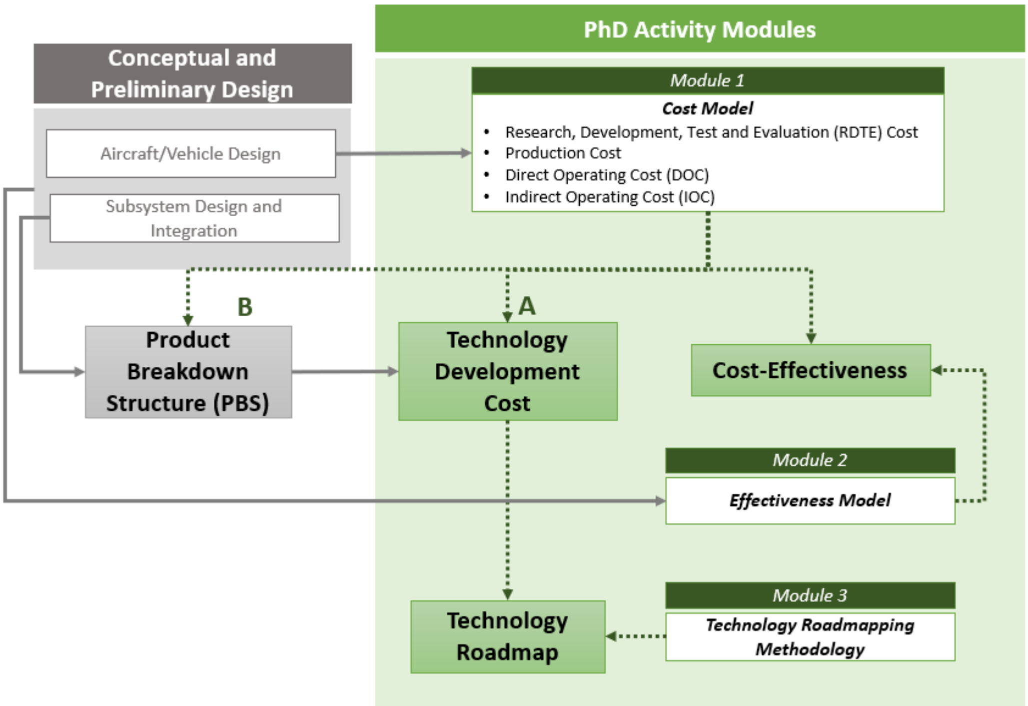


Figure 14: Overview of PhD Activities

As shown, the three main modules addressed during the study focus on the development of suitable approaches to tackle the C-E and sustainability of future RLV, which is the key topic of the overall work. However, Figure 14 also stresses the link of the proposed activity flow within the more general framework of preliminary and conceptual design methodologies. Indeed, a central aim of this study is to support the design of future RLVs by providing information on the economic feasibility, the C-E and the technological sustainability of future concepts. In account of this, the work will benefit of the major outputs from preliminary and conceptual design to tackle complementary aspects often neglected during vehicle design, but key for the overall success of a project.

In this context, it is specified that the development of methodologies for conceptual and preliminary design of RLVs is not a primary focus of this work. This topic was already extensively tackled in literature (Czysz & Vandenkerckhovet, 2001; Hammond, 1999, 2001; Humphries Sr et al., 2001). On this basis, starting from existing vehicle designs, great emphasis will be put in studying new approaches to complement them with information about their C-E and technological sustainability. Referring to Figure 14, the research focuses on the development of three main modules, i.e., Cost Model (Module 1), Effectiveness Model (Module 2), and Technology Roadmapping Methodology (Module 3). Notably, Module 1 entails the development of a cost model specifically tailored for RLVs. The proposed cost model covers the overall RLV Life Cycle Cost (LCC), entailing Research, Development, Test and Evaluation (RDTE) (or, simply, Development) cost, Direct Operating Cost (DOC) and Indirect Operating Cost (IOC). Taking into account the key limitations of State-of-the-Art (SoA) methodologies for cost estimation, great attention is devoted to establish a cost model able to grasp the effect of peculiar RLV design characteristics onto costs. As highlighted in Figure 14, vehicle characteristics stemming for preliminary and conceptual design activities are exploited as input for the cost model. In Module 2 an Effectiveness Model for RLV is established. In particular, after defining the attributes which contribute to the definition of overall vehicle effectiveness, a multi-objective decision analysis approach is applied to evaluate the contribution of each attribute and derive a comprehensive estimation of effectiveness. As shown in Figure 14, the results from cost and effectiveness analyses converge into a Cost-Effectiveness assessment. Eventually, Module 3 describes the main steps of the Technology Roadmapping methodology adopted in this Dissertation. Moreover, with the aim to exploit as much as possible the outcomes from the new cost model for technology analysis as well as the key results from preliminary and conceptual design, two paths are studied in order to connect Module 1 with Module 3 and provide and insight onto technology development cost. In particular:

- Path A, in which Development Cost results are used to derive a preliminary estimation of technology development cost at vehicle level. Notably, basing on the overall TRL achieved, the remaining development effort (i.e., cost) is estimated;
- Path B: in which results from LCC assessment and the subsystems breakdown provided by the Product Breakdown Structure (PBS) (stemming from preliminary and conceptual design) are exploited to obtain a technology assessment (i.e., a list of technologies of interest) and a detailed estimation of the Cost at Completion (CaC) for each technology.

For sake of clarity, the PBS "*is the hierarchical breakdown of the products such as hardware items, software items, and information items (documents, databases, etc.)*" (NASA, 2016a). In the present Dissertation, the "hardware items" included within the PBS are the systems, subsystems, equipment, and components constituting the RLV (i.e., the product). In addition, CaC is the cost to be sustained to perform technology development up to TRL 9. Definitions related to the TRL scale are provided in Section 4.1.1.

Information from Path A and path B substantially integrates the results from the technology Roadmapping Methodology, providing a deeper insight for the technological sustainability of the proposed concepts. In this context, it is worth specifying that the core of this Dissertation is the development of Module 1 and Module 2, which address great part of the innovative aspects introduced within this work. Module 3 and the resulting Cost-Effectiveness assessment are mainly based on state-of-the-art; the main novelty of this part lies in the application of these methodologies to RLVs.

On this basis, before proceeding with the description of newly-developed models, Chapter 2 starts from the main outcomes of the historical overview provided in Chapter 1 and introduces the key characteristics of the RLVs addressed all along this Dissertation. In particular, the most promising RLV design options are discussed and their preliminary requirements are elicited. In the framework of the most interesting RLV designs, Chapter 2 also introduces the case studies used to test the new Cost-Effectiveness (C-E) and roadmapping approaches introduced in the subsequent chapters. Chapter 3 addresses the cost model for RLVs proposed in this work, whilst Chapter 4 deals with the Technology Roadmapping Methodology adopted with application to the selected case studies. Moreover, Chapter 4 describes the new strategies for technology development cost estimation (i.e., Path A and Path B in Figure 14) and Chapter 5 tackles the C-E assessment for future RLVs. Then, basing on the outcomes from Module 1 and on the proposed Effectiveness Model (Module 2), a final C-E assessment for the case studies of interest is provided. Chapter 6 draws major conclusions and proposes future works to enhance the estimation of C-E and sustainability of RLVs. Eventually, Chapter 7 lists the different appendixes and annexes used as references within the main text.

1.4 Chapter 1 Abbreviations

ASALM	Advanced Strategic Air-Launched Missile
CaC	Cost at Completion
C-E	Cost-Effectiveness
CIRA	Centro Italiano Ricerche Aerospaziali
CNES	Centre national d'études spatiales
CNRS	Centre National de La Recherche Scientifique
CRV	Crew Return Vehicle
DC-X	Delta Clipper Experimental
DC-XA	Delta Clipper Experimental Advanced
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DOC	Direct Operating Cost
EC	European Commission
EHTV	European Hypersonic Transport Vehicle
ELV	Expendable Launch Vehicle
ESA	European Space Agency
FESTIP	Future European Space Transportation Investigations Programme
FICG	Fundacion de la Ingenieria Civil De Galicia
FLPP	Future Launchers Preparatory Programme
FLTP	Future Launchers Technologies Programme
FOI	Totalforsvarets Forskningsinstitut
FY	Fiscal Year
H2020	Horizon 2020
HRE	Hypersonic Research Engine
HST	High-Speed Transportation
HTHL	Horizontal Take-Off Horizontal Landing
IOC	Indirect Operating Cost
ISS	International Space Station
IXV	Intermediate eXperimental Vehicle
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LCC	Life Cycle Cost
LEO	Low Earth Orbit
NASA	National Aeronautics and Space Administration
NASP	National AeroSpace Plane
NEO	New Economic Opportunities
NHRF	National Hypersonic Flight Research Facility
NLR	Stichting Nationaal Lucht- En Ruimtevaartlaboratorium
ONERA	Office National d'Etudes et de Recherches Aerospatiales
PBS	Product Breakdown Structure
RBCC	Rocket-Based Combined Cycle
RCCFD	Reusable Combined Cycle Flight Demonstrator

RDTE	Research, Development, Test and Evaluation
REL	Reaction Engines Ltd
RLV	Reusable Launch Vehicle
RM&S	Reliability, Maintainability and Supportability
SABRE	Synergetic Air-Breathing Rocket Engine
SED-WR	Scramjet Engine Demonstrator – WaveRider
SoA	State-of-the-Art
SSTO	Single Stage to Orbit
STRATOFLY	Stratospheric Flying Opportunities for High-Speed Propulsion Concepts
SUS	SKYLON Upper Stage
TBCC	Turbine-Based Combined Cycle
TPS	Thermal Protection System
TRL	Technology Readiness Level
TSTO	Two Stage to Orbit
TUHH	Technische Universitat Hamburg-Harburg
UKSA	United Kingdom Space Agency
US	United States
VKI	von Karman Institute for Fluid Dynamics
VTHL	Vertical Take-off Horizontal Landing
VTVL	Vertical Take-off Vertical Landing

Chapter 2

Future reusable space transportation and re-entry concepts

This Chapter aims at introducing the typical characteristics of Reusable Launch vehicle (RLV) concepts collected by means of the literature review reported in Section 1.2. In particular, Section 2.1 provides an overview of the vehicle types and the mission concepts of interest. At this purpose, Section 2.1.1 summarizes the most promising design options under consideration for future RLVs in terms of configuration (i.e., number of stages, take-off and landing mode, propulsion type, etc.) and mission (i.e., target orbit, manned vs. unmanned, etc.), justifying the current emphasis towards Two Stage To Orbit (TSTO) concepts with airbreathing first stage. This is complemented in Section 2.1.2 by a preliminary elicitation of high-level requirements for future RLVs. The latter is subsequently exploited in Section 5.4, where the Effectiveness Model proposed in the framework of this work is discussed. Then, basing on the preferred RLV features discussed in Section 2.1.1, Section 2.2 justifies the focus on the two case studies used to test the cost and effectiveness models as well as the technology roadmapping methodology presented in the following Chapters. Eventually, Section 2.2.1 introduces the main features of Case Study 1 (a TSTO derivative of the STRATOFLY MR3 Cruiser mentioned in Section 1.2.2), whilst Section 2.2.2 reports the main characteristics of the SpaceX Starship vehicle (already referenced in Section 1.2.1) considered as Case Study 2. The list of abbreviations used within the text is provided in Section 2.3.

2.1 Vehicle and Mission Concept Overview

2.1.1 Promising Design Options for future RLVs

The thorough historical overview provided in Section 1.2 highlighted that in the past decades several research efforts were spent to achieve sustained hypersonic flight in the near future for both RLV and High-Speed Transportation (HST) applications. This allowed to explore many design options in terms of (Hammond, 1999; Hunt & Wagner, 1997):

a. Take-off (or launch) mode: Horizontal Take-off (HT), Vertical Take-off (VT), air-dropped/air-launched or launch assisted,
b. Landing (or recovery) mode: None (i.e., splashdown), Horizontal Landing (HL) and Vertical Landing (VL);
c. Propulsion: airbreathing, rocket or combination;
d. Fuel (or, more generically, propellant): liquid (cryogenic, storable, or mixed), solid or hybrid;
e. Reusability: expendable, reusable, or partially reusable;
f. Mission: cruise (i.e. HST vehicle), acceleration to Low Earth Orbit (LEO) (100 km to 2000 km (Sziroczak & Smith, 2016)) and re-entry, or combination;
g. Staging: Single Stage to Orbit (SSTO), TSTO or more;
h. Crew: manned or unmanned;
i. Payload: typically between 10,000 lb and 100,000 lb (Hammond, 1999)

Since early RLV efforts, SSTO vehicles have been by far the "*holy grail of launcher technology*" (Sziroczak & Smith, 2016) due to the undeniable advantage of developing manufacturing, and operating a single vehicle and not two dissimilar vehicles as for TSTOs (Stanley et al., 1992). This led to an underestimation of the enormous technological challenge associated to SSTO development and to the failure of initiatives such as NASP (airbreathing), X-33 and X-34 (rocket) as a result of "*a lack of consensus on technology readiness status* (that) *has contributed to under estimating development risk*" (Chase, 2009). Hence, previous experience proves that SSTO vehicles development is technically unfeasible in the near-term. Indeed, they "*have to meet extremely 'tight' performance specifications, since the fraction of cargo mass to vehicle gross mass* *is relatively small and sensitive*" (Dorrington, 1990). This justifies the current shift towards TSTO concepts (such as the newly-proposed TSTO version of the SKYLON SSTO mentioned in Section 1.2.2.), which "*turned out to be specifically suitable with respect to technical and economical affordability criteria*" (Deneu et al., 2005). In the framework of TSTO RLVs design, it is worth underlying the key role of Staging Mach as design parameter. Notably, it is the maximum Mach attained by the first stage before separation from the second stage. As proved in many trade studies (Bowcutt et al., 2002; Freeman et al., 1995; Hunt & Wagner, 1997), Staging Mach value highly impacts onto the overall vehicle design and, specifically, on the size of each stage. Indeed, as Staging Mach increases, total system gross mass tends to decrease "*because of a more optimal split of the energy content in each stage*" (Hunt & Wagner, 1997). However, in case of airbreathing TSTOs, more technologically advanced propulsion (e.g., scramjet) as well as ticker Thermal Protection System (TPS) is required. As such, the issue of Staging Mach selection for TSTO vehicles shall be carefully handled. On these premises, this Dissertation will primarily focus on TSTO vehicles, deemed the most promising RLV solutions in the near term from a technical perspective. However, the possibility to achieve SSTO capability is not excluded a priori, so that they will be tackled as well (specifically from a costs perspective in Section 3.2).

Another important issue tackled in former RLV studies was the selection of the most suitable propulsion system and, in particular, "*whether the main ascent propulsion systems of future vehicles should only use rocket engine technology, or introduce air-breathing engine technology in combination*"(Dorrington, 1990). To date, greater attention it given to all-rocket concepts (e.g., SpaceX Starship and SpaceLiner) due to their lower technological complexity. However, several studies, mainly in the European context, are dealing with high-speed airbreathing propulsion for HST vehicles (e.g., LAPCAT and STRATOFLY), so that the issue on propulsion system selection is still open. Specifically dealing with TSTO vehicles, the combination of rocket propulsion with scramjet engine is theoretically a feasible option for the second stage. However, only purely rocket orbiters are deemed feasible in the near future due to the immaturity of scramjet technology (Hunt & Wagner, 1997). For the first stage, the aforementioned issue about the selection of the most proper ascent propulsion system is still to be solved so that, in the present work, both rocket, airbreathing as well as combined solutions are addressed. Nevertheless, high-speed airbreathing propulsion seems by far the most interesting solution for TSTO first stages despite the lower technology readiness currently achieved. Indeed, from a design perspective, they can provide additional margin and reduced sensitivity to weight growth, resulting in more "*flexibility to build in safety, reliability, maintainability, durability and operability*" (Bilardo et al., 2003). Airbreathing space access vehicles can offer greater mission flexibility (in terms of launch window, orbital offset, rapid rendezvous, etc.) with respect to their rocket counterparts (Hunt et al., 1999) and provide more reliable and cost-effective access to space (Bilardo et al., 2003). Moreover, these systems are expected to provide airline-like operations since they will take-off horizontally from conventional runways, with a substantial improvement in ground operability than rockets (Bilardo et al., 2003).

2.1.2 Preliminary Requirements Definition

Starting from the considerations about promising RLV design solutions in the previous Section, it is possible to derive preliminary requirements for future reusable access to space systems. As it will be clarified in Section 5.4, requirements elicitation is mandatory to derive all the attributes needed for the subsequent Cost-Effectiveness (C-E) analysis. As thoroughly discussed by (Ferretto, 2020), high-level requirements definition is a fundamental step during the conceptual design of new systems. Indeed, the process starts from the identification of stakeholders along with their needs and the elicitation of a mission statement (ECSS (European Cooperation for Space Standardization), 2004). The latter represents "*a concise definition of high-level objectives of a mission*" (Wertz & Larson, 2005), from which primary mission objectives can be obtained, whilst secondary objectives stem from additional stakeholders needs. For sake of clarity, the derivation of the primary objectives allows to define a first set of mission requirements, whilst secondary objectives determine programmatic requirements (Ferretto, 2020). A complete example of requirements derivation can be found in (Ferretto, 2020) for the STRATOFLY MR3 Cruiser and the related H2020 STRATOFLY Project. In that context, for example, the following mission requirement is elicited: "*The flight time of civil passenger flights over long haul and antipodal routes shall be shortened of at least one order of magnitude with respect to the current state-of-the-art for civil aviation*" (Ferretto, 2020). Moreover, a key programmatic requirement is: "*TRL 6 shall be reached by 2030-2035*" (Ferretto, 2020). In the framework of the present work, as clearly stated in Section 1.3, the conceptual design of future RLVs is not a primary goal, while great emphasis is given to propose methodologies in support of conceptual design activities with the aim to assess the C-E and sustainability of future reusable systems. In account of this, a complete analysis of requirements is not provided in this Dissertation. However, as mentioned, to support the activities related to C-E described in Section 5.4 a preliminary requirements assessment is performed basing on previous studies on this subject already available from literature. At this purpose, a suitable mission statement could be that derived for the SKYLON vehicle in (REL (Reaction Engines Ltd.), 2009) and available from (Hempsell & Longstaff, 2010):

"*To achieve the lowest cost access to space possible with both current technology and commercial feasibility.*"

Hence, basing on: 1) the SKYLON objectives specified in (Hempsell & Longstaff, 2010); 2) the requirements for future commercial RLVs specified by (Andrews, 2000); and 3) the operability and supportability requirements for a SSTO system from (Gaubatz et al., 1996), it is possible to collect a preliminary list of desired features for the final system to be easily turned into high-level requirements. The result of this analysis is depicted in Figure 15.

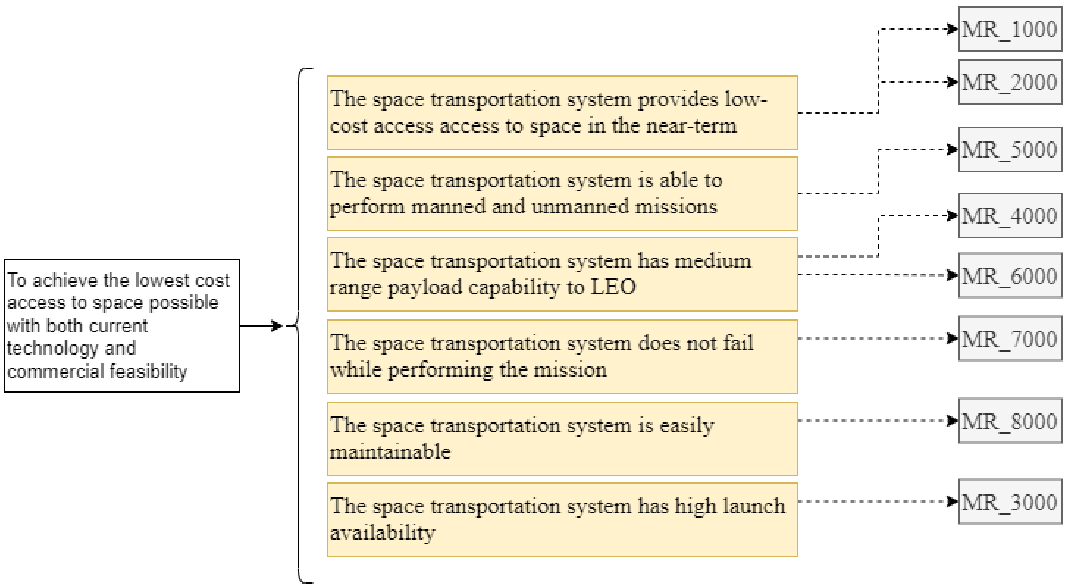


Figure 15: RLV High-Level Requirements derivation from Mission Statement

For sake of clarity, the list of high-level mission requirements applicable to a generic future transportation system reported in Figure 15 is fully elicited in Table 1. Please, notice that the nomenclature followed for requirements definition is the same adopted in (Ferretto, 2020) (MR stands for Mission Requirement).

Table 1: List of High-Level Mission Requirements for a Space Transportation System

MR_1000	The future space transportation system shall provide low-cost access to space.
MR_2000	The future space transportation system shall provide near-term access to space.
MR_3000	The future space transportation system shall guarantee high launch availability.
MR_4000	The future space transportation system shall perform LEO missions.
MR_5000	The future space transportation system shall target manned and unmanned applications.
MR_6000	The future space transportation system shall provide medium range payload capability.
MR_7000	The future space transportation system shall guarantee high mission reliability.
MR_8000	The future space transportation system shall guarantee high maintainability.

Notably, MR_1000 and MR_2000 directly stem from the SKYLON mission statement reported above. As far as the objective of "commercial feasibility" is concerned, it can be translated into requirements thanks to the analysis performed by (Andrews, 2000), according to which the next generation RLVs "*designed to address both near term and future commercial markets must have a payload capability equivalent to the current Space Shuttle, be capable of launching on the order of 150 times per year with high reliabilities (1/10,000 loss of vehicle) and low ($500 per pound) launch costs*". Therefore:

- the high expected launch rate turns into the requirement of high launch availability (MR_3000);
- the foreseen payload capability equivalent to the current Space Shuttle implies the requirement (MR_6000) of medium range payload capability (i.e. around 20,000 lb) also mentioned in (Gaubatz et al., 1996);
- the projected "high reliabilities" lead to MR_7000 on mission reliability also mentioned in (Gaubatz et al., 1996);

Moreover, recalling the discussion on RLV design options in Section 2.1.1. MR_4000 and MR_5000 reflect the fact that LEO is the typical target for manned and unmanned RLV missions. Reference to these requirements is also provided in (Gaubatz et al., 1996), where the importance of maintainability issues (MR_8000) is also highlighted. To conclude, it is worth noticing that the list of requirements in Table 1 is perfectly in line with the introductory discussion in Section 1.1 on typical characteristics targeted for future space transportation systems, such as cost reduction and design attributes expressed as “-ilities”. For sake of clarity, reusability is not explicitly stated as system requirement since it is considered as a means to achieve the mission objectives not a mission objective itself.

2.2 Case Studies

The previous Section collected key characteristics and mission concepts under consideration for future RLVs. However, taking into account that the following Chapters will discuss the proposed models for cost and effectiveness assessment as well as a technology roadmapping methodology specifically tailored for future RLVs, it is required to define more in detail the case studies on which these approaches will be tested. At this purpose, recalling that RLV design is not the objective of this work (Section 1.3), the most recent designs stemming from the historical overview presented in Section 1.2 have been thoroughly considered with the aim to select suitable case studies. In this context, since Cost-Effectiveness (C-E) assessment aims to compare competing design alternatives (Section 5.1), at least two case studies should be selected in order to allow a comparison and choose the most promising option from a C-E viewpoint. From a broad perspective, the current focus onto TSTO solutions for future RLVs leads to select these concepts as case studies (Section 2.1.1). Moreover, since both airbreathing and rocket concepts are still under evaluation, it is deemed appropriate to considered both propulsive strategies within the case studies. Looking at the European scenario, several airbreathing HST efforts have been just completed (e.g., LAPCAT and STRATOFLY) and other studies on rocket concepts are still on-going (i.e., SpaceLiner and Themis) (Section 1.2.2), whilst a TSTO version of LAPCAT/STRATOFLY cruiser vehicles has not been proposed yet. Complementary, in the US framework, current RLV studies (Section 1.2.2) are exclusively targeting rocket TSTO concepts (e.g., SpaceX Starship and New Glenn). Indeed, despite the interest in developing and testing scramjet propulsion, technology demonstrators are quite different than real target vehicles (e.g., the X-51 SED-WR) so that, like in Europe, no noteworthy airbreathing TSTO concepts are under study in the US nowadays. In account of this, due to the goal of this work to test developed models both on rocket and airbreathing TSTO vehicles, a preliminary airbreathing concept is proposed within Dissertation. Notably, considering the great involvement of the Author in the H2020 STRATOFLY Project activities, it is deemed interesting to explore a TSTO version of STRATOFLY MR3 Cruiser. Main results of this work are provided in Section

2.2.1, where a preliminary design of the so-called STRATOFLY TSTO (i.e., Case Study 1) is proposed. As far as the rocket TSTO case study is concerned, the SpaceLiner HST concept seems interesting as possible case study since a SpaceLiner TSTO is currently under study at Deutsches Zentrum für Luft- und Raumfahrt (DLR). However, very few design information is currently available from literature (Sippel et al., 2016, 2019). More data is available for the SpaceX Starship applied to a Mars mission, but both LEO and HST scenarios are envisaged as well (Musk, 2017b). By far, the most interesting feature of the SpaceX Starship is that it is a concrete near-term RLV since is it currently under flight test by SpaceX (SpaceX, 2021). For this characteristic, the SpaceX Starship is chosen as second (and last) case study (i.e., Case Study 2) in this Dissertation (Section 2.2.2). As a result, the two case studies tackled in this work will allow to compare in terms of C-E competing concepts belonging both to the European and to the US RLV scenarios.

2.2.1 Case Study 1: STRATOFLY MR3 evolution as a Two Stage to Orbit

2.2.1.1 Background and Options

As mentioned in Section 1.2.2, the present study has been carried out in parallel to the H2020 STRATOFLY Project, which aimed at optimizing the design of the STRATOFLY MR3, a civil hypersonic aircraft carrying up 300 passengers on antipodal routes (Viola et al., 2021). As documented in (Ferretto, 2020), a thorough cost assessment was performed during the project to determine the viability of the analyzed concept and key results reveal that almost 24.5 B€ are required just to accomplish the development of this complex and innovative system. In account of this, it is reasonable to assume that such a huge economic effort might discourage future investments towards a single-purpose vehicle targeting a narrow public of business class passengers. However, the potential use of the same vehicle concept with minor modifications to deliver payload into orbit might attract more space-related sponsors in Europe interested in supporting the required development effort, thus paving the way for a European multi-purpose reusable vehicle. In this context, Section 1.2.2 already reported that the ambitious goal "*to realize two major future challenges: a new space transportation system, and a hypersonic transport aircraft with only one development program and investment*" (Koelle, 1988) was pursued (even if not successfully completed) in the framework of the Sänger II project. In addition, an unmanned TSTO-launcher version of the SpaceLiner ultra-high speed passenger transport (Section 1.2.2) is currently under development at DLR (Sippel et al., 2016) with the aim of "*enabling dramatic savings on development cost and moreover by manufacturing the vehicles on the same production line, also significantly lower hardware cost than would result for a dedicated new lay-out*". Therefore, the exploitation of STRATOFLY MR3 civil aircraft concept as a first stage of a STRATOFLY TSTO launch vehicle seems promising. It is also perfectly in line with the purpose of this Dissertation to test the methodologies proposed in the next Chapters onto TSTO case studies, deemed more feasible in the mid-term as highlighted in Section 2.1.1. However, in accordance with the Research Outlook stated in Section 1.3, it is underlined that a thorough conceptual design of a STRATOFLY TSTO launcher is not a primary objective of the present work. As such, a preliminary STRATOFLY TSTO configuration is here proposed benefitting as much as possible of the detailed design outcomes from the H2020 STRATOFLY Project and of similar TSTO designs already studied in literature. Notably, the many commonalities between the Sänger II first stage (the so-called EHTV introduced in Section 2.1.1) and STRATOFLY MR3 can guide towards the definition of a first version of STRATOFLY TSTO vehicle to be then properly refined in the future with dedicated analyses. Indeed, like STRATOFLY MR3, EHTV was an airbreathing vehicle, but the EHTV was equipped with turboramjet engines and the STRATOFLY MR3 with Air Turbo Rocket (ATR) engines and Dual Mode Ramjet (DMR). For completeness, Table 2 collects main data available from (Koelle & Kuczera, 1989) for the EHTV in both RLV first stage and HST configurations. The same design features are also reported for the STRATOFLY MR3 (Ferretto, 2020).

Table 2: Comparison of EHTV and STRATOFLY MR3 main characteristics

	EHTV		STRATOFLY MR3
	RLV First Stage	HST	
Vehicle total length [m]	92	92	94
Wing span [m]	46	46	41
Wing area [m^2]	880	880	1296
Vehicle net mass [ton]	142	149	186*
Maximum propellant mass [ton]	120	120	181
Payload [ton]	66-91 (upper stage)	35-40 (250 pax./cargo)	33 (300 pax./cargo)
Maximum Take-Off Weight (MTOW) [ton]	300-350	270-280	400
L/D ratio, max (hypersonic)	4.4	5.3	6.5
Number of engines, thrust level (max) [kN]	6 x 300 kN	6 x 350 kN	6 x 250 kN (ATR) + 1 x 5000 kN (DMR)
Mach (max)	6.8	4.4	8
Flight altitude (max) [km]	31	24.5	33
Flight range [km]	2 x 3,500	10,500	18,700

Please, notice that mass data for the STRATOFLY MR3 in Table 2 is the same assumed for the LAPCAT MR2.4 vehicle (precursor of STRATOFLY MR3) (Figure 16). Moreover, for sake of clarity, vehicle net mass represents the mass (with engines) at the end of the main propulsion phase with residuals (Koelle, 2013). Basing on this definition, the net mass of the STRATOFLY MR3 should account for the residual fuel mass after the cruise phase. However, since it can be considered negligible with respect to the fuel mass already consumed during cruise, the value for vehicle net mass reported in Table 2 is, more properly, the vehicle dry mass (with engines). As far as STRATOFLY MR3 payload mass is concerned, a total amount of 80 plus 30 kg is assumed for each of the 300 passengers carried (Ferretto, 2020).

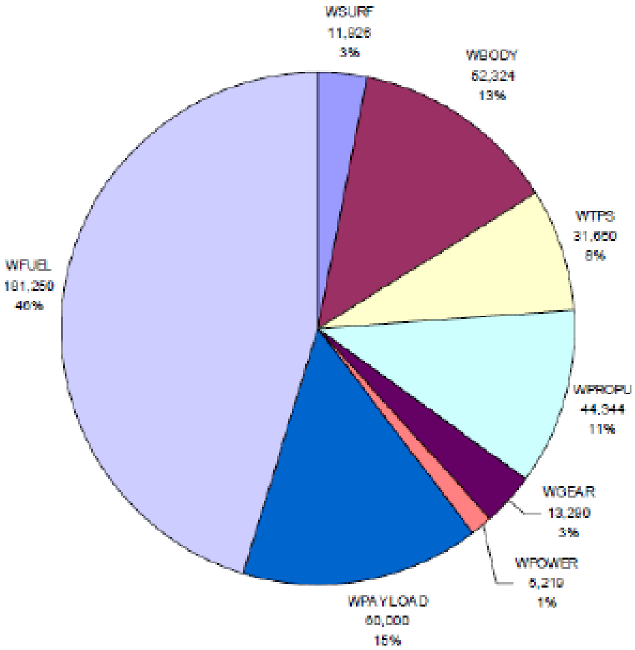


Figure 16: LAPCAT MR2.4 Mass Breakdown (Steelant, Varvill, et al., 2015)

From Table 2, it emerges that the overall dimensions in terms of fuselage length and wing span of EHTV (as HST) and STRATOFLY MR3 Cruiser are comparable. Moreover, by analyzing EHTV characteristics as first stage RLV, it can be noticed that minor modifications are introduced with respect to the HST version in order to host the larger payload constituted by the upper stage. In the RLV version, this results in a slight increase of the maximum thrust level required for take-off and a decrease of the lift-to-drag (L/D) ratio. This worsening of the aerodynamic characteristics is due to the presence of the second stage, for which two different upper stage options were envisaged, i.e., the manned winged HORUS and the unmanned ballistic CARGUS (Figure 12). At this point, considering the similarities between the two EHTV versions provided in Table 2, a preliminary version of STRATOFLY TSTO first stage can be derived basing on the STRATOFLY MR3 characteristics. Yet, considering that for a TSTO the design of the two stages is strictly interconnected, it is necessary to size the first stage taking into account the requirements of the second stage. However, being a brand-new concept proposed within this Dissertation, no guidelines exist in literature about possible RLV solutions based on the STRATOFLY MR3. Therefore, in this initial exploratory phase, any staging configuration mentioned in Section 2.1.1 should be carefully explored to evaluate pros and cons of each idea and select the best alternative. For example, considering the Sänger II vehicle depicted in Figure 12, a back-to-back configuration can be a critical solution considering the presence of air intake and nozzle in the dorsal part of the vehicle (Figure 13(b)), right where the second stage should lie. Its feasibility is not excluded a priori, but is should be carefully assessed with detailed structural analyses in further studies. Similarly, a payload-bay configuration like that recently proposed in an alternative TSTO SKYLON-version (Figure 9, left) should be considered as an option. However, the volume effectively available in the passengers' cabin shown in Figure 13(b) for STRATOFLY MR3 should be evaluated in order to determine whether it is sufficient to host a second stage carrying a meaningful payload (i.e., not too small) into orbit. Moreover, due to the presence of a dorsal propulsive flow path within the STRATOFLY MR3, a payload release from the upper fuselage as for SKYLON TSTO seems not feasible. Again, this solution requires detailed analyses and, possibly, a vehicle re-design, which are out of the scope of this work.

2.2.1.2 Selected Configuration

From this analysis, it appears that despite the highly integrated propulsion of the STRATOFLY MR3 might enhance its performance, it certainly complicates the feasibility of any possible TSTO solution. In account of this, considering the capability of STRATOFLY MR3 to reach the high layers of the atmosphere, the air-launch solution seems particularly attractive at the current stage. As a result, similarly to the WhiteKnightTwo (Figure 7(b)) but at hypersonic speed, a preliminary STRATOFLY TSTO concept able to reach stratospheric altitudes and release from the lower side of the fuselage a second stage vehicle can be proposed. For sake of clarity, the overall vehicle configuration should be similar to that of the already operational Lockheed L-1011 Stargazer able to air-launch a small expendable rocket second stage, i.e. the Pegasus XL (Hammond, 1999; Northrop Grumman, 2022) (Figure 17). Since a similar hypersonic air-launched concept has not yet been studied in literature, its overall feasibility has to be deeply analyzed in future analyses. However, it is by far an attractive solution since it allows to maintain basically unaltered the external characteristics of the STRATOFLY MR3 vehicle when used as RLV first stage apart from a lower fuselage modification to host the second stage. However, this modification is considered negligible for the purposes of the present work.

Figure 17: Lockheed L-1011 Stargazer with Pegasus-XL (Northrop Grumman, 2022)

2.2.1.3 Preliminary First Stage Mission Profile Definition

Once the basic STRATOFLY TSTO vehicle arrangement is determined, it is necessary to define a mission profile for the new concept. At this purpose, considering the similarities between the Sänger II EHTV with the STRATOFLY MR3 discussed in Section 2.2.1.1, the mission profile reported in Figure 18 is taken as reference. Notably, an ascent trajectory similar to that proposed for the EHTV can be suggested in the first instance for the STRATOFLY TSTO first stage as well. Looking at the main mission characteristics (i.e., maximum Mach and altitude achieved) of the EHTV as RLV in Table 2, it can be noticed that lower values are envisaged with respect to the HST version. As a result, starting from the STRTAOFLY MR3 features as HST (Table 2), a reduction in maximum Mach and altitude can be expected when a RLV mission is considered. Notably, in line with EHTV, the second stage of the STRATOFLY should be released (or, more properly, air-launched) at an altitude between 31-33 km and at a maximum Mach between 6.8-8 to exploit the full potential of ATR and DMR engines. After separation, the first stage can return to launch site or fly to a different airport. Thus, even from this guess of mission profile, it emerges the great flexibility and operability of the STRATOFLY MR3 in the proposed TSTO configuration. Indeed, thanks to the foreseen aircraft-like characteristics, a return to the launch site is not strictly required for the separated first stage but, if more convenient (for example, from a fuel consumption point of view), any suitable alternate airport can be targeted. Hence, it is important to carefully evaluate all the possible alternative trajectories for the first stage after separation, ranging from the fly-back to the initial site up to a full hypersonic cruise to another airport. Please, notice that such a detailed mission analysis for STRATOFLY TSTO is out of the scope of this Dissertation.

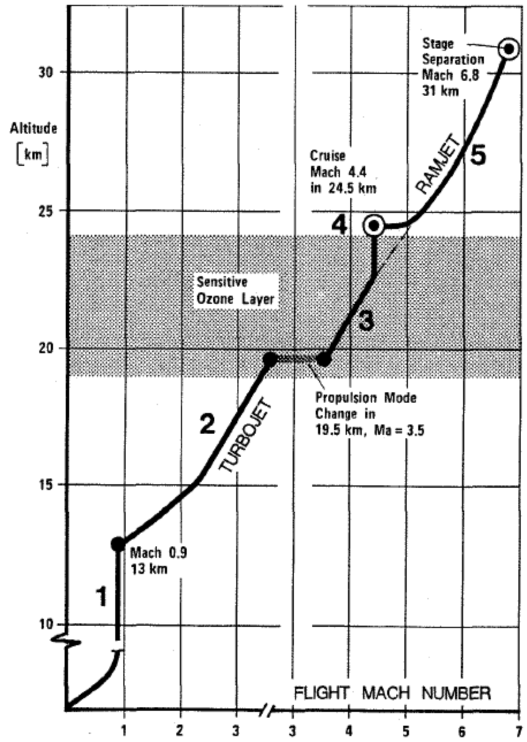


Figure 18: Sänger II EHTV Mission Profile as RLV (Koelle, 1988)

2.2.1.4 Second Stage Definition

At this point, it is necessary to define the characteristics of the second stage to be air-launched by the STRATOFLY MR3 and which, after separation, delivers the required payload into orbit. Again, considering the need to define a preliminary configuration without entering much into the detail of the design process (Section 1.3), the basic idea is to assess the applicability of an already existing design to the present case. On this basis, information available for Sänger II upper stage options is carefully evaluated with special emphasis onto the Sänger with CARGUS solution displayed in Figure 12(left). Taking into account the already discussed similarity in terms of dimensions between EHTV and STRATOFLY MR3, it seems appropriate to equip the latter with CARGUS and thus to propose a STRATOFLY TSTO configuration with an expendable second stage similar to the Lockheed L-1011 Stargazer/Pegasus XL mentioned above (Figure 17). For sake of clarity, CARGUS is an expendable stage based on state-of-the-art technology since it is derived from the ARIANE 5 upper stage (Koelle & Kuczera, 1989). Figure 19 from (Koelle & Kuczera, 1989) summarizes its main characteristics.

Please, notice that the maximum payload delivered by CARGUS to LEO is 15 tons, so that the STRATOFLY MR3 would be competitive with the SKYLON vehicle which is supposed to carry the same payload in orbit up to 300 km (Hempsell et al., 2009).

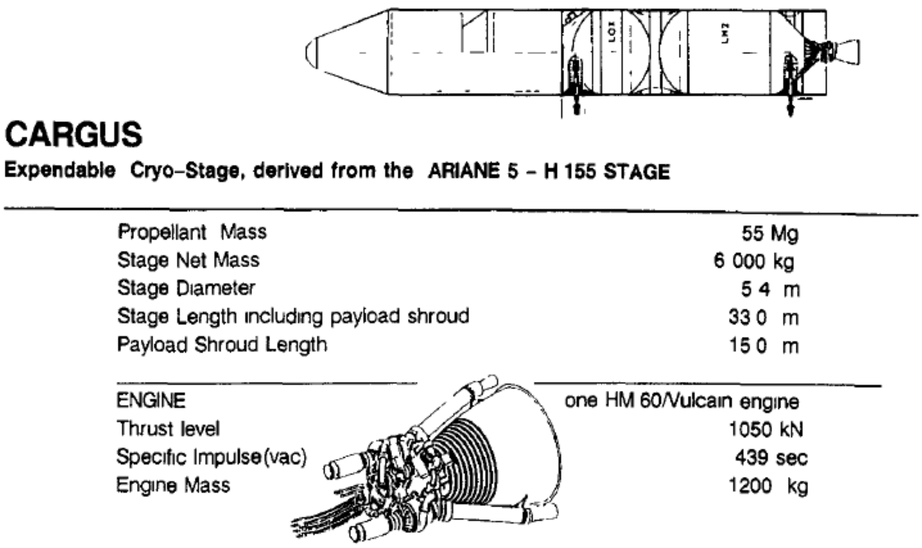


Figure 19: CARGUS Upper Stage key design features

As a result, the initial STRATOFLY TSTO configuration proposed within Dissertation consists of a first stage with the same features of the STRATOFLY MR3 Cruiser and an expendable second stage similar to CARGUS (Koelle & Kuczera, 1989).

2.2.1.5 Preliminary Vehicle and Cargo Capability Sizing

Supposing to fix the propulsive characteristics of the STRATOFLY MR3 Cruiser and thus avoid a re-design of the complex propulsive system already optimized during the H2020 STRATOFLY Project, it is important to assess the capability of the STRATOFLY TSTO to successfully take-off with the thrust provided by the six installed ATRs and then deliver the required cargo. This means that the new TSTO vehicle must have the same Maximum Take-off Weight (MTOW or W_{GTO}) of the STRATOFLY MR3, defined as:

$$W_{GTO} = W_{DRY,1} + W_{pay} + W_{ppl,1} \tag{1}$$

Where:

$W_{DRY,1}$ is the dry mass with engines of the first stage (i.e., STRATOFLY MR3) and it is fixed due to the need to freeze the subsystems design;

$W_{ppl,1}$ is the propellant mass (i.e., liquid hydrogen, LH_2) carried by the first stage;

W_{pay} is the overall payload carried by the TSTO, comprising the CARGUS with the 15-ton payload ($W_{pay,2}$) delivered to orbit. Notably:

$$W_{pay} = W_{DRY,2} + W_{ppl,2} + W_{pay,2} \quad (2)$$

Where $W_{DRY,2}$ is the dry mass with engines of CARGUS second stage (assumed equal to the Net Mass mentioned in Figure 19) and $W_{ppl,2}$ is the propellant mass stored within CARGUS (i.e., 55 tons of LOX/LH_2).
However, it is worth specifying that the preliminary mission profile assumed for the STRATOFLY TSTO first stage (Section 2.2.1.3) implies a reduction of the range covered with respect to the reference HST mission, with a consequent reduction of the required propellant mass ($W_{ppl,1}$). Indeed, from Table 2 it can be noticed that the flight range of the EHTV as first stage of RLV ($R_{RLV_{EHTV}}$) is lower than the HST version ($R_{HST_{EHTV}}$). Similarly, the range of the STRATOFLY MR3 used as first stage of RLV ($R_{RLV_{STRATOFLY}}$) is expected to decrease with respect to the reference HST mission ($R_{HST_{STRATOFLY}}$), thus justifying the reduction of fuel mass. In this context, the constraint on the W_{GTO} mentioned above and the reduction in fuel mass may allow to accommodate the increased payload requirement of the STRATOFLY TSTO linked to the adoption of the CARGUS. The latter weights 76 ton (Figure 19), more than twice the STRATOFLY HST payload in Table 2. As a result, by fixing in Eq.(1) W_{GTO} (400 ton), $W_{DRY,1}$ (186 ton) and W_{pay} (76 ton), a value of $W_{ppl,1}$ equal to 138 ton can be obtained.
To validate the effective capability to accomplish the prescribed mission for the STRATOFLY TSTO (i.e., to carry CARGUS to LEO) with the available $W_{ppl,1}$, a more detailed mission profile analysis has been performed using the ASTOS software in collaboration with the research team involved in the H2020 STRATOFLY activities. Results are provided in Figure 20, where the plot of propellant mass vs. mission time shows that $W_{ppl,1}$ is sufficient to accomplish the mission with a potential propellant saving of around 30 ton. For sake of clarity, the discontinuity in total mass in Figure 20 is due to the release of the second stage.

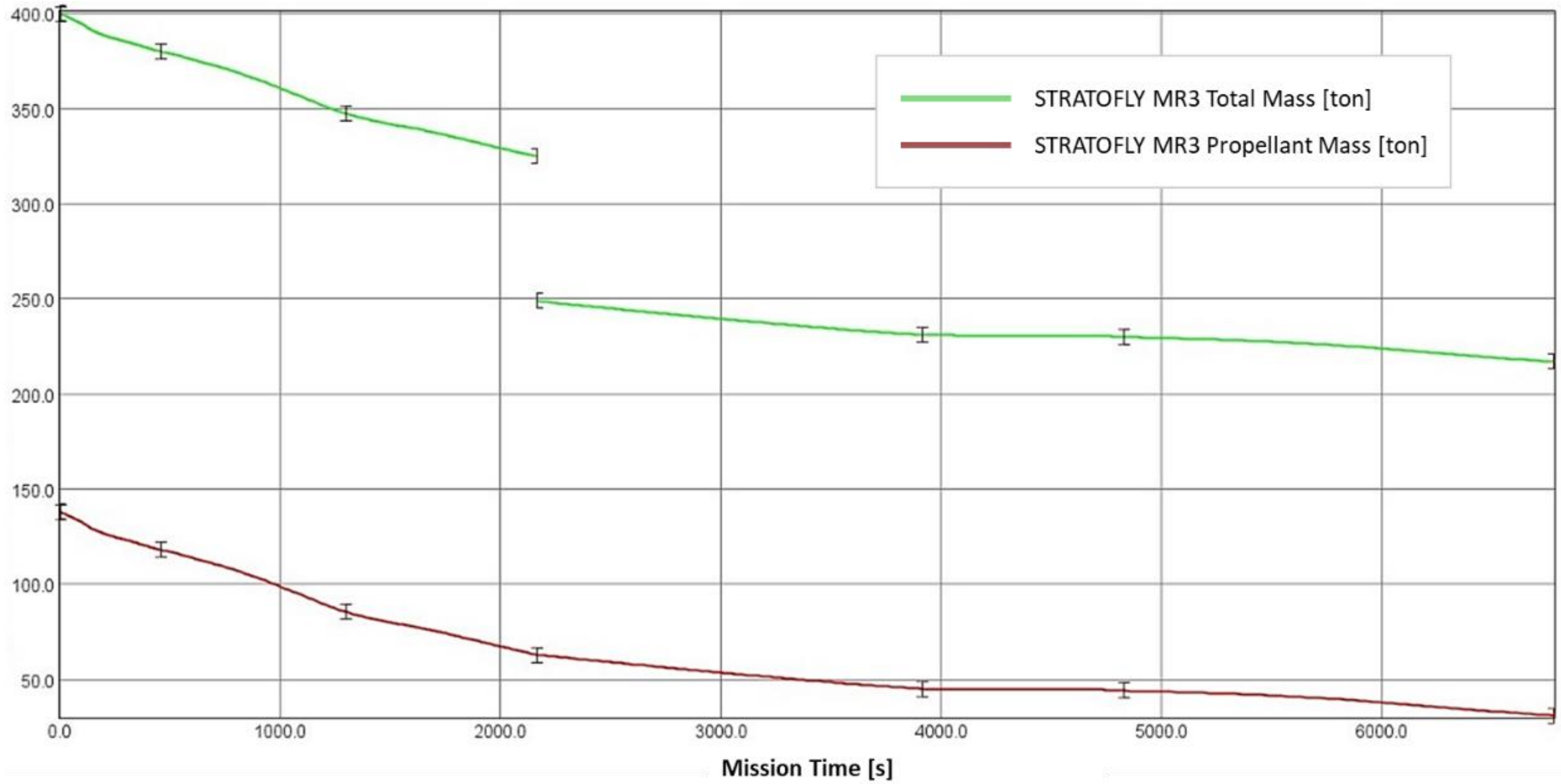


Figure 20: STRATOFLY TSTO First Stage Mission Profile –Propellant vs. Total Mass

Additional outcomes of the mission analysis are depicted in Figure 21, reporting the altitude and the Mach trends along the mission. According to this simulation, a maximum altitude of 31 km is achieved at the end of the cruise, attaining a maximum Mach of 7.38 (below the maximum Mach 8 achievable by the STRATOFLY MR3). Please, notice that the oscillations in the altitude chart (Figure 21) are due to the fact that a high bank angle has been set to perform the turn at 90° and return to launch site. Of course, this result can be improved in future studies thanks to a more detailed definition of vehicle aerodynamics. Indeed, the exploitation of the STRATOFLY MR3 in the envisaged TSTO configuration is associated to a modification of the aerodynamic characteristics originally envisaged within the H2020 STRATOFLY Project. In particular, the presence of a second stage is expected to lower the L/D performance initially estimated to be close to 7 at Mach 8 thanks to the optimized waverider configuration. This is also confirmed in the EHTV design, for which a decrease in L/D was envisaged moving from the HST to the RLV configuration (Table 2). In account of this, it is worth specifying that the simulations discussed above assume a degraded L/D performance of the first stage, hypothesizing a 17% decrease (like the EHTV) as a first approximation. As mentioned, the overall quality and the confidence of simulation results can be enhanced after a more detailed study of vehicle aerodynamic configuration. However, taking into account that the main goal of the detailed (but still initial) mission analysis just reported was to verify whether $W_{ppl,1}$ is sufficient to complete the mission, the feasibility of a STRATOFLY TSTO mission seems promising. Eventually, Figure 22 offers a satellite view of the mission (first stage only) assuming that the vehicle returns to launch site (located in Brussel) after covering a range of almost 8300 km (thus verifying that $R_{HST_{STRATOFLY}}>R_{RLV_{STRATOFLY}}$).

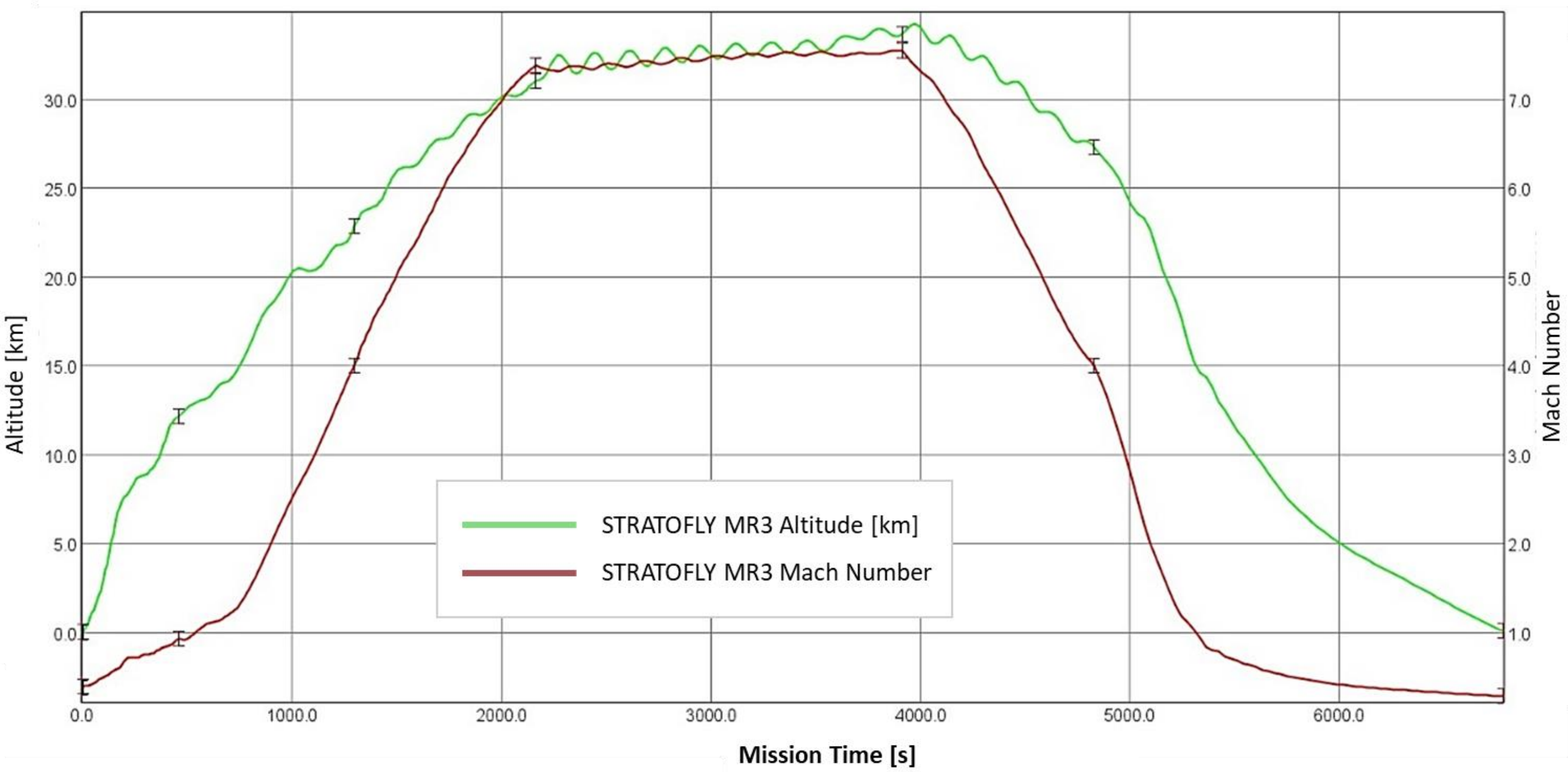


Figure 21: STRATOFLY TSTO First Stage Mission Profile – Altitude and Mach

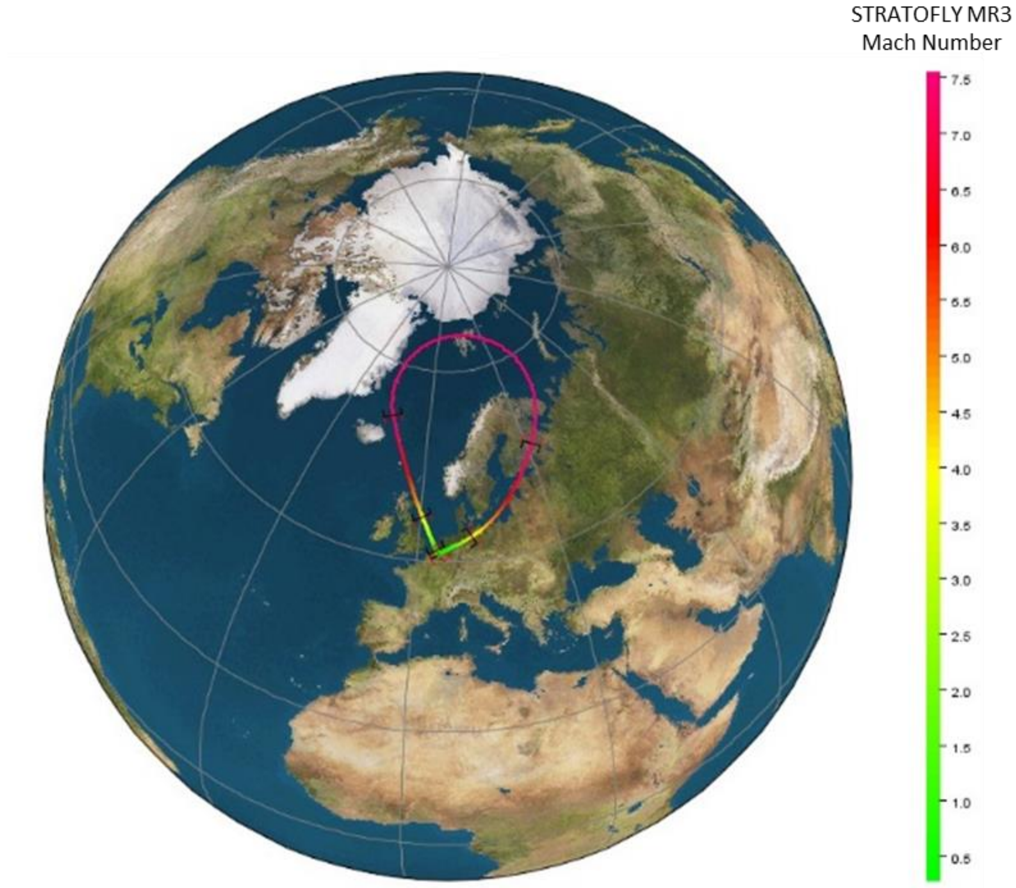


Figure 22: STRATOFLY TSTO First Stage Mission Profile – Satellite View

2.2.1.6 Cargo Capability Verification

After assessing the capability of STRATOFLY TSTO first stage to perform the ascent mission and return to launch site with the available $W_{ppl,1}$, it is important to focus on the second stage mission and preliminary verify the actual possibility for CARGUS to reach orbit after separation. In particular, assuming that CARGUS is ignited around 31 km, the sizing methodology proposed by (Czysz & Vandenkerckhovet, 2001) is here exploited to determine CARGUS capability to achieve a target orbit of 300 km (like SKYLON, by assumption) where the payload is released. The overall process is based on Eq.(3), which defines the weight ratio to orbit ($\mathcal{W}_R$).

$$\mathcal{W}_R = \frac{\mathcal{W}_{GTO}}{\mathcal{W}_{OE}} = \frac{\mathcal{W}_{OE} + \mathcal{W}_{ppl}}{\mathcal{W}_{OE}} = 1 + \frac{\mathcal{W}_{ppl}}{\mathcal{W}_{OE}} \tag{3}$$

Where, considering the simple example of a SSTO vehicle, $\mathcal{W}_{GTO}$ is the MTOW and $\mathcal{W}_{ppl}$ is the total propellant mass hosted. The latter is given by the sum of oxidizer and fuel weights (respectively, $\mathcal{W}_{oxid}$ and $\mathcal{W}_{fuel}$) according to a well-defined mixture ratio $r_{O/F}$ (i.e., $\mathcal{W}_{oxid}/\mathcal{W}_{fuel}$). For sake of clarity, the densities associated to oxidizer and fuel are labelled, respectively, as ρ_{oxid} and ρ_{fuel}, while the overall propellant density is ρ_{ppl}. Moreover:

$$\mathcal{W}_{OE} = \mathcal{W}_{GTO} - \mathcal{W}_{ppl} \tag{4}$$

Furthermore, according to (Czysz & Vandenkerckhovet, 2001), $\mathcal{W}_R$ can also be expressed as:

$$\mathcal{W}_R = \exp\left(\frac{\Delta V}{G \cdot I_{SPE}}\right) \tag{5}$$

Where:
ΔV is the increment in velocity required to reach orbit;
G is the gravitational constant equal to 6.67×10^{-11} Nm^2/kg^2;
I_{SPE} is the effective specific impulse in [s] (see (Czysz & Vandenkerckhovet, 2001) for additional information).

By merging and rearranging Eq.(3) and Eq.(5), Eq.(6) can be obtained:

$$I_P = \frac{\rho_{ppl}}{\mathcal{W}_R - 1} = \left[\frac{\rho_{fuel} \cdot (1 + r_{O/F})}{1 + r_{O/F} \cdot \frac{\rho_{fuel}}{\rho_{oxid}}}\right] \cdot \left\{\exp\left[\frac{\Delta V \cdot \frac{T}{D}}{g \cdot I_{SP} \cdot \left(\frac{T}{D} - 1 - sin\gamma\right)}\right] - 1\right\}^{-1} \tag{6}$$

Where:
I_P is called propulsion index;
T is the thrust generated by the propulsion system to reach orbit [N];
D is the aerodynamic drag encountered [N];
g is the gravitational acceleration equal to 9.81 m^2/s^2;
I_{SP} is the specific impulse in [s];
γ is the flight path angle.

It is interesting to notice that, thanks to the definition of I_P in Eq.(6), it is possible to determine the value of $\mathcal{W}_R$ which can be attained by exerting a specific T in opposition to the D encountered to reach orbit.
Dealing with a TSTO, the terms in Eq.(6) should be carefully defined considering the characteristics of each stage. In the present application, considering that the focus is onto the second stage, it is worth re-expressing Eq.(3) basing on the nomenclature adopted so far for STRATOFLY TSTO mass characteristics:

$$W_{R,2_A} = \frac{W_{GTO,2}}{W_{OE,2}} = \frac{W_{OE,2} + W_{ppl,2}}{W_{OE,2}} = 1 + \frac{W_{ppl,2}}{W_{OE,2}} \tag{7}$$

In addition, basing on CARGUS data in Figure 19:

$$W_{OE,2} = W_{DRY,2} + W_{pay,2} = 6\ ton + 15\ ton = 21\ ton \tag{8}$$

As a result, using the inputs available for CARGUS, $W_{R,2_A}$ is equal to 3.6190 and it represents the mass ratio to be achieved through CARGUS basing on its design properties. Subsequently, from Eq.(6) it is possible to derive an additional estimation of $\mathcal{W}_R$ for CARGUS, labelled $W_{R,2_B}$ as reported in Eq.(9). It expresses the mass ratio effectively achievable thanks to the propulsive characteristics of the stage. In case $W_{R,2_B}$>$W_{R,2_A}$, the upper stage can potentially reach the target orbit starting from the separation point. As such, by comparing the results from Eq.(7) and Eq.(9), it is possible to obtain a preliminary estimation of the effective possibility of CARGUS to reach the required orbit.

$$W_{R,2_B} = 1 + \rho_{ppl} \left[\frac{\rho_{fuel}(1 + r_{O/F})}{1 + r_{O/F}\dfrac{\rho_{fuel}}{\rho_{oxid}}} \right]^{-1} \left\{ exp\left[\frac{\Delta V \dfrac{T}{D}}{g\ I_{SP}\left(\dfrac{T}{D} - 1 - sin\gamma\right)} \right] - 1 \right\} \tag{9}$$

Notably:

$$\Delta V = V_{orb} - V_{sep} \tag{10}$$

$$V_{orb} = \sqrt{\frac{G\, M_{Earth}}{R_{orb}}} \tag{11}$$

$$R_{orb} = R_{Earth} + z_{orb} \tag{12}$$

$$V_{sep} = a_{sep}\, Mach_{sep} \tag{13}$$

$$D = 0.5\, \rho\, V_{orb}^2\, C_d\, S_{cross} \tag{14}$$

Where:
V_{orb} is the orbital speed, i.e., the speed required to reach the target orbit (z_{orb}) at 300 km;
V_{sep} is the speed at separation condition (31 km) for a separation Mach ($Mach_{sep}$) of 7.38 and at a speed of sound (a_{sep}) equal to 304.67 m/s;
R_{Earth} is the Earth radius (6,371 km);
M_{Earth} is the Earth mass ($5.972 \cdot 10^{24}$ kg);
ρ is a mean density value between separation altitude and z_{orb};
S_{cross} is the CARGUS cross-sectional area equal to 22.90 m^2 (Figure 19);
C_d is the drag coefficient associated to CARGUS. Basing on the relationship between drag coefficient and Mach provided in (Balesdent, 2011) (Figure 23) and deemed applicable to a launch vehicle stage at early design, a C_d equal to 0.25 can be assumed considering the worst condition encountered (i.e. around Mach 8).

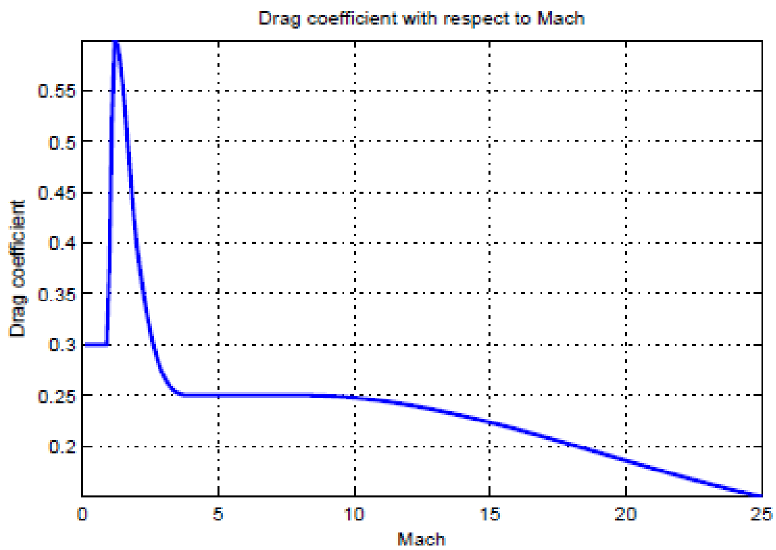


Figure 23: Drag Coefficient as a function of Mach (Balesdent, 2011)

Therefore, by applying Eq.(9), it is possible to determine a $W_{R,2_B}$ equal to 4.1348. Since $W_{R,2_B} > W_{R,2_A}$, the CARGUS orbit achievement is preliminary verified and the initial design of the STRATOFLY TSTO vehicle can be considered concluded for the scope of this Dissertation.

2.2.2 Case Study 2: SpaceX Starship TSTO

As introduced in Section 1.2.1, SpaceX is developing a fully reusable TSTO concept. The first stage is called Super Heavy rocket (or booster), while the second stage is referred as Starship (or spacecraft). Please, notice that in the remainder of this Dissertation the term "SpaceX Starship TSTO" will refer, for simplicity, to the overall SpaceX TSTO, while "Starship" only to the second stage.

Conceived with the aim to deliver payload to LEO (Figure 24(a)), performing mission to Moon, Mars (and beyond) as well as for intercontinental passenger transport (as HST), "*Starship is designed to evolve rapidly to meet near term and future customer needs while maintaining the highest level of reliability*" (SpaceX, 2020).

(a) (b)

Figure 24: (a) Artist's impression of satellite payload release from Starship payload bay in LEO (Musk, 2017a); (b) Starship crew (left) and uncrewed (right) configurations (SpaceX, 2020)

Both crew and uncrewed Starship versions are under design (Figure 24(b)). However, it is worth highlighting that the crew configuration is specifically targeting the ambitious SpaceX goal of "*making life multiplanetary*", transporting up to 100 people from Earth into LEO and on to the Moon and Mars (Musk, 2017c; SpaceX, 2020). In account of this, recalling that this Dissertation focuses on RLV performing LEO mission, the uncrewed Starship will be considered hereafter. At this purpose, despite great part of design information available for the Starship refer to the Mars mission (Musk, 2017a, 2017b, 2017c), data related to the LEO scenario can be extrapolated. As far as payload capability is concerned, SpaceX claims that Starship can deliver over 100 tons to LEO. Nevertheless, recent independent simulation studies at DLR (Sippel et al., 2019) using data available in literature (Musk, 2017b, 2017c) revealed that, more realistically, 40 tons can be effectively delivered to LEO assuming a return to launch site scenario. Despite this estimation is far below Space X projections, a 40-tons payload capability is still highly competitive compared to the most promising payload options discussed in Section 2.1.1. Both the Starship and the Super Heavy are equipped with a number of rocket engines called Raptor currently under development at SpaceX. As shown in Figure 25, Raptor is a full-flow LOX/CH_4 fueled rocket engine "*and is going to be the highest chamber pressure engine of any kind ever built*" (Musk, 2017b)

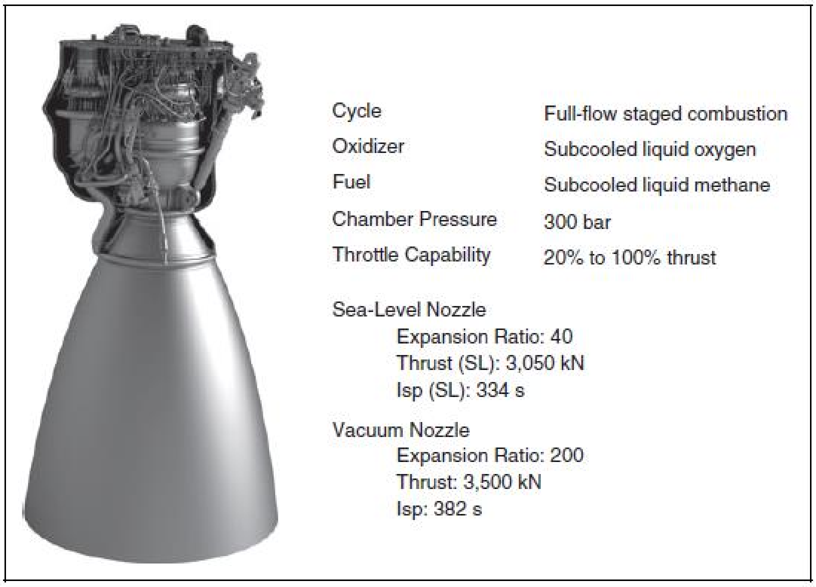


Figure 25: Key characteristics of the Raptor engine (Musk, 2017b)

Considering that the design of the SpaceX Starship TSTO is still on-going, the Starship and Super Heavy Booster characteristics are constantly under modification. In account of this, for the purposes of this Dissertation, the design features mentioned in (Musk, 2017b) are mostly taken as reference (except for the Super Heavy Propellant mass, for which the lower value provided in (SpaceX, 2022) is used). For sake of clarity, Table 3 collects the main design features of interest for this work. This data will be fundamental to pursue the cost and Cost-Effectiveness analysis, respectively, in Section 3.4.2 and in Section 5.5. As far as Raptor Engine dry mass is concerned, it is not reported in literature. However, since it will be a fundamental parameter within the proposed cost model (Section 3.2), a preliminary estimation is required. At this purpose, considering that Raptor is a liquid methane-liquid oxygen (methalox) engine, few information is available in literature for the sizing of such an innovative engine. Therefore, a preliminary assessment of Raptor engine dry mass is performed by exploiting relationships provided in (Zandbergen, 2015) for kero-lox and storable engines. This allows to derive to derive a dry mass of 2448 kg. The final value of Raptor engine dry mass reported in Table 3 is obtained by assuming 30% mass reduction thanks to 3D printing manufacturing (Melle et al., 2019).

Table 3: SpaceX Starship TSTO design characteristics from (Musk, 2017b)

	Starship	**Super Heavy**
Number of Raptor Engines	9	42
Dry Mass (with engines) [ton]	150	275
Dry Mass (without engines) [kg]	134,579	203,036
Propellant Mass [ton]	1950	3400
Residuals [ton]	204 (6% of Propellant Mass)	Not required
Net Mass (without engines) [kg] (Dry Mass without engines plus residuals)	407,035.79	Not required
Raptor Engine Dry Mass [kg]	1713.43	
Launch Mass [ton]	5815 (with 40 ton of payload to LEO)	

2.3 Chapter 2 Abbreviations

ATR	Air Turbo Rocket
C-E	Cost-Effectiveness
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMR	Dual Mode Ramjet
EHTV	European Hypersonic Transport Vehicle
H2020	Horizon 2020
HL	Horizontal Landing
HST	High-Speed Transportation
HT	Horizontal Take-off
L/D	Lift-to-drag
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LEO	Low Earth Orbit
MR	Mission Requirement
MTOW	Maximum Take-Off Weight
NASP	National AeroSpace Plane
pax	Passenger
RLV	Reusable Launch Vehicle
SED-WR	Scramjet Engine Demonstrator – WaveRider
SSTO	Single Stage to Orbit
STRATOFLY	Stratospheric Flying Opportunities for High-Speed Propulsion Concepts
TPS	Thermal Protection System
TSTO	Two Stage to Orbit
US	United States
VL	Vertical Landing
VT	Vertical Take-off

Chapter 3

Parametric Cost Model for Future Reusable Space Transportation and Re-Entry Systems

This Chapter aims at introducing the parametric cost model specifically tailored for Reusable Launch Vehicles (RLVs) developed within this work. Notably, after a brief introduction to key concepts of costs analysis in Section 3.1.1, the literature review proposed in Section 3.1.2 summarizes the key features of the most meaningful State-of-the-Art (SoA) approaches for RLVs cost estimation. Then, basing on the outcomes of the literature analysis, Section 3.1 describes in detail the newly developed cost model with special emphasis onto development, production, and operating costs up to the final cost per kg assessment. The final goal is to provide a flexible tool for cost estimation of the most promising RLV configurations elicited in Section 2.1.1 to be then used in Chapter 5 in support of Cost-Effectiveness (C-E) assessment. Main outcomes of the cost model (i.e., Life Cycle Cost) will be also exploited by the Technology Roadmapping Methodology described in Chapter 4 and assessing the technological sustainability of future RLV concepts. In addition, after introducing some considerations about uncertainty issues in cost estimation (Section 3.2.5), ideas for possible software implementation of the cost model are summarized in Section 3.3. Eventually, the model is applied to the case studies described in Section 2.2 to test the proposed equations and, as mentioned, provide the cost inputs for the final C-E assessment performed in Chapter 5. The list of abbreviations used within the text is provided at the end of the Chapter.

3.1 Literature Review

3.1.1 Introduction to Life-Cycle Cost analysis and Parametric Estimating

According to a general definition, Life-Cycle Cost (LCC) analysis entails *"the total cost incurred by a system, or product, throughout its life"* (INCOSE, 2015). As shown in Figure 26, the main LCC phases are Concept (Definition), Design, Development ("Develop" in Figure 26), Production and Test ("Prod/Test"), Operations and Disposal.

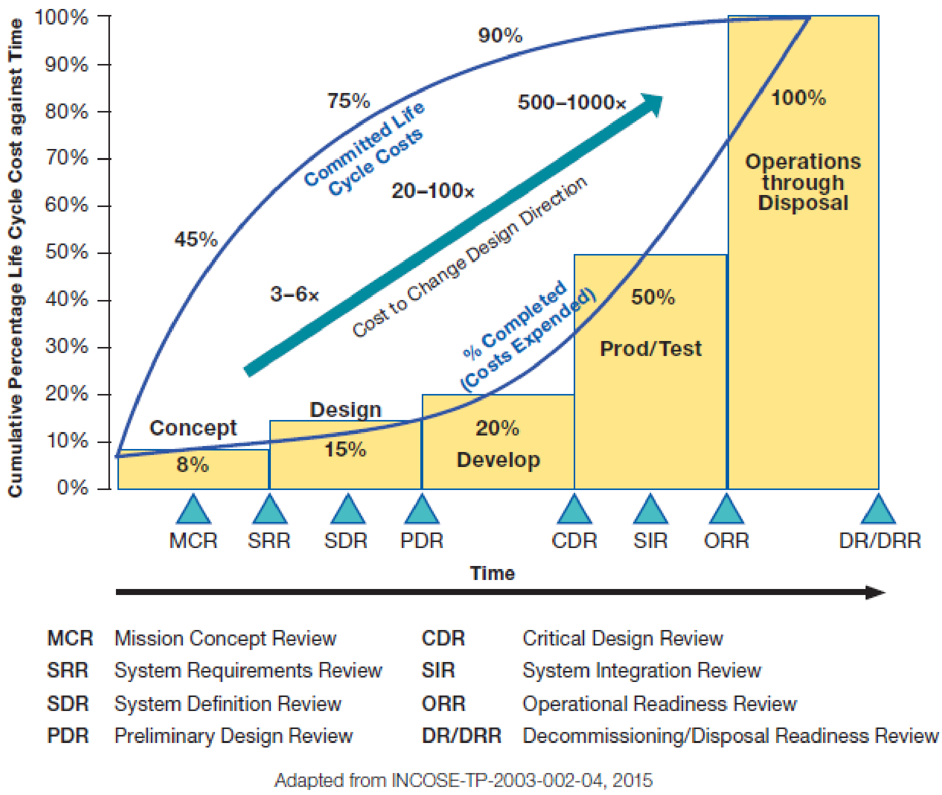


Figure 26: Life-Cycle Cost Impacts from Early Phase Decision-Making (Hirshorn et al., 2017)

The costs incurred during concept definition, design and development phases of aerospace projects are usually lower than the expenditures sustained during operations. This is particularly true for reusable aerospace products (Roskam, 1990), for which great part of life cycle duration consists in the operational phase.

Along with the increasing trend of outflows along the life cycle, Figure 26 highlights that the capability to predict committed costs since the very beginning of design process may be beneficial for the success of the overall project. Indeed, the early identification and solution of issues related to system development, production and operations can avoid sudden changes in design direction and prevent from costly re-design and verification activities later in the life cycle, thus leading to consistent cost savings. From a mathematical perspective, LCC analysis is performed through application of a cost model, which is made up of cost items (or cost categories) and determines the costs incurred during LCC phases. The cost model is usually based on one of the following cost estimating techniques (Hammond, 1999; INCOSE, 2015):

1. Detailed bottom-up estimating, applicable when the availability of design data allows to specify materials and labor costs at component level;
2. Analogous estimating, in which the cost of a new system is obtained by adjusting the cost of similar items taking into account the different complexity and size;
3. Parametric estimating, based on equations called Cost Estimation Relationships (CERs), which express each cost item as a function of sizing and performance parameters (or cost drivers) available since early design stages.

Before entering into the detail of the definition of the most suitable technique for this work, it is worth specifying that one of the target objectives of this Dissertation is to develop a cost model applicable since the early design stages and able to assess the economic viability of the most promising RLV design configurations listed in Section 2.1.1. Notably, the proposed model should exploit the parameters available from preliminary and conceptual design activities (Section 1.3) to derive a LCC estimation, thus allowing to determine the impact of a variation in key design variables onto costs. Going back to the cost estimating techniques defined above, it is clear that the selection of a suitable approach is mostly based on data availability. For the present application, detailed bottom-up estimating is not adequate because design data at component level are not available during conceptual design. Similarly, the exploitation of analogous estimating does not guarantee an objective approach, being highly influenced by the reasoning of the cost analyst and by his/her assumptions in judging the similarities between different projects. This technique may only be acceptable for very early estimations, but it requires cross-verifications using other approaches. Parametric estimating, mainly based on mathematical algorithms and thus less influenced by analyst's opinion, appears to be the most appropriate approach to be followed. This approach, based on the exploitation of readily available design variables as cost drivers, not only is easily applicable at the early stages of a project but also allows to evaluate the impact of design changes onto costs. However, adjustments in terms of correction factors are still required to account for breakthrough technology. As a result, parametric estimating should be carefully handled outside the range of historical data originally used to derive the parametric model.

After selecting parametric estimating as basic technique for cost modelling a mathematical approach to derive CERs is required. At this purpose, the flowchart from (ISPA, 2008) reported in Figure 27 shows the general framework exploited in this Dissertation for new CERs development.

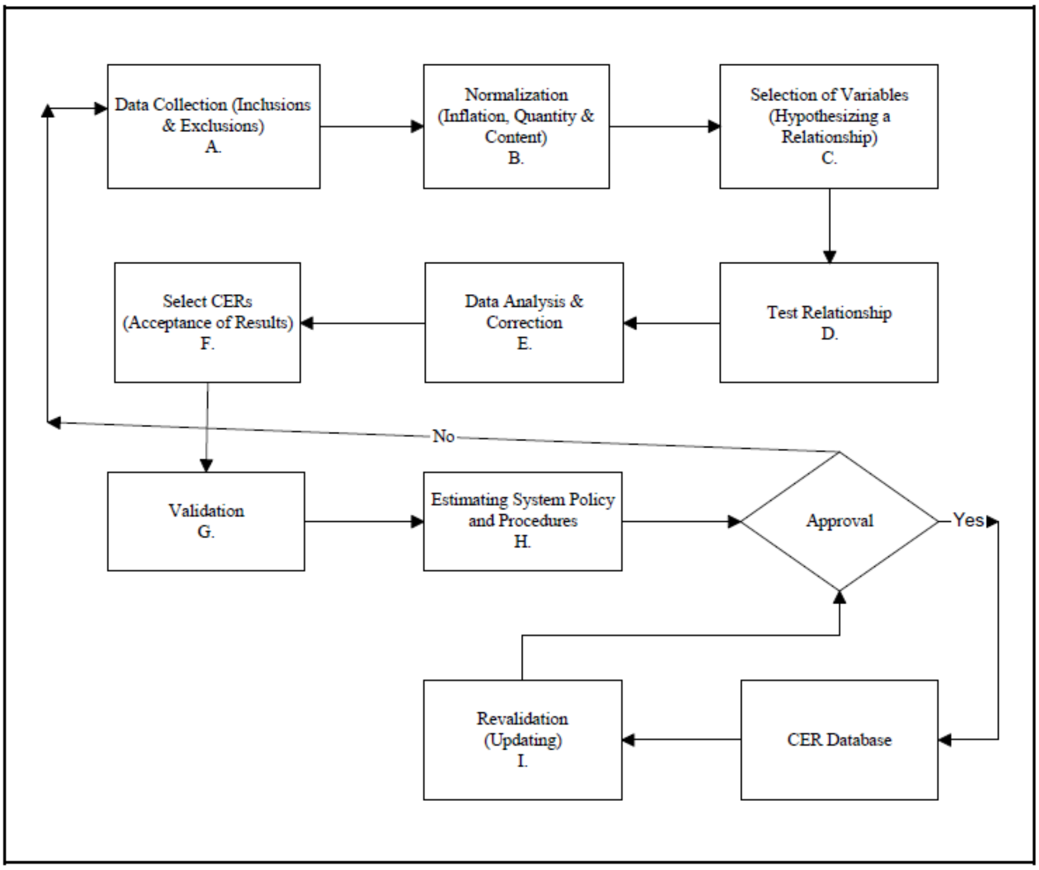


Figure 27: Typical CER Development Process (ISPA, 2008)

The overall process starts with historical cost data collection (Step A. in Figure 27), in which available data is reviewed to include acceptable points and exclude possible outliers. Then, raw data is adjusted in a uniform format, i.e., normalized by inflation, quantity, and content (Step B.). Normalization by inflation converts initial cost data coming from several sources and therefore each referred to a specific Fiscal year (FY) to a common desired base year using a proper inflation index. As stated in (ISPA, 2008), "*there are no fixed ways to establish universal inflation indices (past, present, or future) that fit all possible situations*" and factors such as the Consumer Price Index (CPI) can be used. The latter is defined by the US Bureau of Labor Statistics as "*a measure of the average change overtime in the prices paid by urban consumers for a market basket of consumer goods and services*". In alternative to that the Work-Year (WYr) costing unit defined in (Koelle, 2013) as "*the total company annual budget divided by the number of productive full-time people*" can be adopted so that raw cost data (expressed in a specific currency and referred to a certain FY) can be converted to WYr using the conversion factors collected in Section 7.1. Additional information about WYr exploitation for costs conversion is provided in Section 3.1.2.3. Furthermore, normalization for content allows to check data for consistency in content, ensuring that "*a particular cost category has the same definition in terms of content for all observations in the database*" (ISPA, 2008), while normalization by quantity is required to isolate the "Learning Curve" contribution from cost data. The Learning Curve is usually applicable to the production phase and it represents the gradual improvement in productivity stemming from the production of many units. This improvement can be quantified in terms of reduction of time required to perform production tasks (Figure 28) which directly translates into a decrease in labor cost. As a result, in the context of normalization by quantity, costs adjustment generally involves the assessment of Theoretical First Unit (TFU) cost (i.e., the cost of the first item produced during series production) starting from total production cost and assuming a proper value of Learning Curve. Further details on this topic can be found in Section 3.1.2.3.

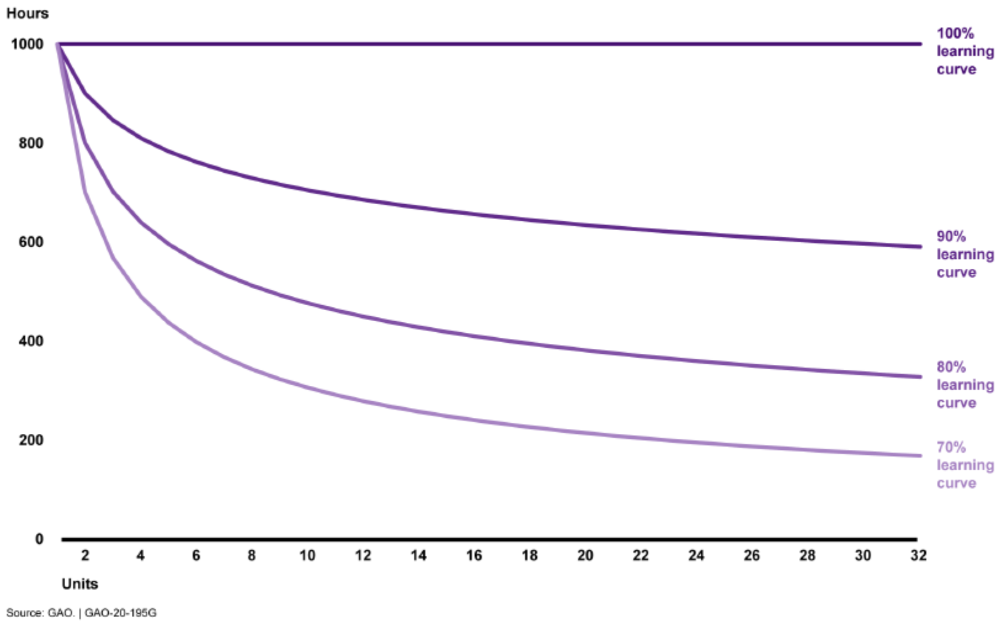


Figure 28: Graphical representation of "Learning" (GAO, 2020)

Once normalization is complete, cost drivers to be included in the newly developed CER are selected among available design variables and operating parameters and the parametric relationship between them is hypothesized (Step C. in Figure 27). According to the guidelines provided in (ISPA, 2008), the mathematical forms collected in Table 4 should be explored during this phase considering both single and multiple cost drivers equations.

Table 4: CER Categories and Algebraic Forms considering multiple cost drivers derived from (ISPA, 2008)

Category	**Cost**	**Cost Drivers**	**Coefficients**	**Algebraic Form**
Linear	y	x, w, z	a, b, c, d	$y = a + bx + cw + dz$
Power	y	x, w, z	a, b, c, d	$y = ax^b w^c z^d$
Triad 1	y	x, w, z	a, b, c, d, e, f, g	$y = a + bx^c + dw^e + fz^g$
Triad 2	y	x, w, z	a, b, c, d, e	$y = a + bx^c w^d z^e$

Notably, CER coefficients in Table 4 should be obtained by adopting a proper regression technique (or best-fit method) such as the MPE-ZPB (Minimum-Percentage-Error Zero-Percentage-Bias) optimization method, deemed particularly suitable for CERs derivation according to (ISPA, 2008). For sake of clarity, MPE-ZPB is a constrained optimization method, seeking coefficients for which the resulting CER has the smallest possible percentage error, subject to the constraint that its percentage bias is zero. As a result, the minimum-percentage-error CER is selected, not from among all possible CERs, but only from among those with zero bias. The set of new and alternative CERs derived for a specific cost item (e.g., Development Cost) using MPE-ZPB should be evaluated in order to select the "optimal" CER among options. At this stage, three main statistical indicators should be evaluated to test the assumed relationships and perform data analysis (Steps D. and E.):

1. **Sample Standard Error**, also referred as %Std. Error (or Standard Error (SE)) and defined as the "*Root-mean-square (RMS) of all percentage errors (i.e., differences between estimate and actual, divided by the estimate) made in estimating points of the data base using the CER, normalized by the number of data points and CER coefficients*" (ISPA, 2008);
2. **Sample Percentage Bias**, also referred as %Bias, defined as the "*algebraic sum, including positives and negatives, of all percentage errors (i.e., differences between estimate and actual, divided by the estimate) made in estimating points of the data base using the CER, divided by the number of data points", being a "measure of how well overestimates and underestimates of data-base actuals are balanced*" (ISPA, 2008);
3. **Sample Correlation-Squared between Estimates and Actuals,** also referred as R^2, a statistical measure of the extent of linearity in a relationship between two quantities.

Specifically, the "optimal" CER can be chosen (Step F.) by considering the one associated to lowest %Std. Error, lowest %Bias and highest R^2. Indeed, according to (Hammond, 1999), "*R^2 is an indicator of the goodness of fit varying between 0 and 1, where 1 is a perfect fit. One generally wants R^2 to be 0.7 or larger. SE measures the variation of cost about the regression equation. [...] The lower the SE as a percent of the mean value of the sample cost data, the better the regression fit*".

Then, the final CER needs to be validated (Step G.) in order to demonstrate its effective capability to predict costs. In this phase, the new CER should be extensively tested using, as much as possible, independent test data not considered in the original statistical population. In case of successful model validation, the model is ready to be exploited and, in case of availability of new cost data, it should be updated and revalidated (Step I.). Please, notice that Step H is applicable in case of parametric techniques developed in the framework of contracts with the U.S Government only (see (ISPA, 2008) for additional details).

3.1.2 Existing parametric cost models for space vehicles

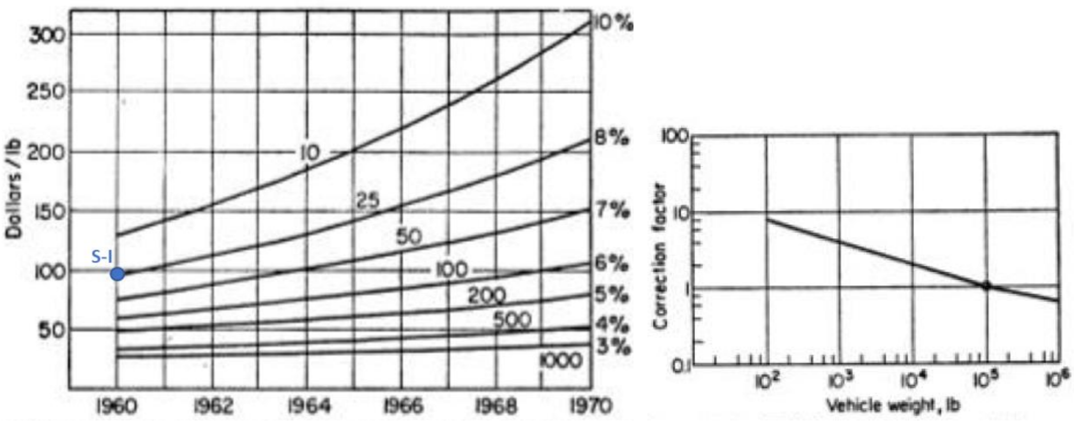
The strategy for new CERs derivation reported in the previous Section, starting with a phase of cost data collection, highlighted that parametric cost modelling is mostly based on the heritage from past projects. For RLVs, considering that up to now only the partially reusable Space Shuttle and the Falcon launcher have been effectively flown (Section 1.2.1), the cost estimation process has to face a substantial lack of actual cost data. In account of this, alternative strategies have to be followed to collect required cost information and derive suitable parametric cost models. In the past, the heritage from Expendable Launch Vehicles (ELVs) and aircraft systems have been used to obtain cost estimating methodologies able to predict the costs of future RLVs and High-Speed Transportation (HSTs). In addition, cost estimations from confidential tools developed in the framework of previous RLV projects (e.g., FESTIP), based on the expertise of the costs' analysts involved in such projects/initiatives, have proven to be a useful benchmark for new CERs derivation. In account of this, the following Sections summarize the (few) available approaches for RLVs cost estimation, recalling their main features and stressing the reasons for which they have been selected as reference in developing the new cost model proposed in this Dissertation.

3.1.2.1 Economy of Space Flight (Koelle & Huber, 1961)

Following a chronological order, the Handbook of Astronautical Engineering by (Koelle & Huber, 1961) is the first noteworthy example of the importance of considering economic aspects along with technical disciplines in space flight projects. Indeed, as stated, "*it is economy which will, to a great extent, determine the progress in space-flight development, and not just the basic technical knowledge*". In addition, a definition of the three main categories constituting the total cost of space-flight activities is provided:

1. Basic transportation cost to deliver a payload of weight X from a point A to a point B anywhere in space;
2. Payload cost, including the cost of scientific instruments and/or cockpit and cargo, propulsion for correction maneuvers and ground-support equipment for payload;
3. Mission cost, i.e., costs sustained after arrival at destination until mission accomplishment (e.g., operations on lunar surface).

In this subdivision, basic transportation cost not only represents the key contribution but it is also "*most adaptable to theoretical investigation and correlation with actual experience*" so that it is suitable to mathematical modelling, while payload and mission costs strongly depend on the specific application under analysis (scientific, military, or commercial) and it is more difficult to treat them on a uniform and structured basis. This consideration constitutes an important benchmark also for this Dissertation, in which great attention is given to the analysis of transportation cost without entering into the detail of costs associated to payload and mission operations performed in orbit. In the framework of basic transportation cost, (Koelle & Huber, 1961) defines and analyzes three cost elements: development, production, and operational cost. For development cost, available cost data for several reference concepts (e.g., X-15 and Saturn) is exploited to derive a preliminary dependence between cost and unit weight to be used to establish the "*right order of magnitude*" for costs. However, this dependence is deemed unsuitable for the present work not only since it reflects the costs of technologies available in the 1960s but also because it is based on a heterogenous group of reusable and expendable vehicles with different design features. For production cost, the importance of experience as "*one of the most influential factors on production cost*" (Koelle & Huber, 1961) is stressed. Then, a production cost per unit weight equal to 96$ (FY1960) per lb for the 25th vehicle of the 100,000-lb-size class (specifically, the Saturn S-I stage) is used in as starting point to derive the accumulated production cost trend over years in Figure 29(a).



(a) (b)

Figure 29: (a) Estimated production cost of space vehicles with reference Saturn S-I cost per lb highlighted; (b) Correction factor for vehicle production cost (Koelle & Huber, 1961)

Notably, in Figure 29(a), 10, 25, 50, …,1000 is the total number of units produced in the timeframe considered, while 10%, 8%, 7%, …, 3% is the annual increase in production rate with respect to the previous year thanks to the learning effect. Values obtained from Figure 29(a) are referred to production units with a dry weight of 100,000 lb and they should be multiplied by the correction factors in Figure 29(b) to consider the actual vehicle dry weight. As for development cost, this approach for production cost assessment is judged not applicable in the present work because it is built on a specific (and outdated) cost datum for an expendable rocket stage (i.e., the Saturn S-I). As far as space-flight operational cost is concerned, a remarkable cost breakdown based on the definitions commonly adopted for aircraft operation (ATA (Air Transport Association of America), 1957) is proposed, suitable both to expendable and reusable launchers. Specifically, operational cost, also referred as operating cost, is determined in terms of Direct Operating Cost (DOC) and Indirect Operating Cost (IOC) (with Total Operating Cost (TOC) given as the sum of DOC and IOC). In detail, DOC (C_O) is defined as:

$$C_O = C_V + C_P + C_T + C_L + C_M + C_C + C_S + C_Q \tag{15}$$

Where:

C_V is vehicle production cost;

C_P is propellant cost;

C_T is vehicle transportation cost from factory to launch site;

C_L is vehicle launch cost, i.e., cost of (on-ground) launch crew and operation of the launch complex;

C_M is vehicle maintenance and repair cost in case of recoverable stages;

C_C is crew cost (for manned systems);

C_S is insurance and interest cost (not applicable to government flight operations);

C_Q is other recurring cost.

Complementary, IOC (C_I) is assessed as

$$C_I = C_R + C_G + C_F + C_D + C_Z \qquad (16)$$

Where:

C_R is range cost and/or general overhead costs;

C_G is ground support equipment cost per launch pad

C_F is launch facility (construction) cost;

C_D is vehicle development cost;

C_Z is other non-recurring cost

It is worth noticing that in this costs' subdivision, development cost is included into IOC in terms of amortization of development expenses, while amortization of Production Cost is attributed to DOC. Both contributions can be attributed to a single flight in case of expendable systems or subdivided among lifetime flights in case of reusable vehicles. In addition, each cost item in Eq. (15) and (16) is accompanied by a well-defined CER, such as:

$$C'_T = K_T S(W_{s,1} + W_{s,11} + \cdots + W_{s,n} + W_2) \qquad (17)$$

Where:

C'_T is vehicle transportation cost (C_T) for a multistage vehicle unit;

K_T is specific transportation cost for stages between manufacturing and launch site ($ per lb-mile)

S is the distance between manufacturing and launch site in miles;

$W_{s,1}$ is the structural weight of the first stage with engines in lb;

$W_{s,11}$ is useful payload weight delivered by first stage in lb;

$W_{s,n}$ is the structural weight of the n^{th} stage with engines in lb;

W_2 is the weight of instrumentation and instrument compartment required for the total vehicle in lb.

However, specific values for K_T (even if referred to the 1960s) are not reported in (Koelle & Huber, 1961), so that Eq.(17) is not practically applicable. Similar considerations apply to the other operating cost items involved in Eq. (15) and (16), which are mainly expressed in terms of "specific costs" (for which detailed values are not specified) multiplied by total weight.

> As a result, the parametric model for development, production and operating cost provided in (H. H. Koelle & Huber, 1961) is not directly suitable to meet the goals of this Dissertation. However, this reference offers a complete overview of cost categories applicable to launchers and it surely represents a useful benchmark to evaluate the completeness of alternative categorizations and nomenclatures proposed in other literature sources.

3.1.2.2 Booz-Allen CER (Booz-Allen & Hamilton, 1967)

In the late 1960s, a CER for production cost assessment of advanced airbreathing engines was developed in the framework of the «Supersonic Transport Development and Production cost Analysis Program» for the Federal Aviation Administration (FAA). Such CER was reported in (Booz-Allen & Hamilton, 1967). Despite the original report (Booz-Allen & Hamilton, 1967) is not available, the CER is provided by (Korthals-Altes, 1986) (Eq.(18)). As reported by (Korthals-Altes, 1986), (Booz-Allen & Hamilton, 1967) stated that the best characteristics to regress engine cost against are maximum thrust, highest operational altitude, and engine thrust to weight ratio. Notably, the relationship between these cost drivers and engine production cost was derived thanks to 57 observations (i.e., reference cost data), mainly military advanced turbojets, including the J-58 engine used on the S-71 aircraft.

$$F_{ab} = 5.5T_{MAX}^{0.56} \cdot Alt^{1.93} \cdot \left(\frac{TN}{W}\right)^{0.48} \tag{18}$$

Where:

F_{ab} is total production cost of air-breathing engine in FY1963 US$;

T_{MAX} is maximum rated thrust in kg;

Alt is absolute engine operational altitude in km;

$\frac{TN}{W}$ is normal rated thrust divided by dry engine weight.

Basing on (Korthals-Altes, 1986), Eq. (18) can be considered applicable to advanced airbreathing concepts such as ATR (Air Turbo Ramjet) and Scramjet. In addition, from the application in (Korthals-Altes, 1986), the Engine Production Cost calculated through Eq. (18) is Engine TFU Production Cost.

Therefore, even if proposed in the 1960s Eq. (18) seems promising for the purposes of the present work since it deals with advanced propulsive technologies still of great interest for future RLVs. It is also interesting the definition of well-defined engine-related cost drivers based on authors' experience, explored and verified thanks to the availability of actual cost data for military engines.

3.1.2.3 TransCost (Koelle, 1991, 2013)

The TransCost (TC) model is undoubtedly the most widespread reference in the space cost estimating scene. Progressively updated by D.E. Koelle since its first release in 1971, it is a "*launch vehicle-dedicated system model"* (Koelle, 2013) for the assessment of economic viability of future space transportation systems. A remarkable characteristic of this model is that it is based on a comprehensive database gathered between 1960 and 2012 and made up of US, European and Japanese space vehicle studies. This Dissertation mainly focuses on the last version (8.2) of the TC Handbook published in 2013, which enriched the original cost database of governmental "business-as-usual" (BaU) contracts with cost data on commercial RLV developments. However, a former version of the methodology dated back to 1991 (Koelle, 1991) will be referenced as well in this study.

The TC model is deemed particularly suitable for the present work because it is intended for the initial conceptual design phase of space transportation systems and engines. As such, proposed cost drivers are in line with the type of design parameters effectively available for the space vehicles under study. In addition, TC is presented as a "*transparent model*" (D. E. Koelle, 2013), so that reference data points (i.e. design parameters for a well-defined vehicle concept and related cost data) are graphically displayed. It means not only that cost data can be visualized but, most importantly, can be re-handled autonomously by the reader and updated with additional data (if available) to derive new CERs.

The costs subdivision proposed in TC methodology entails:

1. Development Cost, also referred in this Dissertation as Research, Development, Test and Evaluation (RDTE) cost following the nomenclature by (Roskam, 1990). RDTE includes the costs associated to design, analysis and test activities of breadboards, brass-boards, prototypes, qualification and proto-flight units (Hammond, 1999);
2. Production Cost, dealing with flight units production cost;
3. Ground and Flight Operations Cost, consisting of vehicle and ground station operations and maintenance costs.

Notably, Figure 30 provides a graphical overview of the TC model. Please, notice that both Development and Production Cost sub-models subdivide vehicle costs into engine and vehicle system (i.e., the vehicle excluding engines) contributions.

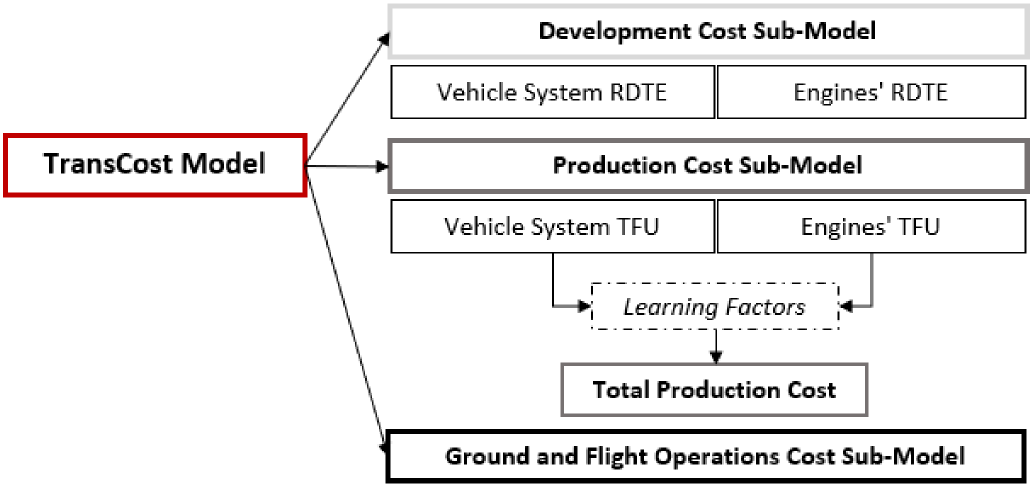


Figure 30: TransCost Model Overview

Table 5 shows the list of engine types treated in TC along with detailed information about availability of RDTE and Production CERs for each cost category. Similarly, Table 6 provides an insight on CERs availability for the types of vehicle systems (without engines) analysed in TC. Please, note that HTO stands for Horizontal Take-Off, whilst VTO for Vertical Take-Off. Table 5 and Table 6, showing at a glance the list of vehicle systems and engines solutions tackled by the cost model, allow to evaluate in parallel for RDTE and Production costs the capability of TC to provide CERs for each vehicle/engine type. In addition, starting from the complete set of items covered by the model, it is possible to define those of interest for this Dissertation.

Table 5: Engine CERs availability in TC

Engine Type	**RDTE CER? (YES/NO)**	**Production CER? (YES/NO)**
Solid Propellant Rocket Motor	YES	YES
Liquid Propellant Rocket Engine with Turbopumps	YES	YES
Pressure-fed Liquid Propellant Rocket Engine	YES	YES
Airbreathing Turbojet Engine	YES	YES
Airbreathing Ramjet Engine	YES	NO

Table 6: Vehicle System (without engines) CERs availability in TC

Vehicle System (without engines) Type	RDTE CER? (YES/NO)	Production CER? (YES/NO)
Solid-propellant Rocket Strap-on Booster or Stage System	YES	YES
Propulsion System/Module	YES	YES
Expendable Ballistic Rocket Vehicle	YES	YES
Reusable Ballistic Launch Vehicle	YES	YES
Winged Orbital Rocket Vehicle	YES	YES
HTO First Stage Vehicle or Advanced Aircraft	YES	YES
VTO First Stage Fly-back Rocket Vehicle	YES	NO
Crewed Re-Entry Capsule	YES	NO
Crewed Space System	YES	YES

Notably, the whole list of engine types is judged applicable to RLVs, while in Table 6 Propulsion Systems/Modules, Crewed Re-entry Capsules and Crewed Space Systems are excluded from further analyses. Indeed, Propulsion Systems (such as the GALILEO Retro Propulsion Module) are characterized by "*their own basic structure, but no external (load carrying) structure, no own power supply and no own intelligence equipment like telemetry or guidance and control*" (Koelle, 2013), while Propulsion Modules are more generically spacecraft-integrated propulsion systems. From this definition it clear that these are payload-related systems and, therefore, not strictly related to space transportation systems (see the definition from (Koelle & Huber, 1961) in Section 3.1.2.1 for further details). Similarly, Crewed Re-entry Capsules (like Mercury and Gemini) should be attributed to payload cost as well. Furthermore, according to (Koelle, 2013) Crewed Space Systems comprise *"all those manned space systems which have NOT been covered by the previous CERs"* such as Winged Re-entry Systems (like Space Shuttle Orbiter and Hermes), Orbital Space Station Systems (e.g. ISS) and Interorbital Spacecraft/Lander Vehicles (like Apollo CSM and Lunar Lander). It is specified that the main difference between Winged Re-entry Systems and

Winged Orbital Rocket Vehicles mentioned in Table 6 is that the formers are not provided with major propulsion capability but they are designed to perform unpowered re-entry. Therefore, considering the diversity of the concepts handled as "Crewed Space Systems", related CERs are considered too generic and not suitable for the current application.

Recalling the CERs nomenclature summarized in Table 4, TC CERs for RDTE and Production cost are expressed in Power form as in Eq.(19):

$$C = aM^x \tag{19}$$

Where:

C is RDTE/Production Cost for the system or element (i.e., vehicle system or engine) in WYr;

a is the "*system-specific constant value*" for RDTE/Production cost;

x is the "*system-specific cost-to-mass sensitivity factor*" for RDTE/Production cost.

The formulation reported in Eq. (19) is referred as "core" CER in TC and it can be tuned with the ad-hoc correction factors (f_i) collected in Table 7. The latter gathers the complete list of f_i factors with related applicable cost items.

Table 7: List of correction factors (f_i) for TransCost core CERs

Factor	Cost Item
Systems engineering/integration factor (Development) - f_0	RDTE
Development standard factor - f_1	RDTE
Technical quality factor - f_2	RDTE
Team experience factor - f_3	RDTE
Learning Curve factor - f_4	Production/Operations
Refurbishment factor - f_5	Operations
Deviation from optimal schedule - f_6	RDTE
Program organization factor - f_7	RDTE
Productivity of region - f_8	RDTE /Production
Impact of subcontractor - f_9	RDTE/Production
Reduction factor due to experience / cost engineering - f_{10}	RDTE
Reduction factor due to absence of government contracts - f_{11}	RDTE
Systems engineering / integration factor (Production) - $f_0{}'$	Production
Production cost improvements factor - $f_{10}{}'$	Production
Government contracts factor for production - $f_{11}{}'$	Production
Impact of launch vehicle type - f_v	Operations
Impact of assembly and integration mode - f_C	Operations

RDTE Cost Assessment in TC. For RDTE cost, the core formulation in Eq.(19) can be enriched as follows:

$$H = C f_1 f_2 f_3 f_8 f_9 f_{10} f_{11} \tag{20}$$

Where H is the RDTE cost of the generic element after application of RDTE correction factors. It is underlined that f_2 is specific for each element and defined by an inherent technical criterion. Additional information about this factor can be found in the examples of RDTE CERs reported below in this Section.

At this point, the RDTE cost (C_{tot}) of the overall launch system (vehicle plus engines) can be expressed by specifying Eq. (20) for each element with correction factors applicable at launch vehicle level:

$$C_{tot} = f_0 \left(\sum H_V + \sum H_E \right) f_6 f_7 \tag{21}$$

Where $\sum H_V$ and $\sum H_E$ are, respectively, the sum of RDTE costs for all vehicle system (without engines) elements and the sum of RDTE costs for all engine elements composing the launch vehicle. Furthermore:

$$f_0 = 1.04^N \tag{22}$$

$$f_7 = n^{0.2} \tag{23}$$

Where:

N is the number of vehicle stages;

n is the number of subcontractors involved in the project.

Examples of RDTE CERs from (Koelle, 1991, 2013)**.** Basing on the lists of engine types and vehicle systems collected, respectively, in Table 5 and in Table 6, RDTE CERs formulations from TC are herein reported, focusing on the relationships of interest for this Dissertation. For each equation, its suitability to the goals of current research stated in Section 1.3 is thoroughly assessed, highlighting limitations to be addressed by the new cost model proposed in Section 3.2 in order to improve the cost estimating process.
Starting from vehicle systems (excluding engines) CERs, Eq.(24) and Eq.(25) are applicable, respectively, to Solid-Propellant Rocket Strap-on Boosters & Stage Systems (in case of reusable systems like Solid Rocket Boosters (SRBs) the cost of recovery equipment plus the required instrumentation has to be added) and Reusable Ballistic Launch Vehicles (referred as VTVL Liquid Propellant Rocket SSTO in this work basing on the nomenclature defined in Section 2.1.1). Both equations are based on an extensive database of cost data (mainly from other cost estimations for Eq.(25) due to the unavailability of actual data) so that they are considered sufficiently reliable for the scope of this work.

$$H_{VR} = 19.5 M^{0.54} f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{24}$$

$$H_{VB} = 803.5 M^{0.385} f_1 f_2 f_3 f_8 f_9 f_{10} f_{11} \tag{25}$$

Please, notice that the factor f_2 in Eq.(25) is defined as:

$$f_2 = \left(\frac{\varepsilon^*}{\varepsilon}\right)^2 \quad (26)$$

$$\varepsilon = M_N/(M_P + M_{P/L}) \quad (27)$$

Moreover:
ε is the Net Mass Fraction (NMF)
M_N is vehicle net mass, i.e., vehicle mass at the end of the main propulsion phase (with engines) already introduced in Section 2.2.1;
M_P is ascent propellant mass;
$M_{P/L}$ is payload mass;
ε^* is a nominal value for NMF for a reference project with the same $(M_P + M_{P/L})$ of the vehicle under study (values of ε^* for selected concepts are available in TC).

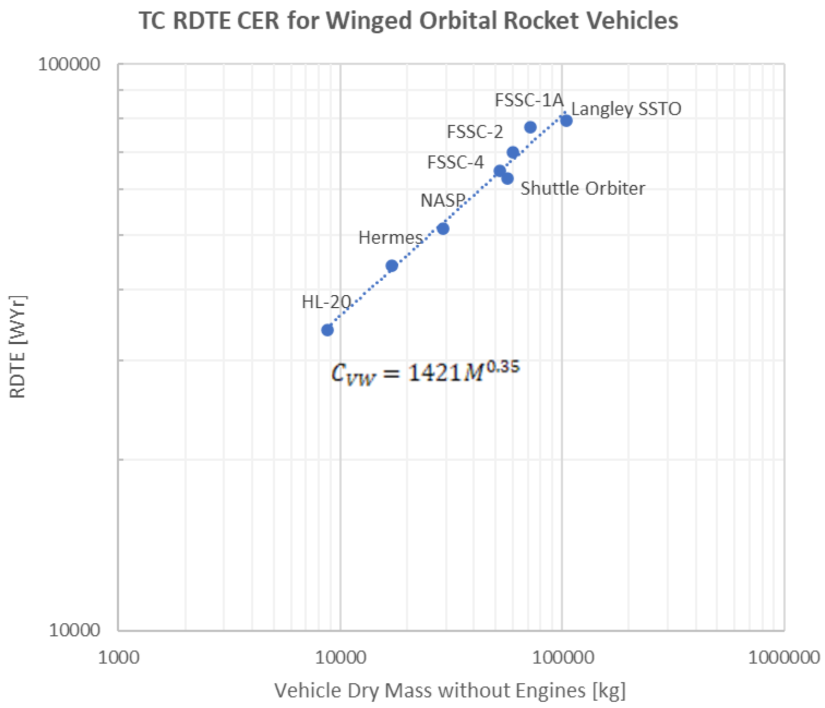
Therefore, the final value of f_2 is obtained by comparing vehicle NMF with the NMF associated to a reference project with similar characteristics and for which cost data is available. It is a measure of the technological complexity of the new vehicle with respect to the reference and, consequently, of the cost associated to technology improvement. For example, if $\varepsilon^* > \varepsilon$, f_2>1, meaning that the new is characterized by advanced materials which decrease the NMF. However, this technology advancement requires an increase in RDTE effort quantitatively expressed by f_2>1.

Eq. (28) provides RDTE cost for Winged Orbital Rocket Vehicles, comprising VTHL SSTO such as FSSC-1A and FSSC-02, HTHL (with Launch Assist System) SSTO (i.e., FSSC-4) as well as to a Winged Second Stage of TSTO such as Space Shuttle Orbiter or Hermes. This CERs with underlying database is depicted in Figure 31(a).

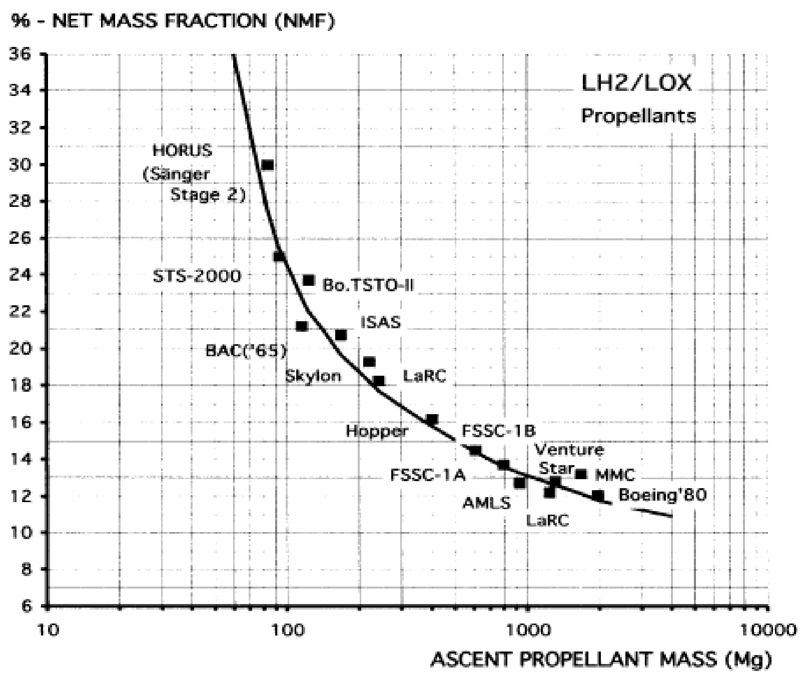
$$H_{VW} = 1421 M^{0.35} f_1 f_2 f_3 f_8 f_9 f_{10} f_{11} \quad (28)$$

Where M is Vehicle Dry Mass (without engines) in kg and f_2 as in Eq.(26). Notably, ε^* in Eq.(26) can be determined basing on the statistical population reported in Figure 31(b).

As discussed above, Space Shuttle Orbiter and Hermes with their pure re-entry capability are also included into Crewed Space Systems, so that these systems are considered by TC for the derivation of two different CERs. This is mainly related to the lack of cost data for RLVs. Please, notice that the difference between “Winged Orbital Rocket Vehicles” and “Crewed Space Systems” is well specified, so that in this sense the field of application of the two CERs is not ambiguous. However, as stated, Eq. (28) is deemed suitable for a wide range of RLVs with different take-off, landing and staging strategies (i.e., both SSTO and Second Stage of TSTO are entailed). This means that the same value for RDTE cost is estimated for quite diverse vehicle categories, thus excluding the possibility to assess the impact of specific designs onto costs. As such, the granularity level of Eq. (28) is considered unsuitable for the scopes of this Dissertation and a revised version of this CER will be proposed in Section 3.2.1.1.



(a)



(b)

Figure 31: (a) RDTE CER for Winged Orbital Rocket Vehicles from TC; (b) TC chart to be used to determine NMF for Winged Orbital Rocket Vehicle (Koelle, 2013)

The RDTE CER for Advanced Aircraft, Airbreathing SSTO and Airbreathing First Stage of TSTO is:

$$H_{VA} = 2169M^{0.262}f_1f_2f_3f_8f_9f_{10}f_{11} \quad (29)$$

Where M is vehicle Dry weight (with engines) and in which a different formulation for f_2 is proposed with respect to Eq.(26), exploiting the dependence on the maximum Mach reached by the vehicle:

$$f_2 = \mathcal{M}\text{^}0.15 \quad (30)$$

It is underlined that Eq.(29) is mainly based on RDTE data for military aircraft (e.g., Tornado, XB-70) plus the cost of Concorde aircraft and X-30 SSTO. Therefore, even if the CER is suggested for HTHL First Stages, the underlying database does not effectively include Airbreathing First Stages but only the X-30 (included into Winged Orbital Rocket Vehicles as well). Therefore, as for Eq.(28), the capability of this CER to reveal the peculiarities of Airbreathing First Stages is not satisfactory and it will be improved in Section 3.2.1.1.

For VTO First Stage-Flyback Rocket Vehicles and Expendable Ballistic Stages, respectively, Eq.(31) and Eq.(32) apply:

$$H_{VF} = 1462M^{0.325}f_1f_3f_8f_9f_{10}f_{11} \quad (31)$$

$$H_{VE} = 98.5M^{0.555}f_1f_2f_3 \quad (32)$$

Please, notice that $\boldsymbol{f_2}$ is not defined for Eq.(31) due to lack of data, while the definition in Eq.(26) applies in Eq.(32) as well. Notably, dedicated charts like that in Figure 31(b) but specifically for expendable rocket vehicles with LOX/LH2 or storable propellant are provided in support of $\boldsymbol{f_2}$ calculation. It is also pointed out that Eq.(31) was updated by (Trivailo, 2015) by revising original cost data thanks to internal documents available at Deutsches Zentrum für Luft- und Raumfahrt (DLR). The final outcome is a new version of Eq.(31) (i.e., Eq.(33)), which is plotted versus original TC CER in Figure 32.

$$H_{VF,DLR} = 493.27M^{0.3746}f_1f_3f_8f_9f_{10}f_{11} \quad (33)$$

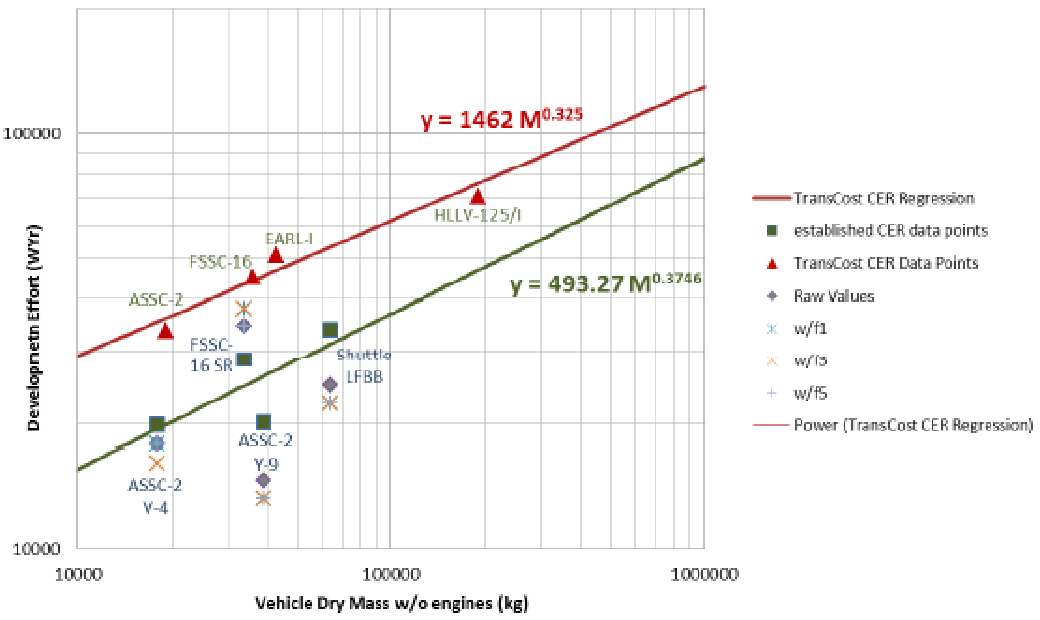


Figure 32:RDTE CER for Winged Orbital Rocket Vehicles from TC Revised vs Original TC CER for RDTE Cost of Fly-back Boosters (Trivailo, 2015)

Moreover, Eq.(32), tailored for expendable vehicles, is not directly suitable to VTVL First Stage RLVs (i.e., underlying database does not include these concepts). However, it is applied by TransCost to assess RDTE cost of Falcon 9 First Stage. As a result, this CER might be considered applicable to semi-reusable first stages, lacking a more detailed CERs at this purpose.

Considering engine types, Eq.(34) can be exploited for Turbojet Engine RDTE assessment, while Eq.(35) for Ramjet Engine RDTE. In both cases, f_2 is not defined. In this context, Eq.(34) was revised by (Ferretto, 2020) by adding the dependence to flight speed with special focus on high speed vehicles like STRATOFLY MR3 (Section 1.2.2 and Section 2.2.1). As a result, Eq. (36) was proposed.

$$H_{ET} = 1380 M_{E_{dry}}^{0.295} f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{34}$$

$$H_{ER} = 355 M_{E_{dry}}^{0.295} f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{35}$$

$$H'_{ET} = (232.4 M_{E_{dry}}^{0.509} + 1.12 v) f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{36}$$

Where $M_{E_{dry}}$ is engine dry mass in kg and v is vehicle cruise (or maximum) speed in m/s.

Eventually, for Rocket Engines RDTE cost, it is worth reporting Eq.(37) for Liquid Propellant Rocket Engines and Eq.(38) for Solid Propellant Rocket Motors:

$$H_{EL} = 277 M_{E_{dry}}^{0.48} f_1 f_2 f_3 f_8 f_9 f_{10} f_{11} \tag{37}$$

$$H_{ES} = 16.3 M^{0.54} f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{38}$$

Where:

$M_{E_{dry}}$ is Liquid Propellant Rocket Engine dry mass in kg;

M is solid rocket motor net mass in kg;

f_2 is defined as a function of the number of qualification tests (N_Q) performed during Liquid Propellant Rocket Engine development:

$$f_2 = 0.026 \left(\ln N_Q \right)^2 \tag{39}$$

It is underlined that Eq.(37) and Eq.(38) are deemed particularly reliable since they were built on a huge database of RDTE costs of Rocket Engines.

As mentioned, the TC version of great interest in this Dissertation is the last issue released in 2013 (Koelle, 2013). However, for the scope of the present work, it is also worth mentioning a former TC version released in 1991 (Koelle, 1991). It is underlined this reference it not directly available by the Author, but information herein reported is extracted from (Berry, 1993). Notably, (Koelle, 1991) collects a set of core RDTE CERs for specific types of Combined Cycle (CC) Engine which has been omitted in (Koelle, 2013) and applicable to Rocket/Ramjet (Eq.(40)), Air Ejector/Ramjet/Scramjet/Rocket (or 4 mode engine) (Eq.(41)) and Turboramjet/Rocket (Eq.(42)).

$$C_e = 300 M_{E_{dry}}^{0.635} \tag{40}$$

$$C_e = 500 M_{E_{dry}}^{0.635} \quad (41)$$

$$C_e = 200 M_{E_{dry}}^{0.635} \quad (42)$$

Where C_e is CC Engine RDTE cost in WYr and $M_{E_{dry}}$ is Engine Dry Mass in kg. By comparing Eq.(40),(41) and (42) with the core RDTE CER for Liquid Propellant Rocket Engines provided in (Koelle, 1991) (Eq.(43)), it can be noticed that all CERs have the same exponent (i.e. 0.635) and the extent of costs associated to the different propulsive strategies depends merely on the coefficient (i.e. 152, 200, 300 or 500). From this preliminary analysis, it emerges that the more costly engine is expected to be the 4-mode engine, which is also the most complex among the various alternatives.

$$C_e = 152 M_{E_{dry}}^{0.635} \quad (43)$$

Moreover, by comparing Eq.(43) with Eq.(37) as in Figure 33, it can be observed that the former tends to overestimate costs. As a result, Eq.(40),(41) and (42) for CC Engines, based on Eq.(43), might in turn overestimate actual costs. Nevertheless, the possibility to preliminary estimate CC Engines RDTE cost starting from data available for Liquid Propellant Rocket Engines appears promising. Basing on this consideration, an updated version of Eq.(40),(41) and (42) is studied in Section 3.2.1.2.

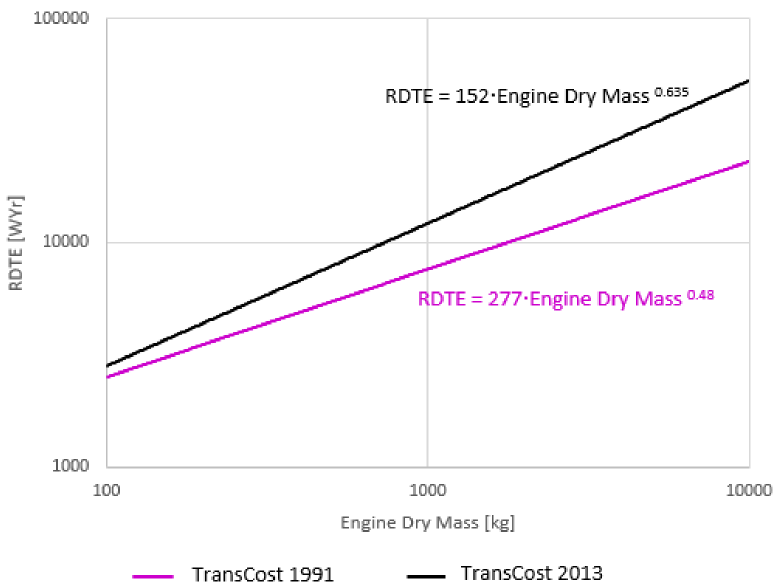


Figure 33: Liquid Propellant Rocket Engine RDTE CER - TC Versions Comparison

Production Cost Assessment in TC. For production cost, the core Power CER in Eq.(19) is still applicable to each element (vehicle system or engine). In this case, numerical values assigned to system-specific constant value and system-specific cost-to-mass sensitivity factor are specifically tailored for production cost. For sake of clarity, the cost resulting from Eq.(19) (labelled as H for RDTE cost) is herein referred as F for production cost. It represents TFU production cost for vehicle system (without engines) or engines as depicted in Figure 30. By applying the correction factors for production introduced in Table 7, it is now possible to express the production cost of the generic I^{th} unit produced as:

$$F_I = F \cdot f_4 f_8 f_{10}' f_{11}' \tag{44}$$

Where:

$$f_4 = I^{\frac{lnP}{ln2}} \tag{45}$$

and $\boldsymbol{P}$ is the learning factor, which represents the "*reduction of effort required for the manufacture of follow-on units compared to the no.1 unit*" (Koelle, 2013). As already introduced in Section 3.1.1, it represents the reduction in time (and, consequently, in cost) required to perform production tasks thanks to a progressive improvement in productivity. Typical values for $\boldsymbol{P}$ in space applications are between 1 and 0.70. For example, by applying Eq.(45) with $\boldsymbol{P}$ = 0.8 (or 80%) it means that each time the number of units produced doubles, the cost is reduced to 80%.

As a result, the total production cost of the launch vehicle (C_F) for all elements produced (of a specified type) during series production is:

$$C_F = f_0'^N \left(\sum_{i=1}^{n} F_{V_i} + \sum_{j=1}^{n_E} F_{E_j} \right) f_9 \tag{46}$$

Where:

f_0' is defined in Table 7 and equal to 1.03;

N is the number of vehicle stages;

n is the number of vehicle systems (without engines) produced of a specified type (e.g., Winged Orbital Rocket Vehicle);

n_E is the number of engines produced of a specified type (e.g., Liquid Propellant Rocket Engine);

Please, notice that Eq.(46) can be generalized to model the total production cost of a launch vehicle composed by several types of vehicle systems (e.g., one per each stage) and of engines.

Examples of Production CERs from (Koelle, 2013)**.** As already performed for RDTE costs, it is worth recalling the TC CERs for TFU Production Cost assessment of interest within this Dissertation for the same elements (i.e., vehicle systems and engines) previously discussed, underlining strengths and weaknesses of each equation. Please, note that all equations herein reported provide Production Cost for the generic Ith unit produced.

As far as vehicle system (excluding engines) is concerned, Eq.(47) is applicable to Solid-Propellant Rocket Strap-on Boosters & Stage Systems. This CER is based on an extensive dataset so that it is considered suitable for this work.

$$F_{ES} = 2.3M^{0.412} \cdot f_4 f_8 f_{10}' f_{11}' \quad (47)$$

For Expendable Ballistic Stages Eq.(48) can be applied:

$$F_{VF_1} = 1.265M^{0.59} \cdot f_4 f_8 f_{10}' f_{11}' \quad (48)$$

Please, notice that Eq.(48) is applicable to both Expendable and Reusable Ballistic Vehicles/Stages with storable propellants. In case of liquid hydrogen as propellant, Eq.(49) can be exploited. For both Eq.(48) and Eq.(49), M is Vehicle Dry Mass without Engines.

$$F_{VF_2} = 1.84M^{0.59} \cdot f_4 f_8 f_{10}' f_{11}' \quad (49)$$

The applicability of Eq.(48) and (49) to Reusable Ballistic Vehicles is justified in TC "since *reusable vehicles require some 40% higher dry mass, they are more expensive to build*", despite the database of ballistic vehicle/stages used to derive these CERs contains only expendable vehicles.

Concerning Winged Orbital Rocket Vehicles, Eq.(50) provides the cost as a function of Vehicle Dry Mass (without engines) in kg (M) :

$$F_{VW} = 5.83M^{0.606} \cdot f_4 f_8 f_{10}' f_{11}' \quad (50)$$

For Eq.(50), the same considerations already introduced for RDTE cost (Eq.(28)) apply. Also in this case, the analysis of underlying database provided in Figure 34 reveals that the CER is intended for a mixed group of RLVs, such as the VTHL Rocket SSTO FSSC-1 and the HL Rocket Second Stage of FSSC-9 vehicle. This results in an unsatisfactory granularity level of the equation.

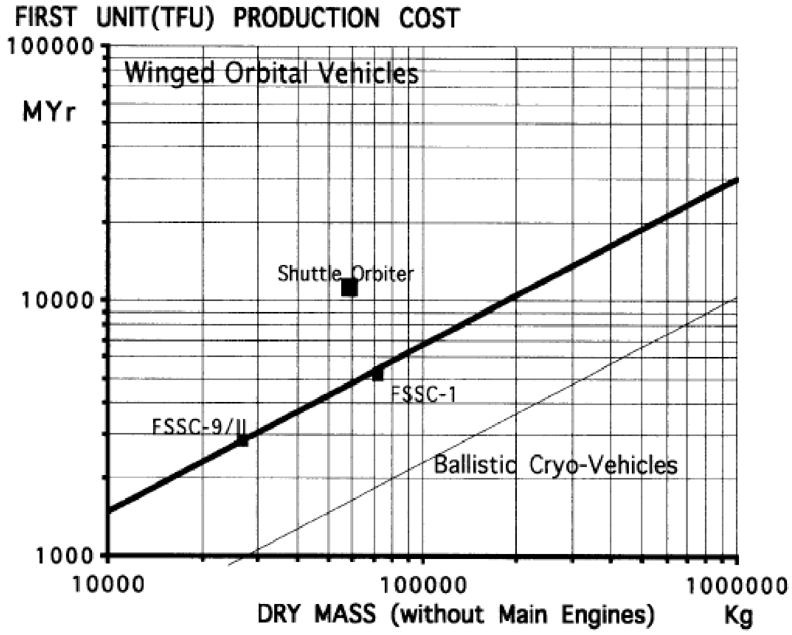


Figure 34: TC CER for TFU Production Cost of Winged Orbital Rocket Vehicles (Koelle, 2013)

Furthermore, for Advanced Aircraft and Airbreathing First Stage of TSTO Eq. (51) can be applied, using as reference mass (M) Vehicle Dry Mass with engines in kg:

$$F_{VF} = 0.357M^{0.762} \cdot f_4 f_8 f_{10}' f_{11}' \quad (51)$$

As discussed for Eq.(29), Eq.(51) is based on a heterogeneous database containing military aircraft, the supersonic Concorde, and the X-15. As such, no Winged First Stages (i.e., HTHL Airbreathing First Stages) are effectively included in the regression line used to derive Eq.(51). It means that this CER might provide only a very preliminary estimation of TFU production cost for this vehicle category. A more detailed CER for this cost item is discussed in Section 3.2.2. It also worth underlying that an updated version of Eq. (51) specifically intended for HST vehicles was already proposed by (Ferretto, 2020). In this new formulation, vehicle maximum flight speed in km/h (ν_k) as additional driver (M is Vehicle Dry Mass with engines in kg):

$$F'_{VF} = (0.34M^{1.75} + 7.06\nu_k^{0.4}) \cdot f_4 f_8 f_{10}' f_{11}' \quad (52)$$

As far as VTO First Stage-Flyback Rocket Vehicles are concerned, Table 6 already showed that a dedicated CER for Production cost of is not available from TC. As such, it is unclear which CER should be applied when dealing with such case studies. Similar remarks were also introduced by (Trivailo, 2015) which, in an attempt to evaluate production cost for SpaceLiner Orbiter, exploited both the CER for Winged Orbital Rocket Vehicles and the CER for High-Speed Aircraft/Winged First Stage Vehicles, proposing, as final estimation, an average result. This proves TC unsuitability to assess Production costs for VTHL Rocket First Stage vehicles and highlights the need to derive a dedicated CER (Section 3.2.2).

For engines, Eq.(53) is proposed by TC for Turbojet Engine Production cost, while Eq.(54) is an updated version of the same equation proposed by (Ferretto, 2020) with the dependence of maximum flight speed (ν in m/s). Moreover, lacking a dedicated CER for Ramjet Engine Production Cost in TC, (Ferretto, 2020) provides Eq.(55) for this missing cost item. Please, note that in Eq. (53) and (54) $M_{E_{dry}}$ is Engine Dry Mass in kg, while T in Eq.(55) is Ramjet Engine Thrust in kN.

$$F_{ET} = 2.29 M_{E_{dry}}^{0.545} \cdot f_4 f_8 f_{10}' f_{11}' \quad (53)$$

$$F'_{ET} = (2.29 M_{E_{dry}}^{0.530} + 0.50\nu^{0.6})\, f_4 f_8 f_{10}' f_{11}' \quad (54)$$

$$F_{ER} = 5.63 \cdot T^{0.35}\, f_4 f_8 f_{10}' f_{11}' \quad (55)$$

Eventually, for Liquid Propellant Rocket Engines Production cost, Eq.(56) is suggested by TC in case of modern liquid propellant rocket engine projects, independently from propellant combination and already including f_{10}' factor. It is judged particularly interesting for this Dissertation because it reflects the production cost decrease due to a significative reduction in engine components and for the application of 3D printing techniques. In addition, it is worth reporting Eq.(57), applicable to state-of-the-art Liquid Propellant Rocket Engines, for which advanced production techniques (such as 3D Printing) are not yet consistently impacting onto TFU Production Cost.

$$F_{EP} = 1.2M_{E_{dry}}^{0.535} f_4 f_8 f_{11}' \quad (56)$$

$$F_{EP(m)} = 3.15M^{0.535} f_4 f_8 f_{10}' f_{11}' \quad (57)$$

For sake of clarity, TFU Production CERs for CC engines and equivalent to Eq.(40),(41) and (42) are not available from (Berry, 1993).

Ground and Flight Operations Cost Assessment in TC (Koelle, 2013)**.** Accounting for Ground and Flight Operations Cost (Figure 30), TC proposes the model graphically depicted in Figure 35, showing the contribution of DOC, Refurbishment and Spares Cost (RSC) and IOC to this cost category and listing the main cost drivers involved in major DOC items.

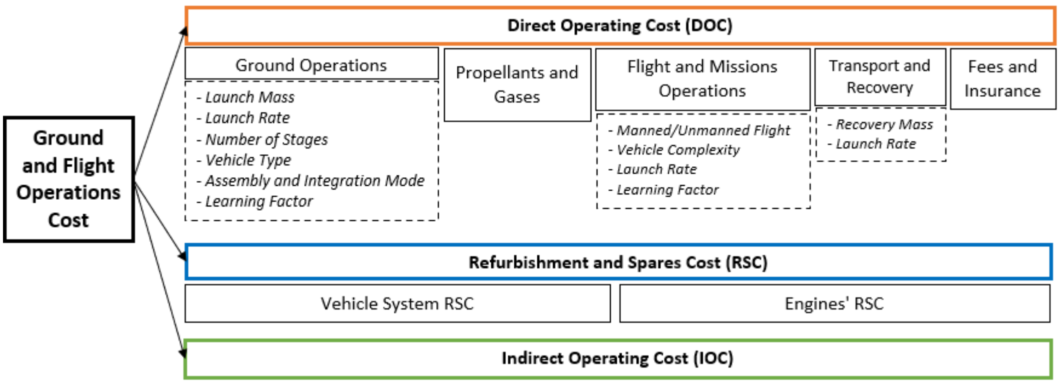


Figure 35: Detail of Ground and Flight Operations Cost Model from TC

Notably, as far as DOC is concerned, it encompasses:

- Ground Operations Cost (C_c), with assembly integration and checkout and launch preparation as main activities performed;
- Materials and Propellant Cost (C_P), including the cost of fuel, oxidizer, gases, and other consumables;
- Flight and Mission Operations Cost (C_P), i.e., mission planning and preparation, launch and flight operations;
- Transport & Recovery Cost (C_T), with the cost of transportation to launch site (e.g., Space Shuttle Orbiter ferry by a modified B-747 aircraft from landing

site in California to launch site in Florida) and/or the cost of recovery operations, such as recovery of Space Shuttle Solid Rocket Boosters (SRBs);
- Fees and Insurance ($Fees$), i.e., launch site user fee per launch (for commercial launch providers), Public Damage Insurance, vehicle Loss Charge and Mission Abort Charge.

As a result, according to TC, the following relationship entails main DOC contributions:

$$DOC = C_G + C_P + C_M + C_T + Fees \tag{58}$$

Examples of DOC CERs from (Koelle, 2013)**.** In line with what already performed for RDTE and Production CERs, a brief overview of DOC CERs available in TC and exploited within this Dissertation is provided.
Notably, Ground Operations cost (in WYr) can be assessed as:

$$C_G = 8 \cdot M_0^{0.67} \cdot L^{-0.9} \cdot N^{0.7} \cdot f_v f_c f_4 f_8 f'_{11} \tag{59}$$

where:
M_0 is the launch mass of the total system in ton;
L is the Launch Rate or Launches per Annum (LpA);
N is the number of stages or the number of major vehicle elements.

A preliminary definition of correction factors involved in Eq.(59) (f_v, f_c, f_4 , f_8 and f'_{11}) can be found in Table 7. Moreover, detailed values for f_v depending on launch vehicle characteristics are collected in Table 8.

Table 8: Values suggested for f_v correction factor (Koelle, 2013)

Reusability	Vehicle/Stage Type	f_v
Expendable	Liquid-propellant vehicle with cryogenic propellants	1.0
	Liquid-propellant vehicle with storable propellants	0.8
	Solid-propellant vehicle	0.3
Reusable	Automated cargo vehicle	0.7
	Crewed/piloted vehicle	1.8

As stated in TC, in case of vehicles constituted by different stage types, appropriate average values should be used. In addition, Table 9 gathers values to be assigned to f_c for different assembly and integration modes. Considering f_4, in the context of operations cost, it is related to the reduction of turnaround time (i.e., the time required to re-launch preparation for RLVs) increasing the number of LpA thanks to the progressive experience acquired by the team involved in on-ground turnaround activities. This factor should be assumed between 0.70 and 0.85, depending on the vehicle size, complexity, and launch frequency. From this analysis, it could be stated that TC CER for Ground Operations also models the costs associated to "on-line" maintenance activities for RLVs performed after each flight. On the contrary, "Off-line" maintenance activities (or "major-overhaul" in the aeronautical domain) are included into RSC.

Table 9: Values suggested for f_c, correction factor (Koelle, 2013)

Assembly and Integration Mode	f_c
Vertical assembly and checkout on the launch pad:	1.0
Vertical assembly and checkout, then transport to launch pad	0.7
Horizontal assembly and checkout, transport to launch pad, erection	0.5

Materials and Propellant Cost can be obtained by simply multiplying the material/propellant cost per unit mass or volume (using the values suggested in TC) by the total amount of that material/propellant available on-board. Moreover, Eq. (60) is preliminary suggested for unmanned Flight and Mission Operations Cost assessment,

$$C_M = 20(\sum Q_N)L^{-0.65}f_4 f_8 \quad (60)$$

Where N is the number of stages or the number of major vehicle elements and Q assumes a specific value depending on the i^{th} element type constituting the overall launch vehicle, notably:

- Small Solid Motor Stages: $Q_i = 0.15$ each;
- Expendable liquid-propellant stages or Large Boosters: $Q_i = 0.4$ each;
- Recoverable or Fly-back Systems: $Q_i = 1.0$ each;
- Unmanned Reusable Orbital Systems: $Q_i = 2.0$ each
- Crewed Orbital Vehicles: $Q_i = 3.0$ each.

Recalling Figure 35, the second component of Ground and Flight Operations cost in TC is RSC. This item is applicable only to RLVs and it covers the cost of major overhaul of both vehicle and engines. As mentioned, it could be compared to aircraft "major overhaul" since it deals with all off-line activities (i.e., detailed vehicle system inspection, exchange of critical elements like TPS panels, replacement of rocket engine, etc.) required to restore RLV characteristics for the next flights. Total RSC includes both the cost of spare parts and the manpower required to perform refurbishment operations and it mirrors the costs subdivision already proposed for RDTE and Production Cost, i.e., vehicle system (without engines) and engine. As far as vehicle system (without engines) RSC component is concerned, the following relationship is suggested:

$$R = f_5 \cdot TFU \tag{61}$$

Where:

R is the Vehicle System RSC share per flight;

TFU is Vehicle System TFU Production Cost obtained through Production Cost sub-model;

f_5 is defined as in Table 7 and it is expressed as a percentage value varying with the vehicle type.

Due to the limited operational experience for RLVs, very few data is available in terms of RSC (mainly related to Space Shuttle Orbiter and the X-15) to properly assess $\boldsymbol{f_5}$ for main RLVs categories. Furthermore, these few data should not be intended as fully representative of actual RSC considering that they are referred to experimental and prototype vehicles with technologies of the 1960s and 1970s. As such, TC suggests to integrate cost data related to airbreathing commercial aircraft refurbishment experience since they can constitute an important benchmark to derive future RLVs RSC. As a preliminary result, TC states that RSC and, consequently, $\boldsymbol{f_5}$ for future RLVs would be most probably higher than aircraft maintenance effort but lower than experimental vehicles as provided in Figure 36. In particular, Figure 36 highlights in blue the $\boldsymbol{f_5}$ values suggested for a Mach 4 HST, a Mach 7 Booster (i.e., a first stage) and an Orbital Winged Rocket Vehicle since they are of great interest for this Dissertation (see Section 2.1.1). For engines, no specific RSC relationships are reported in TC for airbreathing engines as well as for rocket engines. For the rocket engines, some useful guidelines related to future reusable rocket engines with self-diagnosis systems are reported, such as Rocketdyne estimations, according to which refurbishment effort per engine would be some 240 Wh (Work hours) every 20 flights plus 10% spares.

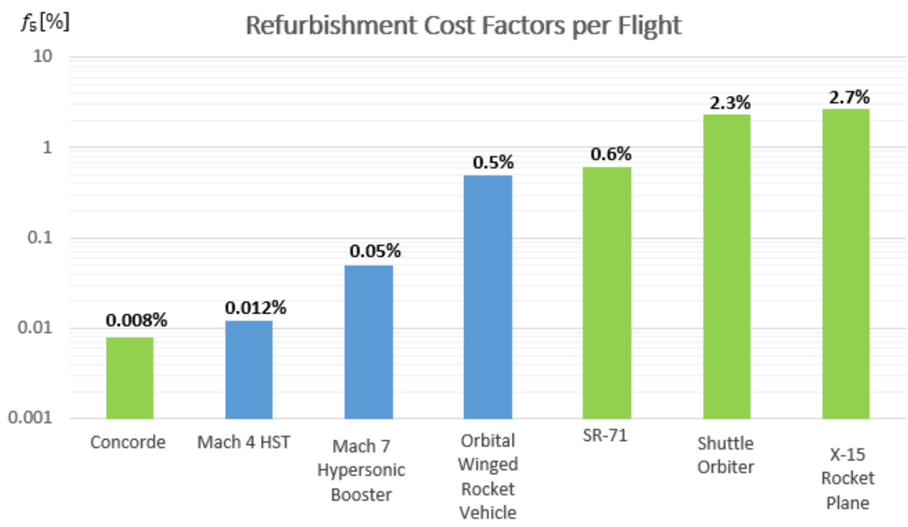


Figure 36: Values for f_5 correction factor suggested by TC

Another contribution to DOC according to (Koelle, 2013) is Fees and Insurance. However, due to poor statistical information, no CERs are suggested for this cost item, but only some guidelines. Further details about this topic are provided in Section 3.2.3.2. Considering the last contribution to Ground and Flight Operations Cost shown in Figure 35, i.e., IOC, it includes all activities not strictly related to flight operations, such as program administration and system management, marketing, and contracts (labelled as Commercialization Cost) as well as launch site infrastructure Operations & Support (O&S). For Commercialization Cost, the information collected in Figure 37 allows to estimate the staff cost (in WYr per Launch) associated to overall indirect operations as a function of LpA for three main organizational cases:

A) dedicated launch provider company with 100% of the launch vehicle procurement cost contracted to one or more other companies;

B) a more cost-efficient combination of launch vehicle prime contractor and launch provider requiring a reduced personnel effort;

C) vehicle manufacturer also performs the launch service with a minimum of only 20% external subcontract share.

Please, notice that IOC data in Figure 37 is based on staff cost data from ARIANESPACE and from STARSEM (a Russian-French Company). Equations shown for each scenario have been explicated by the Author of this Dissertation.

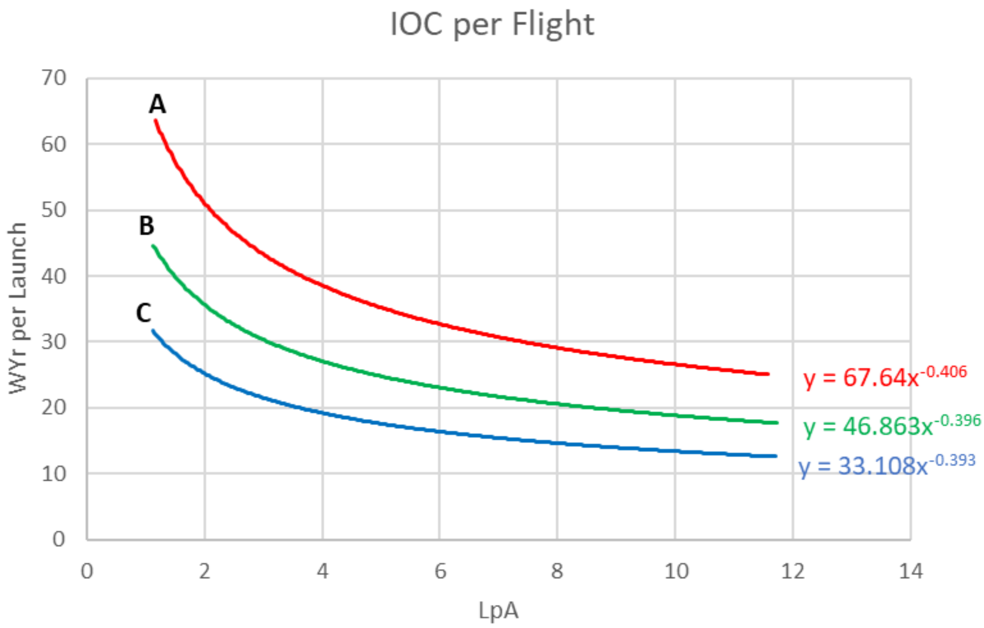


Figure 37: Commercialization Cost vs LpA from TC

3.1.2.4 NASA (Repic et al., 1973)

As far as Operating Cost is concerned, in 1973 NASA proposed a modified version of the ATA CERs (ATA (Air Transport Association of America), 1957) (already mentioned in Section 3.1.2.1) originally applicable to civil aircraft, specifically for turboprop, subsonic and supersonic turbojet aircraft. In this context, the updated NASA model (Repic et al., 1973) herein referred as “NASA-modified ATA CERs” aimed at assessing the DOC for airbreathing HST, evaluating the impact of advanced hypersonic technologies onto costs through proper correction coefficients. Specifically, the NASA-modified ATA CERs are tailored for an airbreathing HTHL HST in the Mach range from 5 to 12 able to perform any passenger or cargo-carrying hypersonic cruise mission. Notably, the approach reports DOC formulas for:

- Fuel Cost;
- Crew Cost, i.e., the cost of flight crew salary, fringe benefits, training programs and travel expense. Please, notice that this cost item does not include the cost of cabin crew, which is assigned to IOC;
- Insurance Cost;
- Depreciation Cost, defined as "*an expense provided to recover the original cost of the aircraft, plus the initial stock of spare parts, over an assigned depreciation life of the aircraft*" (Repic et al., 1973);
- Maintenance Cost.

NASA-modified ATA CERs for these cost items are reported hereafter. Please, note that original equations provide ton-mile cost. However, for the scope of this work, it is judged more convenient to provide them as a cost per flight using proper conversion factors.

For Fuel Cost per flight (DOC_{Fuel}), Eq.(62) recalls the formulation already discussed in Section 3.1.2.3 when dealing with TC Ground and Flight Operations Costs but also including the impact of reserve fuel fraction on costs:

$$DOC_{Fuel} = C_f \cdot m_{fT} \cdot (1 - K_R) \quad (62)$$

Where:

C_f is the cost of fuel per unit weight;
m_{fT} is fuel mass per flight;
K_R is reserve fuel fraction per flight [%].

Updated costs per unit weight for FY2021 can be found in (Sninsky, 2020). Specifically dealing with HST vehicles, LH_2 represents a promising solution not only for high specific energy contents but also for its environmental sustainability. A complete discussion on this topic can be found in (Fusaro, Vercella, et al., 2020), which provides a model to estimate the price of LH_2. As shown in Figure 38, main cost drivers of the methodology are production scenario (i.e., Current, Near-term Future and Long-term Future, associated to an increasing daily production rate) and the percentage of electricity coming from renewable sources or from the grid.

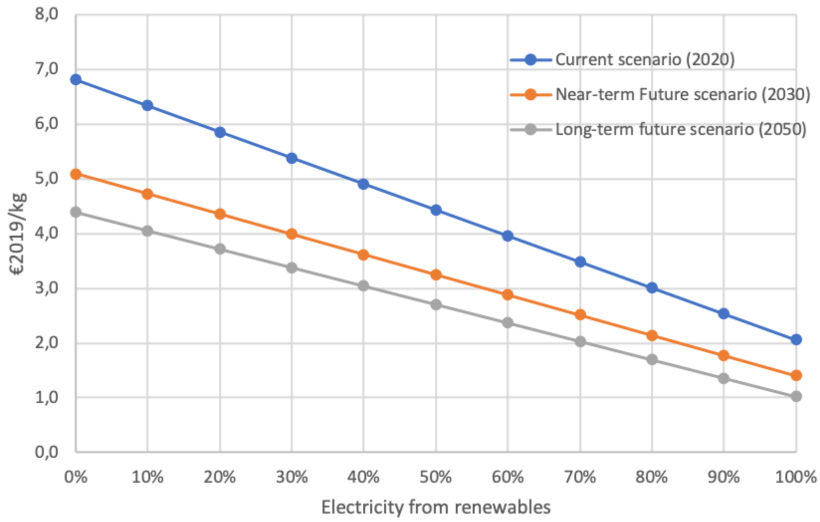


Figure 38: Summary of Liquid Hydrogen Cost (Fusaro, Vercella, et al., 2020)

Going back to (Repic et al., 1973), Crew Cost per flight (DOC_{Crew}) can be determined through Eq.(63), which is based on the definition of block hour (BH). As reported in (Repic et al., 1973), "block time" or "block hours" (t_B) refer to "*the time from initial aircraft movement prior to taxi and take-off (...) until the engines are shut down after landing*" and, according to ATA, it can be obtained by adding to flight time (t_F, in hours) 0.25 hours required for pre-flight and post-flight taxi.

$$DOC_{Crew} = K_C \cdot t_B \tag{63}$$

Where K_C is the crew cost per BH equal to 320 US$/BH in FY1973 for a 3-members HST crew.

Moreover, Insurance Cost per flight ($DOC_{Insurance}$) and Depreciation Cost per flight are given, respectively, by Eq.(64) and Eq.(65).

$$DOC_{Insurance} = \frac{IR \cdot C_{HST}}{L} \tag{64}$$

$$DOC_{Depreciation} = \frac{C_{HST} + 0.1(C_{HST} - C_E) + 0.4C_E}{L_d \cdot L} \tag{65}$$

Where:

IR is the annual insurance rate [%];
C_{HST} is aircraft acquisition cost (or aircraft price);

L is the number of flights/launches per year;
C_E is acquisition cost of all the engines installed on the aircraft;
L_d is depreciation life [years]

As far as Maintenance Cost per flight ($DOC_{Maintenance}$) is concerned, it is modelled as in Eq.(66):

$$DOC_{Maintenance} = DOC_{M/AF/L} + DOC_{M/AF/M} + DOC_{M/TJ/L} + DOC_{M/TJ/M} + DOC_{M/RJ/L} + DOC_{M/RJ/M} \tag{66}$$

Where:

$DOC_{M/AF/L}$ is maintenance labour cost per flight of airframe and subsystems excluding engines (Eq.(67));
$DOC_{M/AF/M}$ is maintenance material cost per flight of airframe and subsystems excluding engines (Eq.(68));
$DOC_{M/TJ/L}$ is maintenance labour cost per flight of turbojet engines, if present (Eq.(69));
$DOC_{M/TJ/M}$ is maintenance material cost per flight of turbojet engines, if present (Eq.(70));
$DOC_{M/RJ/L}$ is maintenance labour cost per flight of ramjet engines, if present (Eq.(71));
$DOC_{M/RJ/M}$ is maintenance material cost per flight of ramjet engines, if present (Eq.(72)).

$$DOC_{M/AF/L} = (1 + 0.59\, t_F)\left[\frac{0.05}{1000}(M_{AF} + M_{AV}) + 6 - \frac{630}{\frac{M_{AF}+M_{AV}}{1000} + 120}\right] M^{\frac{1}{2}}\, r_L \tag{67}$$

$$DOC_{M/AF/M} = (3.08 t_F + 6.24)(C_{HST} - C_E)/10^6 \tag{68}$$

$$DOC_{M/TJ/L} = (1 + k_{TJ} t_F)(0.6 + 0.027 \cdot T_{TJ}/10^3) \cdot N_{TJ} r_L K_{LTJ} \tag{69}$$

$$DOC_{M/TJ/M} = (2.5 \cdot C_{TJ}/10^5 + 2.0 k_{TJ} t_F \cdot C_{TJ}/10^5)\, K_{MTJ} \tag{70}$$

$$DOC_{M/RJ/L} = \frac{4.53 \cdot 10^{-4} \cdot M_{GTO}}{\frac{L}{D}}(1 + k_{RJ} t_F)\left(\frac{1.2\, N_{RJ} \frac{L}{D}}{M_{GTO}/10^3} + 0.054\right) r_L K_{LRJ} \tag{71}$$

$$\mathrm{DOC}_{M/RJ/M} = (2.5 \cdot C_{RJ}/10^5 + 2.0 k_{RJ} t_F \cdot C_{RJ}/10^5)\, K_{MRJ} \quad (72)$$

Where:

$\mathrm{t_F}$ flight time in hours;
$\mathrm{M_{AF}}$ is airframe and subsystems mass excluding engines in lb;
$\mathrm{M_{AV}}$ is avionics mass in lb;
M is cruise Mach number;
$\mathrm{r_L}$ is average labour rate per hour for all personnel involved in maintenance;
k_{TJ} is the fraction of $\mathrm{t_F}$ spent in turbojet mode [%];
$\mathrm{T_{TJ}}$ is the thrust of each turbojet engine in lb;
N_{TJ} is the number of turbojet engines installed;
K_{LTJ} is ratio of HST turbojets to subsonic turbojets maintenance labor cost;
K_{LRJ} is ratio of HST ramjets to current ramjets maintenance labor cost;
K_{MTJ} is ratio of HST turbojets to subsonic turbojets maintenance material cost;
K_{MRJ} is ratio of HST ramjets to current ramjets maintenance material cost;
C_{TJ} is acquisition cost of all turbojet engines;
M_{GTO} is gross take-off mass in lb;
$\frac{\mathrm{L}}{\mathrm{D}}$ is maximum lift to drag ratio for the vehicle;
k_{RJ} is the fraction of $\mathrm{t_F}$ spent in ramjet mode [%];
N_{RJ} is the number of ramjet engines installed.

Please, note that the coefficients k_{TJ} and k_{RJ} were not originally not included in the reference methodology but they have been here introduced to generalize the equations in order to take account the time of operation of turbojet and ramjet engines along the mission.

To summarize, considering the strict connection between RLVs and HSTs (Section 1.2), the operating cost model by (Repic et al., 1973) can be an interesting benchmark for airbreathing RLVs. However, considering that the model was proposed in the 1970s, each cost item should be carefully updated before exploitation. This applies, in particular, to fuel cost, for which updated cost figures can be found in (Fusaro, Vercella, et al., 2020; Sninsky, 2020). Moreover, the maintenance DOC CERs by (Repic et al., 1973) seem suitable integrate the RSC TC model, thus giving an overall view of the costs associated to the main engine types mounted on RLVs, both airbreathing and rocket.

3.1.2.5 Final comments on state-of-the-art methodologies

Starting from the main characteristics of the cost methodologies presented in the Section 3.1.2, it is clear that the TC Methodology is most suitable than (Koelle & Huber, 1961) to model RDTE and Production costs since it is based on recent and updated launcher data. In addition, it provides a dedicated set of CERs for a range of RLV categories. These equations can be exploited as they are or they can be used as starting point for possible updates. Indeed, TC is mostly based on actual launchers cost data but, to provide a preliminary assessment for future RLVs, it proposes CERs based on independent cost estimations from classified tools developed in the framework of several studies (e.g., FESTIP). Therefore, as a general result, CERs derivation may be based not only on real cost data but, lacking historical costs, they can be built on cost estimation data coming from previous and reliable studies. This also allows to verify whether cost estimations coming from different and independent sources are in line with one another.

However, as emerged from the analyses performed in the previous Sections, some aspects of great importance for the purposes of this Dissertation are not fully tackled in TC, such as a precise definition of vehicle system RDTE and Production costs basing on propulsive strategy, take-off and landing strategy. As a result, the granularity level of proposed CERs is judged not fully appropriate in some cases (e.g., for Winged Orbital Rocket Vehicles and Airbreathing First Stage Vehicles). This also means that some categories are not directly covered by the methodology. In these cases, cost estimation can be only preliminary performed by extending the applicability of other CERs. This is the case of HTHL Rocket First Stages, for which neither RDTE nor Production costs can be directly estimated, and of VTHL Fly-back boosters, not specifically handled in terms of Production cost. Undoubtedly, these considerations stress the need to update TC

RDTE and Production Cost sub-models to address the vehicle systems not tackled by the methodology and thus to cover the full spectrum of design possibilities for RLVs. Updates proposed in the framework of this work and leading to a new set of CERs for the missing items are fully described in Section 3.2. For engines, RDTE and Production CERs of CC engines and Scramjet engines are not available in (Koelle, 2013). Yet, available RDTE relationships for CC Engines from (Koelle, 1991) can be revised basing on updated rocket engine relationships from (Koelle, 2013) as in Section 3.2.1.1, while Production Cost can be preliminary determined using Booz-Allen CER (Eq.(18)). As additional comment about the TC RDTE and Production sub-models, it can be stated that vehicle dry mass (with or without engines) is the main cost driver explored for CERs derivation. The only exception is RDTE CER for Advanced Aircraft, Airbreathing SSTO and Airbreathing First Stage of TSTO (Eq.(29)), in which the dependence on maximum Mach reached by the vehicle is explored. Considering the importance of Staging Mach as design parameter for future RLVs (Section 2.1.1), a dedicated analysis to evaluate its role as cost driver in RDTE and Production cost is carried out in Section 3.2.

As far as Ground and Flight Operations cost is concerned, TC model is again a fundamental benchmark. In this case, the possibility to separately analyse RLVs operating costs from a vehicle systems and engines perspective seems unfeasible due to the well-known lack of data. As such TC CERs at launch vehicle level are mainly adopted. However, also in this case some improvements seem required specifically for Materials and Propellant costs per unit weight/volume which should be updated to current values. Furthermore, generic guidelines for insurance cost are reported in TC without providing a specific CER for this cost items. This could make the estimation of this cost contribution difficult and not straightforward. Therefore, basing on data available in TC, a preliminary approach to estimate insurance cost is proposed in Section 3.2.3. Additionally, the RSC model for engine component in TC mainly focuses on Rocket Engines without detailed information about the maintenance effort required for advance airbreathing engines. In this sense, the maintenance DOC CERs for HST treated by (Repic et al., 1973) could integrate the original TC model, thus giving an overall view of the costs associated to the main engine types mounted on RLVs.

As final remark to this Section, from the analysis of state-of-start in cost methodologies, it emerged a consistent fragmentation in LCC assessment for RLVs. Specifically, each approach mentioned in this literature review can cover only a part of the overall LCC with a substantial inability to deal with all the major configurations envisaged for RLVs in terms of RDTE and Production Costs. Recalling the discussion reported in Section 1.2 on the potential of HST cruiser to become airbreathing fist stage RLVs in the future, it is also lacking a unique framework for cost assessment of both HSTs and RLV. This would allow to easily switch from one case study to the other and evaluate the differences in terms of LCC for the two mission scenarios. This topic will be extensively treated in Section 3.2.

3.2 Cost Model Overview

The state-of-the-art analysis of cost methodologies presented in Section 3.1.2 highlighted the need to develop a complete LCC assessment framework for both RLVs and HSTs to cover major vehicle configurations and mission scenarios. Please, note that only airbreathing HST cruiser vehicles are considered in this work basing on the interest into STARTOFLY TSTO concept described in Section 2.2.1. As a result, the overall cost model proposed in this Dissertation is depicted in Figure 39, herein referred as "HyCost".

As shown, HyCost mirrors the classical costs subdivision proposed by (Koelle, 2013) and summarized in Section 3.1.2.3. Notably, it consists of Development (or RDTE) Cost, TFU Production Cost and Ground and Flight Operations Cost. In turn, RDTE and TFU Production costs are split between Vehicle System and Engines components, while total RDTE and Production costs of the launch vehicle can be assessed by applying, respectively, Eq.(21) and Eq.(46). Moreover, Ground and Flight Operations Cost are made up of DOC, RSC and IOC. Each cost item is evaluated with specific CERs and the applicability of each equation is to a single or to both vehicle types (i.e., HSTs and RLVs) is highlighted with ad-hoc colour code in Figure 39.

As depicted, HyCost combines newly derived CERs (properly emphasized in Figure 39) with State-of-the-Art (SoA) methodologies discussed in Section 3.1.2. to provide a comprehensive approach for LCC assessment of hypersonic vehicles.

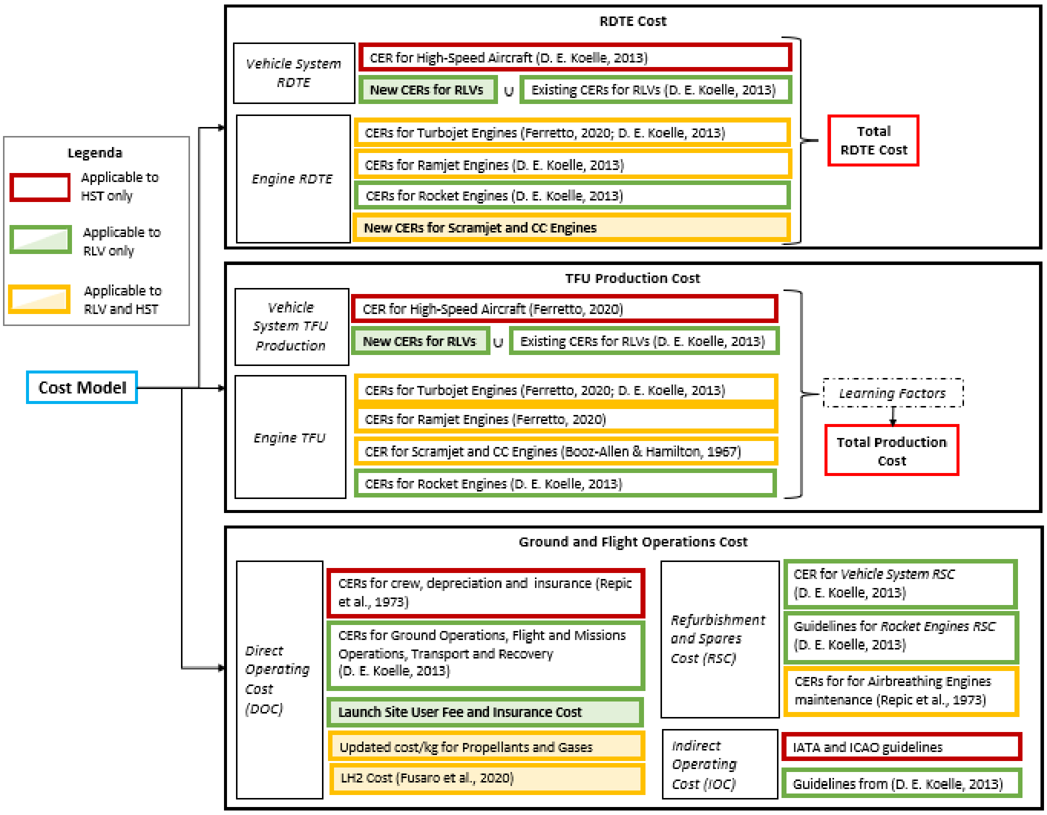


Figure 39: Proposed Cost Model Overview (HyCost)

On this basis, Section 3.2.1 describes the proposed model for RDTE cost assessment, while Section 3.2.2 entails Production cost model. Moreover, Section 3.2.3, with special emphasis in the description of a new approach for launch site user fee cost estimation. Moreover, Section 3.2.4 provides a summary of final figures obtained from cost assessment, i.e., cost per flight (or ticket price from a commercial perspective) and cost per unit mass. In addition, considering the impact of uncertainties in cost estimation, a brief discussion about this topic is reported in Section 3.2.5, whilst Section 3.3 collects some idea about a possible software implementation of HyCost. Eventually, Section 3.4. describes the application of the proposed cost model to the case studies introduced in Section 2.2 with the goal to test and validate some of the noteworthy relationships included within HyCost and to provide an order of magnitude of the LCC to be expected for future RLVs. Please, notice that the full collection of new CERs for RDTE and Production Cost developed in this work is reported in Section 7.2.

3.2.1 Development Cost

In the framework of the thorough analysis carried out in Section 3.1.2 about TC and TC-derived approaches (Ferretto, 2020; Trivailo, 2015), the applicability of available CERs to RLVs and HSTs has been assessed, underlying limitations or gaps of such SoA methodologies. At this point, by comparing the vehicle types modelled by TC (and TC-derived equations) with the RLV designs for SSTO and TSTO (including HSTs) currently under study in the aerospace community (Section 2.1.1), the list of Vehicle Systems to be entailed by the new cost model is provided in Table 10.

Table 10: List of Vehicle Systems (without Engines) to be handled in HyCost and RDTE CERs availability (Case 1,2 or 3)

Vehicle System (without Engines)	Case 1	Case 2	Case 3
VT(VL) Solid Propellant Rocket 1st Stage	X		
VT Liquid Propellant Rocket Stage (Expendable)	X		
VTVL Liquid Propellant Rocket 1st Stage		X	
VTHL Liquid Propellant Rocket 1st Stage	X		
HTHL Liquid Propellant Rocket 1st Stage			X
HTHL Airbreathing 1st Stage		X	
VTHL Liquid Propellant Rocket SSTO		X	
HTHL Liquid Propellant Rocket SSTO		X	
VTVL Liquid Propellant Rocket SSTO	X		
HTHL Airbreathing HST		X	
HTHL Airbreathing SSTO		X	
Liquid Propellant Rocket 2° Stage with HL		X	

For sake of clarity, Table 10 also specifies, for each vehicle system, the availability status of RDTE CERs in literature or the need to develop a missing CER basing on the following cases:

- **Case 1:** RDTE CER available from TC or TC-derived (no update required or envisaged);
- **Case 2:** RDTE CER available from TC but to be updated or revised (i.e., New CER required);
- **Case 3:** Missing RDTE CER to be developed (i.e., New CER required).

Dealing with rocket vehicles, additional remarks are required. Since this Dissertation mainly focuses on RLVs, expendable launchers are not specifically mentioned in Figure 39. Moreover, considering the great amount of data on expendable launchers provided in TC, no further analyses are carried out on this topic in the framework of the present work. Therefore, in case of fully or partially expendable systems constituted by one or more VT Liquid Propellant Rocket Stages (also mentioned in Table 10) Eq.(32) is suggested. Moreover, considering the current interest in RLV concepts equipped with Liquid Propellant Rocket Engines (Section 2.1.1), great attention is given to this specific propulsive strategy. As such, no specific relationships will be studied for Solid Propellant Rocket 1st Stages (Table 10), which can be evaluated thanks to Eq.(24). Therefore, moving to one of the main subjects of this Dissertation, i.e., Liquid Propellant Rocket RLVs, as introduced in Section 3.1.2.5 a revision of TC CER for Winged Orbital Rocket Vehicles (Eq.(28)) to tackle specific RLV configurations is judged required. Notably, dedicated relationships for VTHL Liquid Propellant Rocket SSTO, HTHL Liquid Propellant Rocket SSTO and Liquid Propellant Rocket 2° Stage with HL are needed (Table 10). For VTHL Liquid Propellant Rocket 1st Stage and VTVL Liquid Propellant Rocket SSTO, Eq.(33) by (Trivailo, 2015) and Eq.(25) by (Koelle, 2013) seem appropriate, while the derivation of a CER for HTHL Liquid Propellant Rocket 1st Stage is needed because not available from literature. Moreover, it is judged important to update Eq.(32) after adding reusable VTVL Rocket First Stages cost data in the underlying database, thus justifying its applicability to RLV concepts. For airbreathing vehicles, Eq.(29) by TC is here suggested for RDTE cost for HST, as depicted in Figure 39, while the applicability of this CER to Advanced Aircraft, Airbreathing SSTO and Airbreathing First Stage of TSTO has to be reconsidered in order to derive specific CERs for HTHL Airbreathing 1st Stage and HTHL Airbreathing SSTO. To summarize, as represented in Figure 39, Vehicle System RDTE cost for RLVs is modelled in HyCost by keeping existing CERs from literature, when applicable, and by integrating them with new ad-hoc developed

CERs in order to deal with all the main design configurations currently under study in the RLV framework (Section 2.1.1).

Considering Engines RDTE, Table 11 summarizes the list of engine types to be considered in HyCost. Recalling the "cases" already defined for Table 9, the same nomenclature is exploited to specify whether engine RDTE CERs can be extracted from TC or TC-derived methodologies (Case 1) or if specific CERs have to be derived (Case 3).

Table 11: List of Engine Types to be handled in HyCost and RDTE CERs availability (Case 1 or 3)

Engine Type	Case 1	Case 3
Solid Propellant Rocket Engine	X	
Liquid Propellant Rocket Engine	X	
Turbojet Engine	X	
Ramjet Engine	X	
Scramjet		X
CC Engine		X

For Rocket Engines, Eq.(37) and Eq.(38) are directly included in HyCost, respectively, for Liquid Propellant and Solid Propellant Rocket Engines. Similarly, Eq.(34) and Eq.(36) are suggested, respectively, for subsonic and high-speed Turbojets, while Eq.(35) from (Koelle, 2013) is advised for Ramjets. Basing on the colour code proposed in Figure 39, RDTE CERs for Turbojet and Ramjet Engines just cited are deemed suitable to both airbreathing HSTs and RLVs. Eventually, missing a suitable reference in literature, dedicated CERs should be derived to deal with CC and Scramjet Engines.

3.2.1.1 New Vehicle System RDTE CERs

Basing on the list of RDTE CERs in Table 10 and specifically related to Case 2 and Case 3, the path shown in Figure 40 has been followed for the derivation of new RDTE CERs for Vehicle Systems. Please, note that the same flowchart has been also applied for new CERs related to Vehicle Systems TFU Production Cost described in Section 3.2.2.

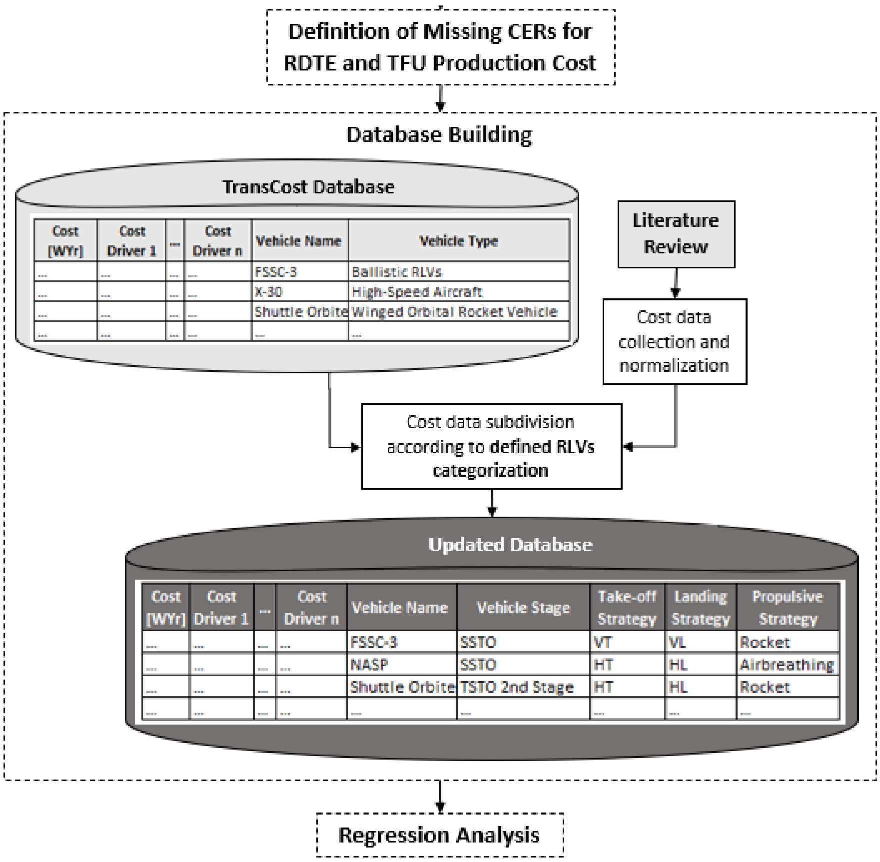


Figure 40: Approach for new Vehicle Systems RDTE and TFU Production CERs derivation

The process in Figure 40 starts with the definition of the list of required CERs for specific RLV types (already performed in Table 10). Then, it proceeds with a phase of database building, collecting all data required to derive equations at the desired granularity level. Specifically, all RDTE cost data in WYr available from TC and related to Vehicle System component are collected in a database labelled "TransCost Database". The latter, also stores for each cost datum the following information:

- n Cost Drivers (e.g., Vehicle Dry Mass, Staging Mach, etc.);
- Vehicle Name, i.e., name of the reference vehicle which cost datum and cost drivers values are referred to (e.g., X-30, Shuttle Orbiter, etc);
- Vehicle Type, generically describing reference vehicle characteristics according to TC definitions (e.g., Winged Orbital Rocket Vehicle).

Subsequently, data contained in the initial TransCost Database is re-categorized according to the RLVs categorization reported in Table 10 and included in a new database, called “Updated Database” in Figure 40. Notably, thanks to an in-depth literature review performed in this study and aimed at finding additional cost data, the original TC RDTE Database is widened relatively to RLVs. Notably, new Vehicle System RDTE cost data from independent cost estimations (mainly output of classified company tools) is collected, normalized to WYr and categorized according to the established RLV classification. Eventually, normalized cost data is added to the Updated Database, which constitutes the final source of Vehicle System cost data for the present research. In this context, Table 12 shows RDTE additional cost data included in the Updated Database, while TC cost data is not displayed for conciseness (however, they are considered to derive new CERs as well). Please, note that in Table 12 $W_{dry(w/o\ eng)}$ and $W_{dry(w/\ eng)}$ stand, respectively, for Vehicle Dry Mass without and with engines. Notably, data for $W_{dry(w/o\ eng)}$ is labelled with (1), while data for $W_{dry(w/\ eng)}$ with (2). In addition, $Mach$ indicates Staging Mach between First and Second Stage in case of a TSTO, whilst TO stands for Take-Off and LND for Landing.

After collecting all relevant cost data in the Updated Database, regression analysis is carried out to derive new CERs as shown in Figure 40. Notably, the regression methodology from ISPA Parametric Estimating Handbook (ISPA, 2008) summarized in Section 3.1.1 is exploited and the multivariate algebraic forms in Table 4 are explored for each required CER listed Table 10 (please, note that this approach applies to Case 2 and Case 3 columns). In particular, MPE-ZPB optimization is applied after extracting required vehicle data from Table 12, thus obtaining a subset of CERs for that Vehicle System along with related statistical criteria (i.e., %Std., %Bias, and R^2). As suggested by (ISPA, 2008), CERs statistical performance is evaluated by implementing MPE-ZPB technique in MS Excel and using Excel-Solver tool for optimization. Subsequently, by evaluating statistical criteria, the best-performing CER associated to lowest. %Std., null %Bias, and highest R^2 is chosen.

Table 12: Updated Vehicle System RDTE Database used for CERs derivation (original TC cost data not included)

Cost [WYr]	$W_{dry(w/o\ eng)}$ **[kg] (1) or** $W_{dry(w/\ eng)}$**[kg] (2)**	$Mach$	**Vehicle Name (Reference)**	**Vehicle Stage**	**TO**	**LND**	**Propulsion**
40046.1	75749.9 (1)	7.71	HTOHL -Sled (1st Stage) (Nau, 1967)	TSTO 1st	HT	HL	Rocket
52368.6	97068.7 (1)	7.71	HTOHL - Runway (1st Stage) (Nau, 1967)	TSTO 1st	HT	HL	Rocket
83416.7	203735.8 (1)	9.04	HTO Rocket (1st Stage) (Gregory et al., 1971)	TSTO 1st	HT	HL	Rocket
63857.6	136305 (1)	10.9	TS-HTHL-R/R-M10 (C) (Sled) (1st Stage) (Chase, 1978)	TSTO 1st	HT	HL	Rocket
108823.5	531655.2 (1)	*	ROT - Rocket (1st stage) (Dreyfuss, 1966)	TSTO 1st	HT	HL	Rocket
72177	76603 (1)	0.8	TS-HTHL-AB/R (D) (2nd Stage) (Chase, 1978)	TSTO 2nd	HT	HL	Rocket
53194	35004 (1)	10	TS-HTHL-TJSJ/R-M10 (F) (2nd Stage) (Chase, 1978)	TSTO 2nd	HT	HL	Rocket
45833	37098 (1)	9.04	Orbiter (Gregory et al., 1971)	TSTO 2nd	HT	HL	Rocket
22335	10290 (1)	5	M5 TSTO (2nd Stage) (Gregory et al., 1994)	TSTO 2nd	HT	HL	Rocket
18761	11646 (1)	6	Commonality M6 TSTO (2nd Stage) (Gregory et al., 1994)	TSTO 2nd	HT	HL	Rocket
40219	26762 (1)	7.71	VTOHL (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
44737	26762 (1)	7.71	HTOHL-Sled (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
49255	26762 (1)	7.71	HTOHL- Runway (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
37207	26762 (1)	7.71	Oxidizer Collection (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
31183	26762 (1)	7.71	Airbreathing Launch Vehicle (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
32410	22680 (1)	7.71	Airbreather /Rocket (2nd Stage) (Nau, 1967)	TSTO 2nd	HT	HL	Rocket
70689	84323 (1)	-	SSTO-HTHL-R (Sled) (B) (Chase, 1978)	SSTO	HT	HL	Rocket
91169	88859 (1)	-	SSTO-R (LOX/LH2) (NASA, 1994)	SSTO	VT	HL	Rocket

84887	72348 (1)	-	SSTO-R (Tripropellant) (NASA, 1994)	SSTO	VT	HL	Rocket
94656	90517 (1)	-	SSTO-VTHL-R (Sled) (A) (Chase, 1978)	SSTO	VT	HL	Rocket
38123	42825 (1)	-	VTOHL (Parkinson, 1995)	SSTO	VT	HL	Rocket
90505	173272 (2)	7.7	SSCRJ (1st Stage) (NASA, 1994)	TSTO 1st	HT	HL	Airbreathing
69046	181437 (2)	7.7	Airbreathing Launch Vehicle (1st Stage) (NASA, 1994)	TSTO 1st	HT	HL	Airbreathing
87922	190509 (2)	9.2	Oxidizer Collection (1st Stage) (NASA, 1994)	TSTO 1st	HT	HL	Airbreathing
36967	109840 (2)	5	M5 TSTO (1st Stage) (Gregory et al., 1994)	TSTO 1st	HT	HL	Airbreathing
37481	107020 (2)	6	Commonality M6 TSTO (1st Stage)) (Gregory et al., 1994)	TSTO 1st	HT	HL	Airbreathing
83222	196843 (2)	9	Airbreather (1st Stage) (Gregory et al., 1971)	TSTO 1st	HT	HL	Airbreathing
102479	382243 (2)	10	TS-HTHL-TJSJ/R-M10 (F) (1st Stage) (Chase, 1978)	TSTO 1st	HT	HL	Airbreathing
54186	177971 (2)	-	LAPCAT A2 (Fusaro, Viola, Ferretto, Vercella, Fernandez Villace, et al., 2020)	HST	HT	HL	Airbreathing
57752	158730 (2)	-	LAPCAT MR2.4 (Fusaro, Viola, Ferretto, Vercella, Fernandez Villace, et al., 2020)	HST	HT	HL	Airbreathing
29120	30600 (2)	-	SR-71 (calculated using (Roskam, 1990))	Military	HT	HL	Airbreathing
11900	9700 (1)	**	Falcon 9 (1st Stage) (Koelle, 2013)	TSTO 1st	VT	VL	Rocket
19944	11600 (1)	**	HyperNova (1st Stage) (Sorto-Ramos et al., 2020)	TSTO 1st	VT	VL	Rocket

* Not available; ** Not required

At this point, considering the vehicle system types labelled as “Case 2” and “Case 3” in Table 10, the remainder of this Section collects the main results from the exploitation of the approach in Figure 40 just described) to derive required CERs. It also describes how the additional literature review carried out to collect cost data for missing CERs (i.e., “Case 3”) derivation is fundamental to update and improve already existing equations (i.e., “Case 2”). Please, notice that all the CERs herein referred should be intended as a specific formulation of the “Core CER” in Eq.(19). $f_1, f_3, f_8, f_9, f_{10}, f_{11}$ correction factors should be applied as in Eq.(20) to each Core CER, while the need to consider f_2 factor is highlighted, if applicable. Notably, all CERs herein discussed are expressed in WYr to provide costs already adjusted for inflation. However, the WYr estimation can be easily converted into to the desired FY and currency using the WYr conversion factors (f_8) collected in Section 7.1.

RDTE CER for HTHL Liquid Propellant Rocket 1st Stage. Firstly, all RDTE cost data related this RLV category is extracted from Table 12 along with cost driver’s values. Notably, in line with TC methodology, Vehicle Dry Mass without Engines (labelled with “(1)” in Table 12) is assumed to highly impact on RDTE costs of rocket RLVs, while Staging Mach is included in this work as possible additional driver considering its great influence since early design stages on basic vehicle characteristics and dimensions (Section 2.1.1). As mentioned, available cost and design data is used to derive new CERs for Vehicle System RDTE cost of HTHL First Stages exploiting the regression methodology from (ISPA, 2008) described in Section 3.1.1 by studying two sets of CERs. Firstly, the dependence of Vehicle System RDTE cost on Vehicle Dry Mass without engines is explored, then Staging Mach is introduced as additional parameter in regression analysis. For sake of clarity, Figure 41 shows an example of implementation of MPE-ZPB technique using MS Excel to derive a Power CER as a function of Vehicle Dry Mass without engines. A similar Excel spreadsheet is also set up to derive Linear and Triad CERs coefficients for the same cost item, thus exploring all the main CER forms collected in Table 4.

	x (Vehicle Dry Mass (w/o engines) [kg])	y (Airframe RDTE [WYr])	ESTy	ESTy-y	[ESTy-y]^2	(ESTy-y)/ESTy	[(ESTy-y)/ESTy]^2	
	75749.86	40046.09	45377.57	5331.48	28424732.09	0.1175	0.0138	
	97068.69	52368.62	51290.43	-1078.19	1162493.09	-0.0210	0.0004	
	203735.84	83416.67	73973.56	-9443.11	89172240.38	-0.1277	0.0163	
	136305.00	63857.58	60653.80	-3203.78	10264205.25	-0.0528	0.0028	
	531655.18	108823.53	118803.70	9980.17	99603767.39	0.0840	0.0071	
Sums =	**1044514.57**	**348512.48**	**350099.06**	**1586.58**	228627438.20	**0.0000**	**0.0404**	
					SS_res			
	y=a*x^b		Bias =	317.32		%Bias = 0.0000%		optimized solution
a =	176.51		Std Error =	7560.22		%Std Error = 11.603%		
b =	0.49		R =	0.97		R^2 = 0.94		
p =	2							
n =	5							

Figure 41: Example of implementation of MPE-ZPB technique in MS Excel to derive Vehicle System RDTE

The resulting list of CERs (with related statistical parameters) is collected in Table 13, including the Power CER in Figure 41. From Table 13, it can be observed that CERs' quality in terms of %Std Error and R^2 is good for all CERs' categories (i.e., Linear, Power and Triad), but the Power CER (Eq.(74)) is associated to the lowest %Std Error and highest R^2. Please, note that, even if not explicitly reported in Table 13, all CERs coefficients are optimized in order to reach zero %Bias as prescribed by MPE-ZPB optimization technique.

Table 13: HTHL Rocket First Stage RDTE CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$41489.61W_{dry(w/o\ eng)} + 0.13$	Linear	18.643	0.869	(73)
$176.51W_{dry(w/o\ eng)}^{0.49}$	Power	11.60	0.936	(74)
$1.031 + 176.49W_{dry(w/o\ eng)}^{0.49}$	Triad	14.21	0.935	(75)

As anticipated, a similar analysis is performed to evaluate Vehicle System RDTE cost for the same vehicle category as a function of both Vehicle Dry Mass (without engines) and Staging Mach. It is specified that, lacking Staging Mach number for ROT – Rocket Booster (Dreyfuss, 1966), the database is restricted to the 4 concepts for which this information is available. Results of the application of MPE-ZPB optimization are reported in Table 14.

Table 14: HTHL Rocket First Stage RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency

CER	Category	%Std Error	R^2	Eq.
$14422.39 + 0.32W_{dry(w/o\ eng)} + 538Mach$	Linear	8.58	0.984	(76)
$13.7W_{dry(w/o\ eng)}^{0.71}Mach^0$	Power	6.69	0.989	(77)

Please, note that results for %Bias are not directly reported since CERs coefficients have been optimized to reach zero %Bias as prescribed by the selected methodology for CERs derivation. It is worth noticing that Power CER (Eq.(76)) is not effectively able to represent Mach dependency (indeed, a power coefficient equal to zero is obtained). This might be related to the poor dataset available, which does not allow to appreciate the envisaged dependence. However, basing on Author's experience in the field of cost estimation, most probably, the driver $W_{dry(w/o\ eng)}$. The latter is able to fully describe Vehicle System RDTE costs without the need of Mach as additional driver for this specific RLV category. This might indicate the existence of a strong relationship between Vehicle Dry Mass and Staging Mach so that the two drivers are not independent. Consequently, it is sufficient to consider $W_{dry(w/o\ eng)}$ as cost driver for the RDTE CER under study. It is also worth specifying that, for Triad 1 and 2 CERs envisaged in Table 4, they are not derived due to lack of enough points in the dataset. Indeed, remembering that only four points are available, Triad 1 and Triad 2 CERs require, respectively, the derivation of five and four coefficients which, in case of four or less datapoints available, would lead to an undetermined %Std. Error. As such, Eq. (67) is the unique equation from Table 14 expressing the relationship between Vehicle Dry Weight (without engines), Mach, and Vehicle System RDTE cost for a HTHL Rocket First Stage. This equation is associated to better values of statistical parameters than Eq.(74). However, it is worth underlying that this performance is highly influenced by the poor dataset available, which is limited to a small range of Staging Mach. Therefore, Eq.(76) is considered applicable to a Staging Mach range between 7.5 and 10.5 but it must be carefully handled outside this range. In general, Eq.(74). should be preferred for RDTE cost estimation of HTHL Rocket First Stages since it is built on a more extensive cost dataset. As such, it is included in HyCost methodology developed in this work. The final core CER, providing Vehicle System RDTE cost in WYr is depicted in Figure 42. Please, notice that up to now no f_2 factor is defined for this case.

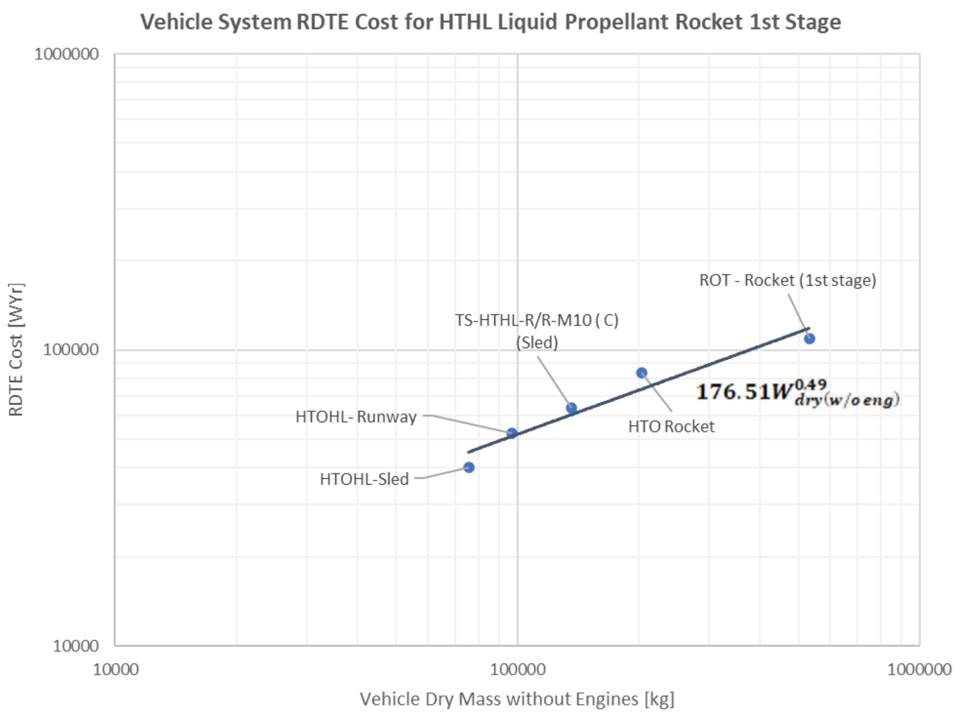


Figure 42: New CER for Vehicle System RDTE Cost of HTHL Liquid Propellant Rocket 1st Stage

RDTE CER for HTHL Airbreathing 1st Stage. Eq.(29) from TC has been considered as starting point in the framework of this work. Notably, original TC database mainly based on advanced and military aircraft data has been enriched with data for HTHL Airbreathing First Stages coming from the extensive literature review summarized in Table 12. The latter reports, for the RLV category here analysed, Vehicle System RDTE cost data for each concept, Vehicle Dry Mass with engines (in line with TC in which RDTE costs is function of this driver for Airbreathing HTO First Stages) and Staging Mach number. Therefore, basing on applicable data from Table 12, Table 15 summarizes the new CERs derived for Vehicle Systems RDTE cost of HTHL Airbreathing First Stages as a function of Vehicle Dry Mass (with engines), i.e., $W_{dry(w/\,eng)}$. These equations have been obtained by applying the regression methodology described in Section 3.1.1, properly implemented in MS Excel. From results in Table 15, it is worth noticing that CERs' quality in terms of %Std Error and R^2 is good for all CERs' categories (i.e., Linear, Power and Triad), but the Linear CER Eq.(78) is associated to the lowest Standard Error and highest R^2. Eq.(78) is graphically shown in Figure 43 with RDTE cost expressed in WYr.

Table 15: HTHL Airbreathing First Stage and Advanced Aircraft RDTE CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$22857 + 0.24W_{dry(w/\ eng)}$	Linear	17.43	0.826	(78)
$481.15W_{dry(w/\ eng)}^{0.41}$	Power	21.03	0.785	(79)
$22857 + 0.053W_{dry(w/\ eng)}^{1.13}$	Triad	17.58	0.814	(80)

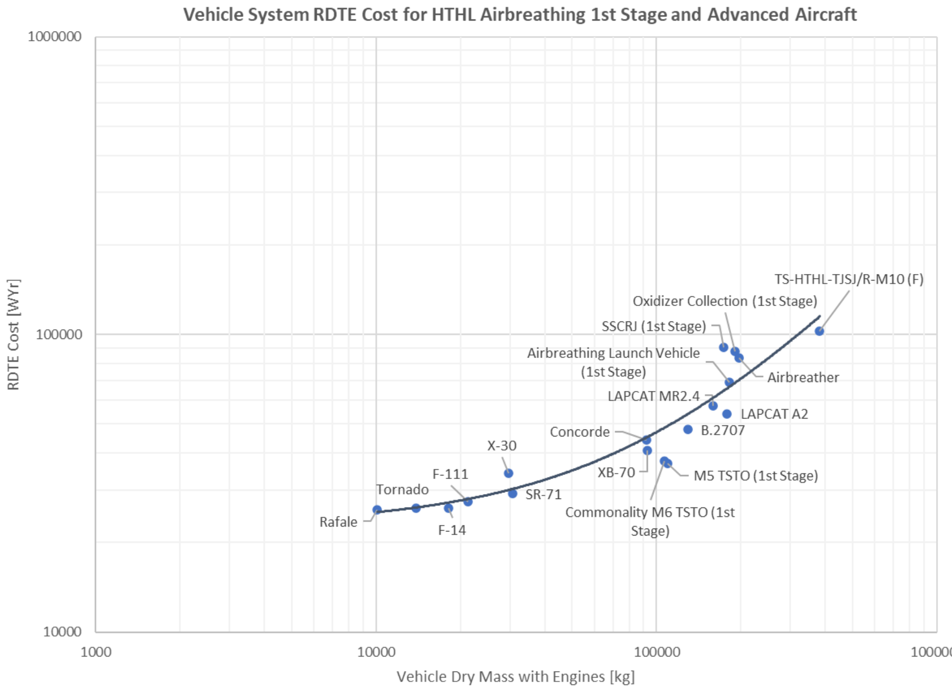


Figure 43: New CER for Vehicle System RDTE Cost of HTHL Airbreathing First Stage and Advanced Aircraft Vehicle System RDTE

Eq.(78) is deemed applicable to Airbreathing First Stages as well as to Advanced Aircraft considering the statistical population at the basis of its derivation (shown in Figure 43). Moreover, it is highlighted that the application of a f_2 factor (Eq.(30)) to Eq.(78) is not recommended since it would introduce a dependence on an additional cost driver (i.e., maximum Mach). Such dependence was justified for the original dataset used by TC to derive Eq.(29) but is not verified for the new dataset used for Eq.(78). However, a dedicated regression analysis considering the dependence of both Vehicle Dry Mass (with engines) and Staging Mach onto Vehicle System RDTE cost of a HTHL Airbreathing First Stage can be performed thanks to the data in Table 12. Results of this analysis are collected in Table 16. From results, it can be observed that the constant term in Linear and Triad 1 CERs (Eq.(81) and Eq.(83)) is null. Furthermore, Triad 2 CER (Eq.(84)) is characterized by the lowest %Std Error and the highest R^2 among all the CERs proposed in Table 15 and in Table 16, even if it is based on a limited subset of concepts from the Updated Database (Table 12). As such, the relationship between Vehicle System RDTE cost and Mach for airbreathing high-speed vehicles previously modelled by TC using Eq.(29) and Eq.(30) is confirmed in Eq. (84) using an independent database. For sake of clarity, no f_2 factor should be applied to Eq.(82) since the relationship with Mach is already included. For completeness, Eq.(84) is graphically shown in Figure 44 in WYr.

Table 16: HTHL Airbreathing First Stage RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency

CER	Category	%Std Error	R^2	Eq.
$0 + 0.12W_{dry(w/\,eng)} + 6258.5Mach$	Linear	22.77	0.816	(81)
$0.95W_{dry(w/\,eng)}^{0.92}Mach^{0.15}$	Power	20.32	0.758	(82)
$0 + 1.15W_{dry(w/\,eng)}^{0.91} + 0.49Mach^{0.71}$	Triad 1	37.21	0.637	(83)
$0.68 + 922.56W_{dry(w/\,eng)}^{0.12}Mach^{1.39}$	Triad 2	15.12	0.856	(84)

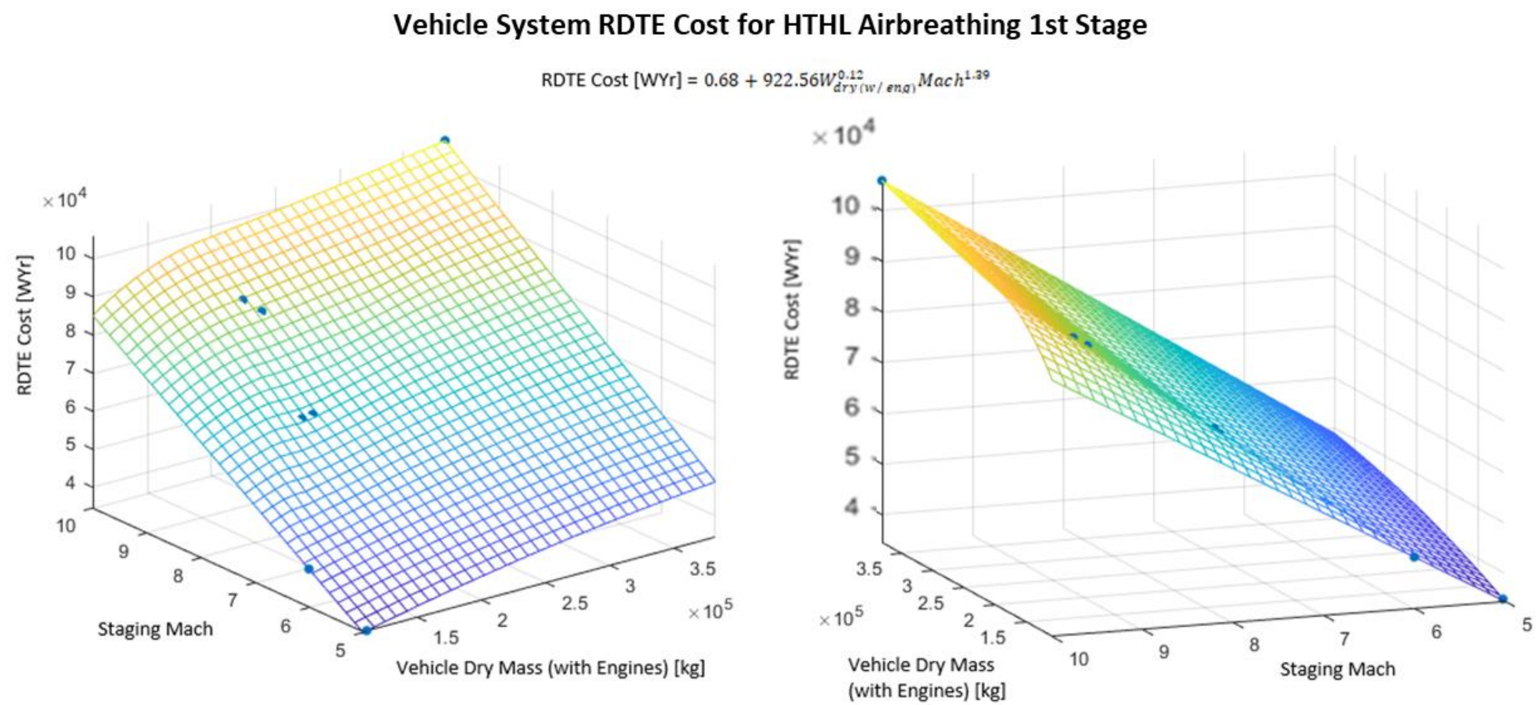


Figure 44: New CER for Vehicle System RDTE Cost of HTHL Airbreathing First Stages

In conclusion, despite the lower quality of associated statistical parameters, Eq.(78) is suggested for implementation in HyCost methodology since it is based on a huger dataset. This CER might be also exploited to preliminary assess RDTE cost for HTHL Airbreathing SSTO Vehicles. Indeed, due to unavailability of cost data for these concepts, it is not possible at this stage to derive a dedicated CER. This lack of previous cost estimation data for airbreathing SSTOs might be the result of the low interest towards these concepts due to their technical unfeasibility in the near term (Section 2.1.1). In addition, Eq.(84) can be exploited in case the Staging Mach of the concept (for which RDTE costs are estimated) is in the Mach range used to derive the CER (i.e., between Mach 5 and Mach 9).

RDTE CER for Liquid Propellant Rocket 2° Stage with HL. Starting from the issues related to TC CER for Winged Orbital Rocket Vehicles (Eq.(28)) discussed in Section 3.1.2.5, the extensive literature review carried out in this work highly focused on cost data collection for Liquid Propellant Rocket 2° Stages with HL in order to derive a dedicated CER for this vehicle type. As a result, applicable concepts from the Updated Database (Table 12) and from the original TC dataset related to Eq.(28) (i.e., Shuttle Orbiter, Hermes, and HL-20 in Figure 31) have been used to derive the new set of CERs in Table 17. Please, notice that the mass-related cost driver considered for these CERs is Vehicle Dry Mass without Engines in line with Eq.(28). By analysing these CERs, it can be stated that CERs' quality in terms of Standard Error and R^2 is good for all CERs' categories (i.e., linear, power and triad), but the Linear CER (Eq.(85)) is associated to the lowest Standard Error and higher R^2 values.

Table 17: Rocket Second Stage with HL RDTE CERs – Dry Mass (without Engines) dependency

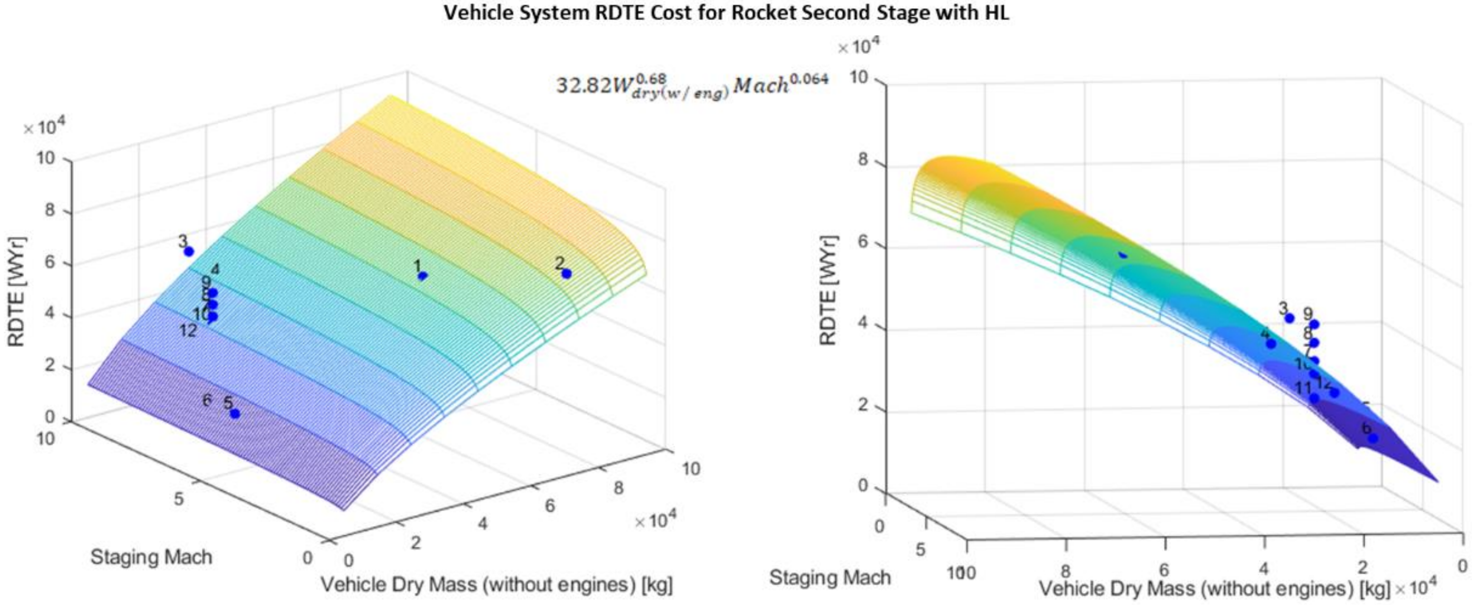
CER	Category	%Std Error	R^2	Eq.
$21470 + 0.69W_{dry(w/out\ eng)}$	Linear	20.33	0.789	(85)
$512.71W_{dry(w/out\ eng)}^{0.43}$	Power	20.61	0.789	(86)
$513.37 + 476.97W_{dry(w/out\ eng)}^{0.44}$	Triad	21.51	0.789	(87)

Moreover, by including Staging Mach as additional driver, the new set of CERs gathered in Table 18 is derived. From these results, it can be noticed that for a Rocket Second Stage with HL multivariate CERs with the dependence of both Staging Mach and Vehicle Dry Mass without Engines provide, in all cases, better statistical performance than CERs based only on a Vehicle Dry Mass without Engines (Table 17). Therefore, for this specific RLV category, the inclusion of

Staging Mach as new driver results into an improvement of the capability to model costs. Specifically, R^2 values for CERs in Table 18 are quite similar to one another, but the Power CER (Eq.(89)) provides the best performance in terms of %Std. Error. The latter, graphically represented in Figure 45 is therefore chosen for implementation in HyCost methodology. However, in case the information about the Staging Mach is not available for a specific design, the exploitation of Eq.(85) is recommended. As far as the f_2 factor is concerned, it was originally envisaged in Eq.(28). Notably, the exploitation of the chart in Figure 31(b) was suggested to derive an estimation of ε^* to be used in Eq.(26) for f_2. However, considering that the statistical population in Figure 31(b) was heterogeneous (i.e., it included all the vehicle concepts originally covered in Eq.(28)), the exploitation of the proposed chart is deemed no more applicable for the new CER just proposed. Indeed, the population in Figure 31(b) might be not fully representative of the characteristics of the specific vehicle category analysed.

Table 18: Rocket Second Stage with HL RDTE CERs – Dry Mass (without Engines) and Staging Mach dependency

CER	Category	%Std Error	R^2	Eq.
$379.21 + 0.90W_{dry(w/\,eng)} + 1889.13Mach$	Linear	14.90	0.901	(88)
$32.82W_{dry(w/\,eng)}^{0.68}Mach^{0.064}$	Power	14.37	0.900	(89)
$1.024 + 53.56W_{dry(w/\,eng)}^{0.65} + 1.13Mach^{1.21}$	Triad 1	17.02	0.889	(90)
$1.035 + 32.81W_{dry(w/\,eng)}^{0.68}Mach^{0.064}$	Triad 2	15.248	0.900	(91)



ID	Concept
1	Shuttle Orbiter
2	TS-HTHL-AB/R-Parallel Lift (D) Orbiter
3	TS-HTHL-TJSJ/R-M10 (F) Orbiter
4	Orbiter
5	M5 TSTO (2nd Stage)
6	Commonality M6 TSTO (2nd Stage)
7	VTOHL (2nd Stage)
8	HTOHL-Sled (2nd Stage)
9	HTOHL- Runway (2nd Stage)
10	Oxidizer Collection (2nd Stage)
11	Airbreathing Launch Vehicle (2nd Stage)
12	Airbreather /Rocket (2nd Stage)

Figure 45: New CER for Vehicle System RDTE Cost of Rocket Second Stage with HL (with Staging Mach dependency)

RDTE CER for VTHL and HTHL Liquid Propellant Rocket SSTO. As discussed, these concepts were modelled in TC under the category “Winged Orbital Rocket Vehicles” (Eq.(28)). Recalling Section 3.1.2.5., a key goal of the present work is to isolate the vehicle types grouped under this categorization and provide dedicated RDTE CERs for each RLV category. Thanks to the thorough literature review aimed at collecting additional cost data, a specific CER Rocket Second Stages with HL has been suggested (Eq.(89)). However, due to scarce additional information collected for VTHL and HTHL Rocket SSTOs, these concepts have been grouped together with the goal to propose a CER valid for both vehicle types. Please, note that in this case the only cost driver under analysis is Vehicle Dry Mass (without engines, in line with Eq.(28)) since the concept of Staging Mach is not applicable to a SSTO vehicles. Notably, after extracting data related to SSTO concepts from Table 12, it is possible to derive the set of new CERs for RDTE cost assessment of HTHL and VTHL Rocket SSTO vehicles collected in Table 19. By analysing these CERs, it can be stated that their quality in terms of %Std. Error and R^2 is good for all CERs’ categories, but the Power CER (Eq.(93)) is associated to the lowest Standard Error. This CER, shown in Figure 46 (in WYr), is included in HyCost.

Table 19: VTHL or HTHL Rocket SSTO RDTE CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$7931.18 + 0.92W_{dry(w/out\ eng)}$	Linear	13.34	0.901	(92)
$1.71W_{dry(w/out\ eng)}^{0.96}$	Power	12.99	0.900	(93)
$1.45 + 0.97W_{dry(w/out\ eng)}^{1.004}$	Triad	14.2	0.889	(94)
$7931.18 + 0.92W_{dry(w/out\ eng)}$	Linear	13.34	0.900	(95)

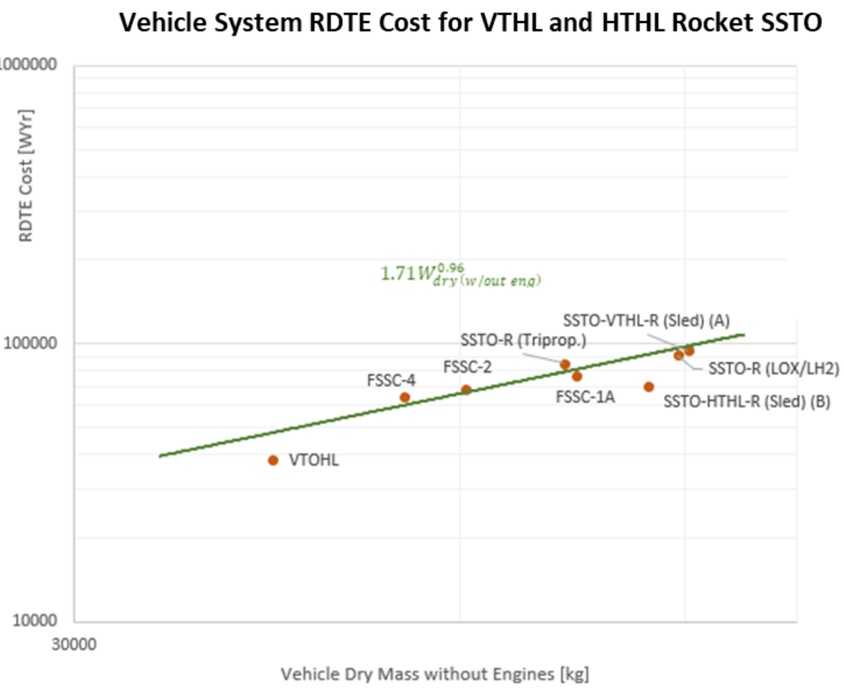


Figure 46: New CER for Vehicle System RDTE Cost of VTHL and HTHL Rocket SSTO

RDTE CER for VTVL Liquid Propellant Rocket SSTO. In this case, TC provides a CER for Ballistic Reusable Launch Vehicles based on a huge dataset of concept SSTO VTVL Rocket vehicles (Eq. (25)). Therefore, the revision of this CER was not a prime goal of this work (Table 10). However, benefitting of the availability of an additional cost datum (i.e., the VTOVL concept in Table 12), the original TC dataset has been enriched, deriving a new version of Eq. (25). Notably, results of regression analysis are provided in Table 20. CERs' quality in terms of %Std. Error and R^2 is good for all categories. However, the Power CER (Eq.(97)) has the lowest Standard Error and highest R^2. This CER, plotted in Figure 47, is therefore included into HyCost.

Table 20: VTVL Rocket SSTO RDTE CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$41392 + 0.16W_{dry(w/out\ eng)}$	Linear	11.18	0.971	(96)
$743.36W_{dry(w/out\ eng)}^{0.39}$	Power	8.15	0.974	(97)
$0 + 743.36W_{dry(w/out\ eng)}^{0.39}$	Triad	8.81	0.974	(98)

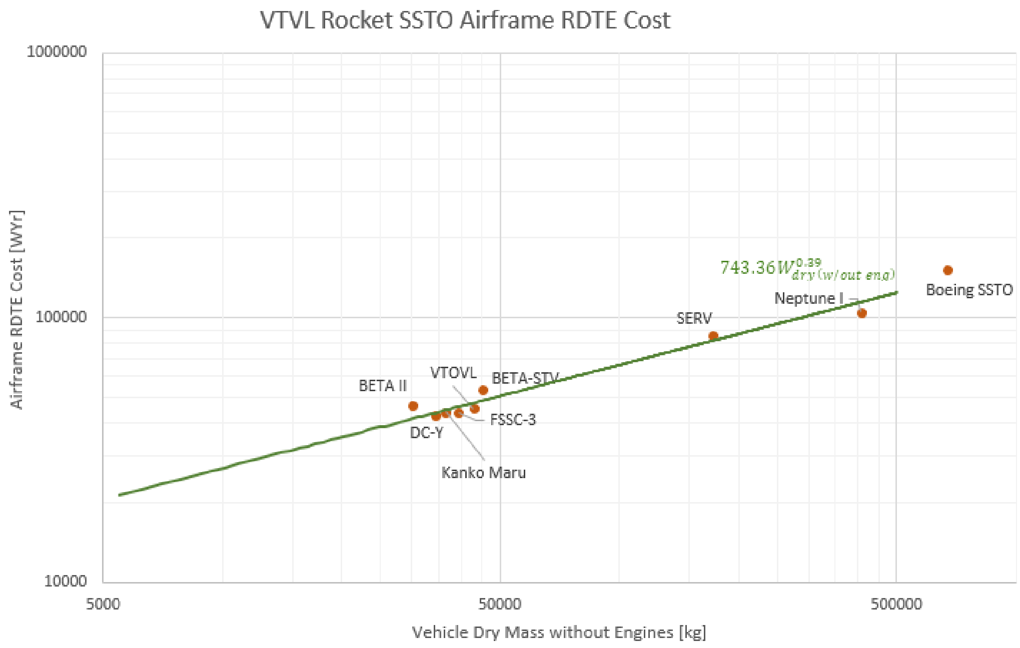


Figure 47: New CER for Vehicle System RDTE Cost of VTVL Rocket SSTO

RDTE CER for VTVL Liquid Propellant Rocket First Stage. As discussed in Section 3.1.2.3, Vehicle System RDTE cost for expendable vehicles can be estimated through Eq.(32) by TC. As mentioned, (Koelle, 2013) suggests the exploitation of this CER also for semi-reusable VTVL First Stage RLVs (such as Falcon 9 Booster). However, no specific relationship is provided for fully reusable VTVL First Stage RLVs. Considering that no suitable cost estimation data emerged from the literature review, it is not possible at the current stage to propose a dedicated CER for fully reusable VTVL First Stages following the regression methodology exploited above. However, in an attempt to further justify the application of Eq.(32) to semi-reusable as well as to reusable concepts, available data for semi-reusable VTVL First Stages (i.e., Falcon 9 and Hypernova in Table 12) have been added to the original RLV population used to derive Eq.(32). For sake of clarity, Figure 48 depicts the overall dataset considered, highlighting the newly added concepts with respect to original TC points. By performing regression analysis with this extended database, the CERs reported in Table 21 can be derived. From results, it can be observed that Eq.(100) is associated to the best statistical performance. This CER, included in HyCost methodology, is graphically shown in Figure 48.

Table 21: VTVL Liquid Propellant Rocket First Stage RDTE CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$4676.38 + 0.999W_{dry(w/out\ eng)}$	Linear	21.52	0.824	(99)
$96.42W_{dry(w/out\ eng)}^{0.56}$	Power	16.845	0.934	(100)
$0 + 96.50W_{dry(w/out\ eng)}^{0.56}$	Triad	8.81	0.934	(101)

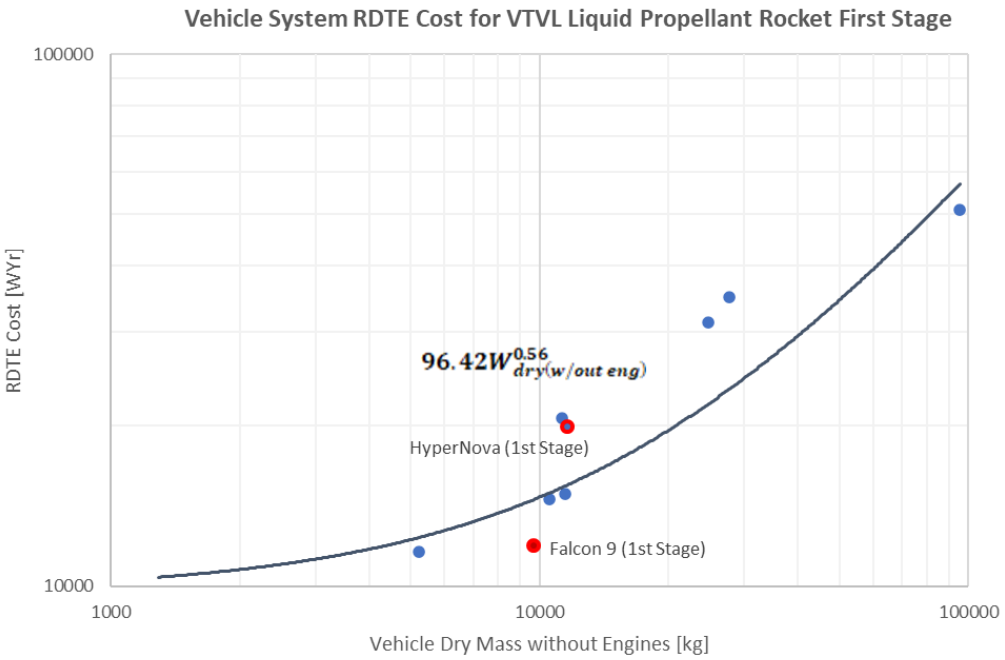


Figure 48: New CER for Vehicle System RDTE Cost of VTVL Rocket SSTO

Please, notice that the f_2 factor originally included in Eq.(32). As mentioned in Section 3.1.2.3, the exploitation of charts like that in Figure 31(b) was suggested. Therefore, considering that Eq.(100) is mostly based on the statistical population of Eq.(32), the adoption of the f_2 factor is advised.

3.2.1.2 New Engine RDTE CERs

As mentioned in Section 3.1.2.5, a detailed expression for Scramjet RDTE cost is missing from literature, while (Koelle, 1991) could represent a useful benchmark for the derivation of updated relationships for Combined Cycle (CC) Engines. In this context, in line with TC, the parameter supposed to have the greatest impact onto Engines RDTE costs is Engine Dry Weight. The latter was already used by (Koelle, 1991) for CC Engines and it is here assumed for Scramjet Engines as well.

Scramjet Engine RDTE Cost. As far as Scramjet is concerned, literature review revealed a substantial lack of RDTE cost data related to this innovative kind of engines. The few available data depicted in Figure 49 refer to concepts from literature equipped with Scramjet engine, notably TS-HTHL-TJSJ/R-M10 (F) from (Chase, 1978) and Air-breather from (Gregory et al., 1971). From Figure 49 it can be noticed that available scramjet data lie slightly above Turbojet Engine RDTE CER by TC (Eq.(34)). Considering the availability of only two datapoints, the Linear CER in Eq.(102) is here suggested. Please, notice that in Eq.(102) H_{ES} is Scramjet engine RDTE cost in WYr. Moreover, the same correction factors introduced by TC for Turbojet and Ramjet RDTE CERs are applied to Eq.(102) as well. For sake of clarity, the new Scramjet RDTE CER is valid in the range of scramjet engine dry masses ($M_{E_{dry}}$ in Eq.(103)) contained in the database, but is must be carefully verified outside of it.

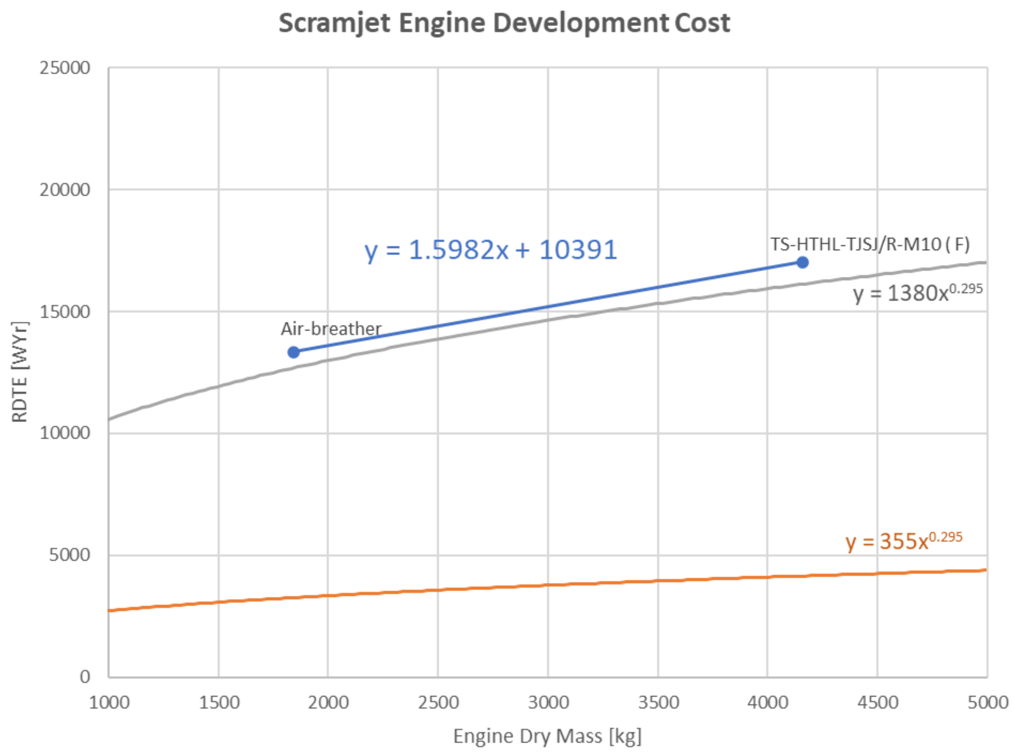


Figure 49: Turbojet, Ramjet and Scramjet Engines RDTE Cost Comparison

$$H_{ES} = \left(1.5982 \cdot M_{E_{dry}} + 10391\right) f_1 f_3 f_8 f_9 f_{10} f_{11} \tag{102}$$

CC Engine RDTE Cost. For CC Engines, considering the great variety of propulsive strategies (combined in a unique engine) currently under study and the limited amount of available data coming from previous cost estimations, it is not possible, at the moment, to derive a RDTE CER for each possible design solution. To overcome this problem, as introduced in Section 3.1.2.5, an update of CERs from (Koelle, 1991) for Rocket/Ramjet (Eq.(40)), Air Ejector/Ramjet/Scramjet/Rocket (or 4 mode engine) (Eq.(41)) and Turboramjet/Rocket (Eq.(42)). is proposed. As described, these CERs are all based on RDTE CER for Liquid Propellant Rocket Engine reported in (Koelle, 1991) (Eq.(43)) and the comparison of this CER with the last version available in (Koelle, 2013) (Eq.(37)) revealed that the former tends to overestimate Engine RDTE Cost. Therefore, with the aim of updating previous TC CERs for CC Engines from (Koelle, 1991) exploiting most recent information on Rocket Engines, a new set of CERs for CC Engines is here proposed. This is accomplished by using as exponent 0.48 (as in Eq.(37)) and not 0.635 as in Eq.(43) and by properly re-scaling the multiplicative coefficient associated to each CC Engine. For example, in order to obtain the updated RDTE CER for Rocket/Ramjet Combined Cycle Engine, the follow relationship is solved:

$$152 : 277 = 300 : X \tag{103}$$

Where:

152 is the coefficient in Eq.(43);

277 is the coefficient in in Eq.(37);

300 is the coefficient in Eq.(40).

X is the unknown, i.e., the updated for Rocket/Ramjet Engines based on the relationship between previous and current coefficients in Liquid Propellant Rocket Engines CERs.

A similar procedure can be followed to derive updated coefficients for the remaining CC Engines CERs. Resulting updated CERs for Rocket/Ramjet, Turboramjet/Rocket, and Air Ejector/Ramjet/Scramjet/Rocket are reported hereafter.

Rocket/Ramjet: $C_{e,NEW} = 546.71 M_{E_{dry}}^{0.48}$ (104)

Turboramjet/Rocket: $C_{e,NEW} = 364.47 M_{E_{dry}}^{0.48}$ (105)

Air Ejector/Ramjet/Scramjet/Rocket: $C_{e,NEW} = 911.18 M_{E_{dry}}^{0.48}$ (106)

3.2.2 Production Cost

As for Development Cost, the State-of-the-Art (SoA) analysis for Production Cost mainly focused on TC and TC-derived approaches (Ferretto, 2020; Trivailo, 2015), thoroughly analysing applicability and key limitations of available CERs to both RLVs and HSTs (Section 3.1.2.5). In this context, the list of Vehicle Systems already provided in Table 10 is re-considered for Production Cost (Table 22) recalling the “cases” already defined in Section 3.2.1. For sake of clarity, the basic structure and main cost items covered by HyCost Production Cost model are depicted in Figure 39.

Table 22: List of Vehicle Systems to be handled in HyCost and Production CERs availability (Case 1,2 or 3)

Vehicle System (without Engines)	Case 1	Case 2	Case 3
VT(VL) Solid Propellant Rocket 1st Stage	X		
VT Liquid Propellant Rocket Stage (Expendable)	X		
VTVL Liquid Propellant Rocket 1st Stage			X
VTHL Liquid Propellant Rocket 1st Stage			X
HTHL Liquid Propellant Rocket 1st Stage			X
HTHL Airbreathing 1st Stage		X	
VTHL Liquid Propellant Rocket SSTO		X	
HTHL Liquid Propellant Rocket SSTO		X	
VTVL Liquid Propellant Rocket SSTO	X		
HTHL Airbreathing HST		X	
HTHL Airbreathing SSTO		X	
Liquid Propellant Rocket 2° Stage with HL		X	

Starting with rocket vehicles, as already discussed in Section 3.2.1, the focus of this Dissertation is on Liquid Propellant RLVs. Therefore, no further studies are deemed required for Solid Propellant Rocket First Stages, for which Eq.(47) is here suggested. Moreover, in case of fully or partially expendable systems made up of one or more VT Liquid Propellant Rocket Stage with storable or cryo propellant, Eq.(48) and Eq.(49) from TC are recommended. The same CERs are also advised in TC for Ballistic Reusable Vehicles, i.e., VTVL Liquid Propellant Rocket SSTO, even if not specifically included in the underlying CER database. As such, a dedicated analysis on VTVL Liquid Propellant Rocket SSTO is carried out in this Dissertation and results are graphically compared with Eq.(48) and Eq.(49). For Rocket 2° Stages with HL and VTHL/HTHL Liquid Propellant Rocket SSTO, included in Winged Orbital Rocket Vehicles (Eq.(50)), the discussion reported in Section 3.2.1.1 applies to Production CER as well, so that dedicated relationships for these RLV types have to be derived. Brand new CERs are needed for VTVL, VTHL and HTHL Rocket 1st Stages, not covered by SoA methodologies. Dealing with airbreathing vehicles, as shown in Figure 39, Eq.(52) by (Ferretto, 2020) is recommended for TFU Production Cost of a HST, while a revision of Eq.(51) by TC for Advanced Aircraft, Airbreathing SSTO and Airbreathing First Stage of TSTO is required in order to derive specific CERs for HTHL Airbreathing 1st Stage and HTHL Airbreathing SSTO. As highlighted for RDTE cost model, Vehicle System Production cost for RLVs proposed in this Dissertation (Figure 39) considers both existing CERs from literature, when applicable, as well as new ad-hoc developed CERs in order to cover main RLV designs. For Engines Production Cost, the list of engine types already reported in Table 11 is re-considered for Production. Notably, for Solid Propellant Rocket Engines, Eq.(47)previously suggested for Strap-on Boosters already included the rocket motor cost contribution, while Eq.(56) is adopted for Liquid Propellant Rocket Engines. Similarly, Eq.(53) and Eq.(54) are advised for subsonic and high-speed Turbojets, while Eq.(55) by is recommended for Ramjets. Eventually, Booz-Allen CER (18), properly adjusted for inflation, can be preliminary exploited for CC and Scramjet Engines.

Considering that SoA approaches are deemed suitable to deal with main engine types required by HyCost methodology, the derivation of new CERs for Production Cost is limited to Vehicle Systems. This is accomplished by exploiting the approach depicted in Figure 40 and thoroughly discussed in Section 3.2.1.1. Notably, basing on the items under Case 2 and Case 3 in Table 22, available TC data can be collected to derive a “TransCost Database” specific to Production Cost. The latter can be then integrated with additional cost data coming from a dedicated literature review and properly categorized to cover the list of RLV concepts in Table 22 in terms of take-off, landing and propulsive strategy. The outcome of this process is the “Updated Database” for Production Cost in Table 23, based on the same nomenclature already discussed for Table 12. At this point, remembering the path in Figure 40, MPE-ZPB optimization can be applied to derive new CERs for required vehicle types in Table 22. From this analysis, statistical parameters for each CER can be obtained, thus allowing to evaluate CERs performance and select the “best” equation (see Section 3.1.1) for further details). Concerning cost drivers, in line with TC, the main parameter supposed to have a great relationship with Production Cost is Vehicle Dry Mass with or without engines (depending on the vehicle type). Therefore, for each concept under analysis, a set of CERs function of Vehicle Dry Mass (with or without Engines) is proposed (according to the basic algebraic forms introduced in Table

4). As already performed for RDTE CERs, an additional set of CERs function of both Vehicle Dry Mass (with or without engines) and Staging Mach is also provided for First Stage Vehicles, considering the great influence of Staging Mach number onto the overall vehicle design (Section 2.1.1). This additional analysis allows to assess the effective impact of Staging Mach onto costs. Please, note that the study on Staging Mach is performed only if sufficient cost data is available. For sake of clarity, proposed CERs for Production Cost herein discussed should be intended as “Core CERs” for TFU Production Cost assessment. Proper correction factors (i.e. f_4, f_8, f_{10}', and f_{11}') should be applied in order to obtain the cost of the generic I^{th} unit (Eq.(44)) as well as Total Production Cost (Eq.(46)).

Table 23: Updated Airframe TFU Production Database used for CERs derivation (TransCost cost data not included)

Cost [WYr]	$W_{dry(w/o\ eng)}$ **[kg] (1) or** $W_{dry(w/\ eng)}$ **[kg] (2)**	$Mach$	**Vehicle Name (Reference)**	**Vehicle Stage**	**TO**	**LND**	**Propulsion**
4250.0	203735.8 (1)	9.04	HTO Rocket (1st Stage) (Gregory et al., 1971)	TSTO 1st	HT	HL	Rocket
12856.7	531655.2 (1)	*	ROT - Rocket (1st stage) (Dreyfuss, 1966)	TSTO 1st	HT	HL	Rocket
1750	37098 (1)	**	Orbiter (Gregory et al., 1971)	TSTO 2nd	HT	HL	Rocket
703	15200 (1)	**	VTO Rocket (2nd stage) (Gregory et al., 1971)	TSTO 2nd	HT	HL	Rocket
1016	20400 (1)	**	NAL Orbiter (Goehlich & Koelle, 2002)	TSTO 2nd	HT	HL	Rocket
136	10665 (1)	**	ASTRO Orbiter (Dreyfuss, 1966)	TSTO 2nd	HT	HL	Rocket
3288	21772 (1)	**	Aztec (2nd Stage) (Kokan et al., 2004)	TSTO 2nd	HT	HL	Rocket
9045	121936 (1)	-	ARTS 3-2 RLV (Wallace et al., 2003)	SSTO	HT	HL	Rocket
2634.4	38123 (1)	-	VTOHL (Parkinson, 1995)	SSTO	VT	HL	Rocket
5029	90517 (1)	-	SSTO-VTHL-R (Sled) (A) (Chase, 1978)	SSTO	VT	HL	Rocket
4555.6	196843.1 (2)	9.0	Air-breather (1st Stage) (Gregory et al., 1971)	TSTO 1st	HT	HL	Airbreathing
7556.1	382243 (2)	10.0	TS-HTHL-TJSJ/R-M10 (F) (1st Stage) (Chase, 1978)	TSTO 1st	HT	HL	Airbreathing
3661.7	78743.6 1 (2)	8.2	Aztec (1st Stage) (Kokan et al., 2004)	TSTO 1st	HT	HL	Airbreathing
1034.5	7892.51 (2)	14.0	Starsaber (1st Stage) (St Germain et al., 2001)	TSTO 1st	HT	HL	Airbreathing
1803.0	15762.31 (2)	14.0	Stargazer (1st Stage) (Olds et al., 1999)	TSTO 1st	HT	HL	Airbreathing
2470.9	136000 (2)	6.0	NAL Booster (Goehlich & Koelle, 2002)	TSTO 1st	HT	HL	Airbreathing
2946.7	177971 (2)	-	LAPCAT A2 (Fusaro, Viola, Ferretto, Vercella, Fernandez Villace, et al., 2020)	HST	HT	HL	Airbreathing
3077.1	158730 (2)	-	LAPCAT MR2.4 (Fusaro, Viola, Ferretto, Vercella, Fernandez Villace, et al., 2020)	HST	HT	HL	Airbreathing
1024.4	26761.91 (2)		SR-71 (Ferretto, 2020)	Military	HT	HL	Airbreathing
4083	178434 (1)	9.04	VTO Rocket (1st Stage) (Gregory et al., 1971)	TSTO 1st	VT	HL	Rocket

1873	70100 (1)	8.48	VTO Rocket (1st stage) (Clegg & Janik, 1967)	TSTO 1st	VT	HL	Rocket
824	17484 (1)	10.8	ASTRO Booster (Root & Fuller, 1963)	TSTO 1st	VT	HL	Rocket
2092	135379 (1)	12.5	SpaceLiner (1st Stage) (Trivailo, 2015)	TSTO 1st	VT	HL	Rocket
124	9700 (1)	**	Falcon 9 (1st Stage) (Koelle, 2013)	TSTO 1st	VT	VL	Rocket
210	11600 (1)	**	HyperNova (1st Stage) (Sorto-Ramos et al., 2020)	TSTO 1st	VT	VL	Rocket

* Not available; ** Not required

TFU Production CER for HTHL Liquid Propellant Rocket First Stage. In order to derive the missing CER for TFU Production cost of a HTHL Liquid Propellant Rocket First Stage, related data available from Table 23 is extracted. (Figure 50). For sake of clarity, the point related to X-15 (not directly reported in Table 23) derives from "TransCost Database". From Figure 50 it can be noticed that the number of available concepts (for which both cost and technical data is available at the required granularity level) is quite limited. For the RLV category under analysis. Moreover, Staging Mach data is very poor so that it is not feasible to explore the influence of Staging Mach onto Production Cost in this case. Indeed, the concept of Staging Mach is not directly applicable to X-15 vehicle, while the related datum is not available for ROT-Rocket (Dreyfuss, 1966).

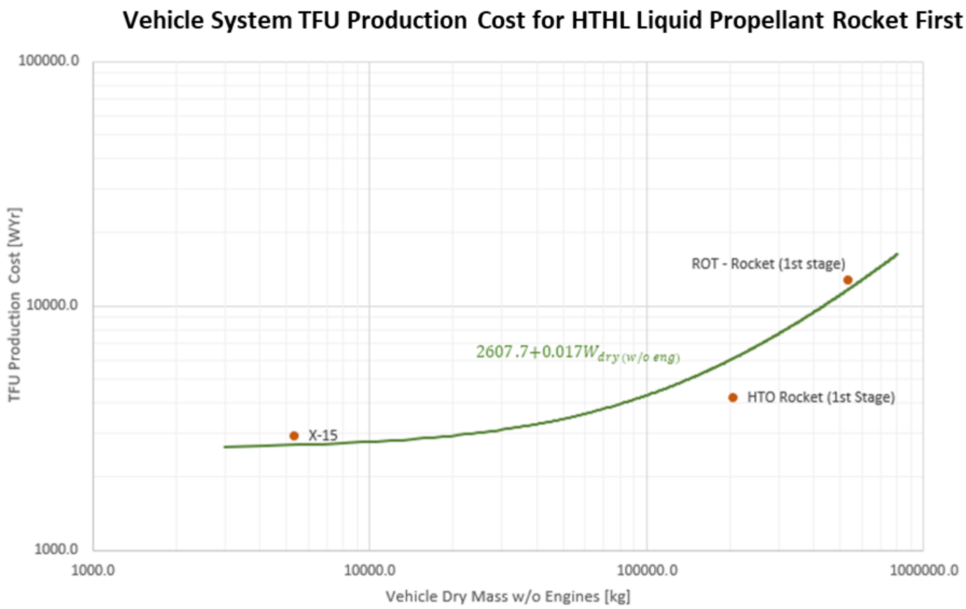


Figure 50: New CER for Vehicle System TFU Production Cost of HTHL Liquid Propellant Rocket 1st Stage

In the framework of Production CERs derivation, it is worth recalling the discussion on data normalization by quantity provided in Section 3.1.1. Notably, RLV production cost data available from literature is typically expressed in terms of Total Production Cost. This means that a certain learning curve factor (i.e., f_4 in Table 7) and a total number of units to be produced are assumed. However, Core Production CERs here considered are based on TFU production cost, so that this information has to be properly extracted from literature data and included in the Updated Database (Table 23). Considering, for example, the reference points for HTHL Liquid Propellant Rocket First Stage, Vehicle System TFU Production

Cost for X-15 and HTO Rocket can be simply extracted, respectively, from (Koelle, 2013) and from (Gregory et al., 1971). Conversely, a TFU Production cost value is not directly provided for ROT-Rocket in (Dreyfuss, 1966), thus it has to be derived from available data. In particular, Table 24 reports production costs for 10th and 40th vehicle unit including engines in M$ FY1966 from (Dreyfuss, 1966). As shown, values are also properly converted to WYr using conversion factors gathered in Section 7.1. Please, notice that ROT-Rocket First Stage Vehicle is equipped with Liquid Propellant Rocket Engines and, specifically, with two H-1 Engines (the same as in S-I Stage of Saturn I) and one F-1 Engine (as in Saturn V First Stage). It is also assumed that 40 First Stage Vehicles (or Boosters) are produced, meaning that 80 H-1 Engines and 40 F-1 Engines are required. Hence, by exploiting available mass data and by applying Eq.(57) by TC, TFU Production Costs for F-1 and H-1 reported in Table 24 can be estimated.

Table 24: ROT – Rocket (1st Stage) Data

ROT – Rocket (1st Stage) Characteristics	
10th Vehicle Production Cost [M$ FY1966]	167
10th Vehicle Production Cost [WYr]	5170
40th Vehicle Production Cost [M$ FY1966]	87
40th Vehicle Production Cost [WYr]	2693
F-1 Engine TFU Cost [WYr] (calc.)	396
H-1 Engine TFU Cost [WYr] (calc.)	127
10th Vehicle (without Engines) Target Production Cost [WYr] (calc.)	4944.2
40th Vehicle (without Engines) Target Production Cost [WYr] (calc.)	2566.6

Subsequently, by assuming a 75% learning curve factor for both engines, the cost of generic ith F-1 unit and jth H-1 can be assessed, along with total production cost for rocket engines. Moreover, it is possible to define **Target Production Costs** for 10th and 40th vehicle units (without engines), respectively, as follows (see results in Table 24).

$$10^{th}\ Vehicle\ (without\ Engines)\ \boldsymbol{Target\ Prod.Cost} = 10^{th}\ Vehicle\ Prod.Cost - (19^{th} + 20^{th}\ H\!-\!1\ Eng.\ Prod.Cost) - (10^{th}\ F\!-\!1\ Eng.\ Prod.Cost) \quad (107)$$

$$40^{th}\ Vehicle\ (without\ Engines)\ \boldsymbol{Target\ Prod.Cost} = 40^{th}\ Vehicle\ \ Prod.Cost - (79^{th} + 80^{th}\ H\!-\!1\ Eng.\ Prod.Cost) - (40^{th}\ F\!-\!1\ Eng.\ Prod.Cost) \quad (108)$$

Please, notice that 19^{th} and 20^{th} H–1 Engine units as well as 10^{th} D–1 Engine unit are installed on the 10^{th} Vehicle unit, whilst 79^{th} and 80^{th} H–1 Engine and 40^{th} D–1 Engine unit on the 40^{th} Vehicle unit.

Thanks to a proper optimization process, a value for Vehicle (without engines) TFU cost can be determined starting from guess values for both Vehicle (with engines) TFU Cost and learning factor. Notably, it can be obtained by imposing, as constraint, minimum difference ($diff$) between 10^{th} Vehicle (without Engines) Production Cost (calculated using guess values for Vehicle (with engines) TFU Cost and learning factor) and 10^{th} Vehicle (without Engines) **Target** Production Cost (datum, from Table 24) as in Eq.(109)..

$$diff = 10^{th}\ Vehicle\ (without\ Engines)\ Prod.Cost\ (\boldsymbol{calc.}) - 10^{th}\ Vehicle\ (without\ Engines)\ \boldsymbol{Target}\ Prod.Cost \quad (109)$$

To minimize $diff$, values for both Vehicle (with engines) TFU Cost and learning factor are modified This optimization process can be carried out using MS Excel Solver Tool and it focuses on re-build the TFU cost (without engines) starting from a known value for the 10^{th} unit (both without engines). However, in order to stick also to the datum for 40^{th} Vehicle Production Cost (without Engines), the learning curve factors applied to engines and vehicle systems (not directly available from (Dreyfuss, 1966)) should be "manually" optimized in order to obtain the lowest difference between 40^{th} Vehicle (without Engines) Production Cost (calculated) and 40^{th} Vehicle (without Engines) Target Production Cost as well (in analogy to Eq.(109)). In account of this, the final suggested TFU cost for ROT-Rocket is 12856.7 WYr as shown in Figure 50. It is highlighted that a similar procedure for Vehicle TFU Production Cost derivation from Total Production Cost has been applied, if required, also to the other cost data in Table 23 in order to set up all information required to perform regression analysis.

Basing on the data for Vehicle Systems (without Engines) TFU Production cost in Figure 50, the regression methodology provided in Section 3.1.1 can be used to derive a set of CERs for HTHL Rocket First Stages according to the CER forms in Table 4. Notably, MBE-ZPB optimization can be implemented in MS Excel and spreadsheets like that already shown in Figure 41 can be set up for each CER form (i.e., Linear, Power, Triad). Please, notice that due to the poor dataset available, only Dry Mass (without engines) dependency can be effectively explored. In account of this, Table 25 summarizes new CERs for the cost item under study. From results, it can be observed that the Linear CER (Eq.(110)) provides best results for all statistical criteria analysed, even if %Std. Error is quite high. Due to lack of the required number datapoints, Triad CER has not been derived. Eq.(110) is graphically shown in Figure 50 and it is suggested for preliminary implementation in HyCost methodology, even if the %Std. Error is not fully satisfactory. In this context, it is strongly recommended to include new points in the database of Figure 50 once, in the future, additional cost estimations coming from new studies would be available.

Table 25: HTHL Rocket First Stage TFU production CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$2607.7+0.017W_{dry(w/o\ eng)}$	Linear	33.33	0.933	(110)
$201W_{dry(w/o\ eng)}^{0.296}$	Power	54.226	0.987	(111)

TFU Production CER for VTHL Liquid Propellant Rocket First Stage. To fill the gap in TC methodology for this cost item, cost data obtained from the additional literature review and collected in Table 23 has been used to derive a dedicated CER through regression analysis. As a result, Table 26 collects the new CERs expressed as a function of Vehicle Dry Mass (without engines). Their quality in terms of R^2 is good for all CERs', even if Standard Error is greater than 20% in all cases. The Linear CER (Eq.(112)) is associated to the lowest Standard Error and highest R^2. Complementary, the new CERs as a function of both Vehicle Dry Mass (without engines) and Staging Mach are gathered in Table 27. In this case, it can be observed that the few available data is not able to model the dependency on Staging Mach, which is not captured in both Linear and Power CERs. Please, note that Triad CERs have not been proposed due to the limited database, not allowing to determine the required number of coefficients. As a result, Eq.(112) in Figure 51 is suggested for preliminary implementation in HyCost.

Table 26: VTHL First Stage TFU Production CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$420.56+0.02W_{dry(w/o\ eng)}$	Linear	23.45	0.850	(112)
$1.55W_{dry(w/o\ eng)}^{0.64}$	Power	24.04	0.814	(113)
$57.24 + 1.25W_{dry(w/o\ eng)}^{0.65}$	Triad	23.87	0.816	(114)

Table 27: VTHL First Stage TFU Production CERs – Dry Mass (without Engines) and Staging Mach dependency

CER	Category	%Std Error	R^2	Eq.
$481.46 + 0.017W_{dry(w/o\ eng)} + 0Mach$	Linear	20.66	0.807	(115)
$1.54W_{dry(w/o\ eng)}^{0.64}Mach^0$	Power	22.84	0.752	(116)

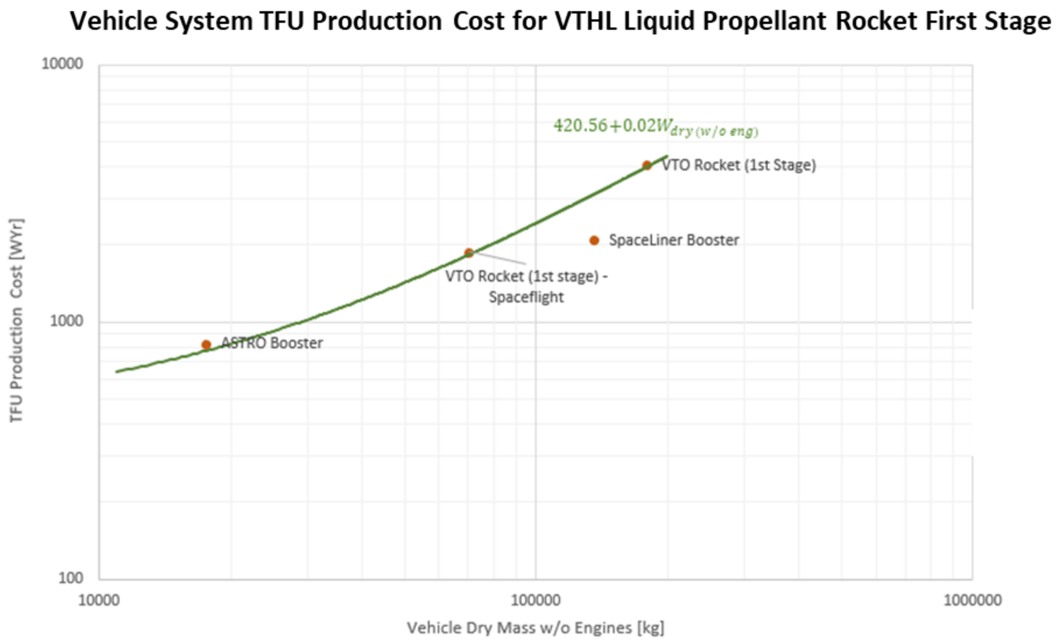


Figure 51: New CER for Vehicle System TFU Production Cost of VTHL Liquid Propellant Rocket 1st Stage

TFU Production CER for HTHL Airbreathing First Stage. With the goal to further specify Eq.(51) provided by TC for HTHL Airbreathing First Stages, the available dataset has been extracted from Table 23. Please, notice that Staging Mach data is applicable only to HTHL Airbreathing TSTO Vehicles, so that a restricted dataset is effectively applicable for analysis on Staging Mach. Therefore, by exploiting the selected regression methodology (Section 3.1.1), a first set of CERs providing the dependence of Vehicle System (without Engines) TFU Production cost on Vehicle Dry Mass is derived (Table 28). Then, an additional set of CERs is obtained by adding Staging Mach in regression analysis (Table 29). From results in Table 28, CERs' quality in terms R^2 is good for all CERs' categories but %Std Error is relatively high in all cases (around 30%). Considering results for regression analysis including Staging Mach as additional cost driver (Table 29), the Power CER (Eq.(121)) has the lowest %Std. Error (lower than %Std. Error of all CERs in Table 28) and highest R^2 value. The Linear CER (Eq.(120)) is not able to capture Mach dependency and associated statistical measures are worst. Eq.(121), graphically shown in Figure 52 is therefore included in new HyCost methodology.

Table 28: HTHL Airbreathing First Stage TFU Production CERs – Dry Mass (without Engines) dependency

CER	**Category**	**%Std Error**	$\mathbf{R^2}$	**Eq.**
$1031.6 + 0.016W_{dry(w/\,eng)}$	Linear	32.63	0.869	(117)
$18.84W_{dry(w/\,eng)}^{0.44}$	Power	31.69	0.769	(118)
$724.44 + 1.022W_{dry(w/\,eng)}^{0.66}$	Triad	33.36	0.821	(119)

Table 29: HTHL Airbreathing First Stage TFU Production CERs – Dry Mass (without Engines) and Staging Mach dependency

CER	**Category**	**%Std Error**	$\mathbf{R^2}$	**Eq.**
$1306.89 + 0.016W_{dry(w/\,eng)} + 0 \cdot Mach$	Linear	34.73	0.911	(120)
$1.55W_{dry(w/\,eng)}^{0.54}Mach^{0.67}$	Power	22.41	0.956	(121)
$1.53 + 10.56W_{dry(w/\,eng)}^{0.5} + 2.24Mach^{1.73}$	Triad 1	49.17	0.876	(122)
$1.55W_{dry(w/\,eng)}^{0.54}Mach^{0.67}$	Triad 2	27.45	0.956	(123)

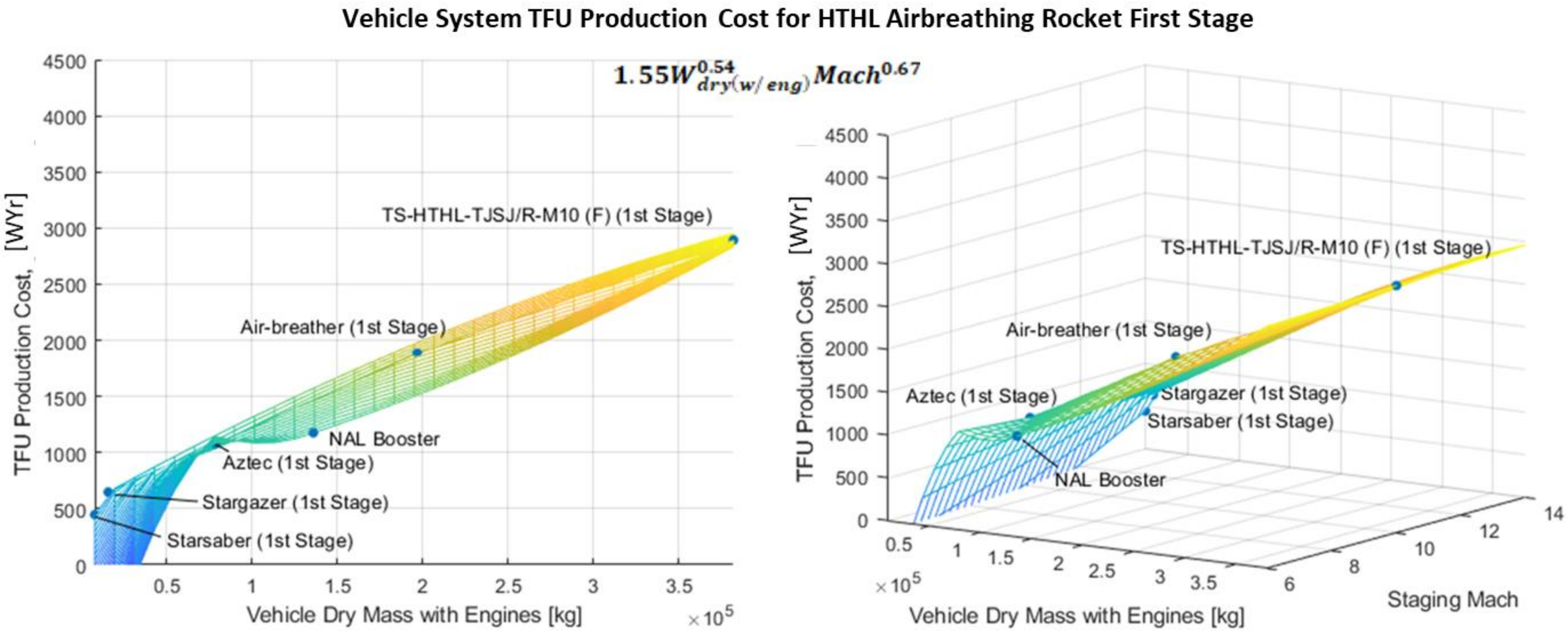


Figure 52: New CER for Vehicle System TFU Production Cost of HTHL Airbreathing First Stage

TFU Production CER for VTVL, VTHL and HTHL Liquid Propellant Rocket SSTO. Dealing with Rocket SSTO vehicles, Figure 53 plots cost data for the additional SSTO concepts resulting from the extensive literature review carried out during this work (Table 23). In the plot, data for VTVL, VTHL and HTHL SSTO vehicles is provided in different colours. From this preliminary analysis based on a restricted number of available concepts, it is not possible to fully appreciate the impact of take-off and landing strategy onto SSTO vehicle TFU Production cost. However, the only point related to a VTVL SSTO (i.e. VTOVL from (Parkinson, 1995) suggests that costs expected for this vehicle category are far above the costs projected by TC CERs for reusable and expendable Ballistic Stages and Vehicles with Storable or Cryogenic Propellants (Eq.(48) and Eq.(49)) as reported in Figure 53.

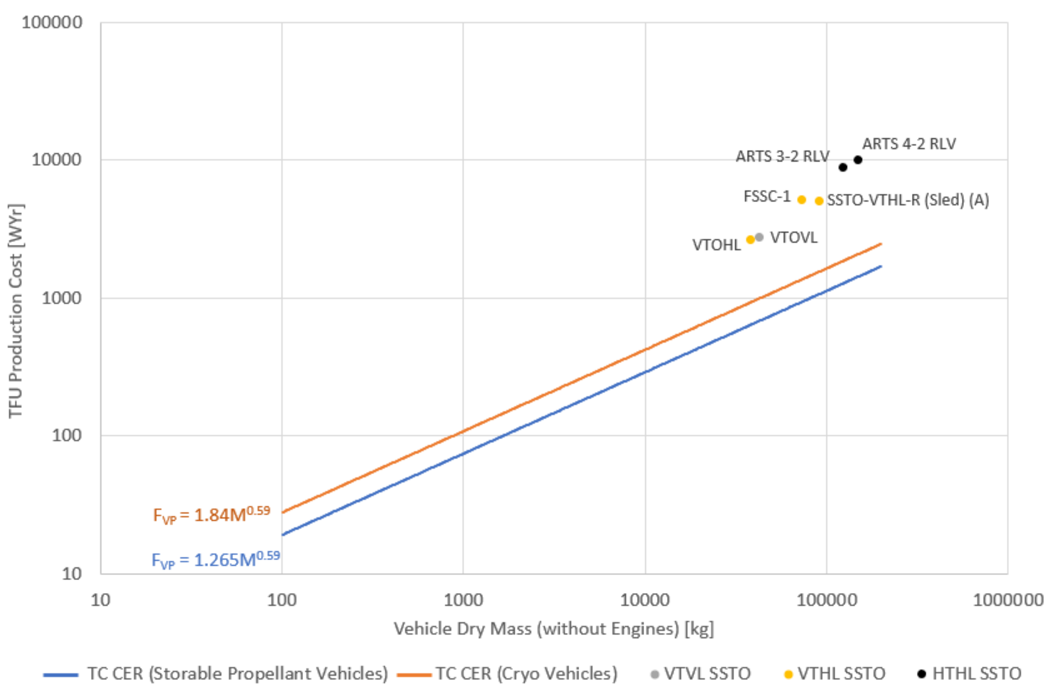


Figure 53: Available TFU Production Cost data for VTHL, VTVL, HTHL Rocket SSTO and comparison with TC CERs

From the analysis here reported, it emerges that the exploitation of Eq.(48) or Eq.(49) to a SSTO vehicle may lead to an underestimation of actual costs. As a result, original TC CERs here mentioned should be applied only to vehicle stages (both expendable and reusable, lacking more detailed data), but dedicated relationships are required for reusable VTVL SSTO vehicles. Similar remarks apply to VTHL and HTHL SSTO vehicles which, as already discussed, are treated by TC as “Winged Orbital Rocket Vehicles” (Eq.(50)), which includes TSTO 2° Stages with HL as well. Notably, the VTHL concept FSSC-1 from FESTIP (mentioned in Figure 10(b)) was considered part of this vehicle category as depicted in Figure 34. At the present stage, due to the limited amount of data available for SSTO concepts, it is not feasible to propose specific CERs for VTVL, VTHL, and HTHL concepts, but a comprehensive and preliminary CER using data from Figure 53 could represent an interesting benchmark for future and more detailed analyses supported by a broader dataset. Therefore, by performing regression analysis on SSTO cost data in Figure 53, the set of CERs function of Vehicle Dry Mass (without Engines) in Table 30 can be obtained. CERs' quality in terms of Standard Error and R^2 is good for all CERs' categories, but the Power CER (Eq.(125)) is associated to the lowest Standard Error and highest R^2. This CER, applicable to VTVL, VTHL and HTHL Rocket SSTO vehicle, is depicted in Figure 54 and it is included in HyCost model.

Table 30: VTVL, VTHL and HTHL Rocket SSTO TFU Production CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$0 + 0.067W_{dry(w/out\ eng)}$	Linear	10.83	0.963	(124)
$0.0495W_{dry(w/out\ eng)}^{1.027}$	Power	10.965	0.963	(125)
$0 + 0.0495W_{dry(w/out\ eng)}^{1.027}$	Triad	12.35	0.963	(126)

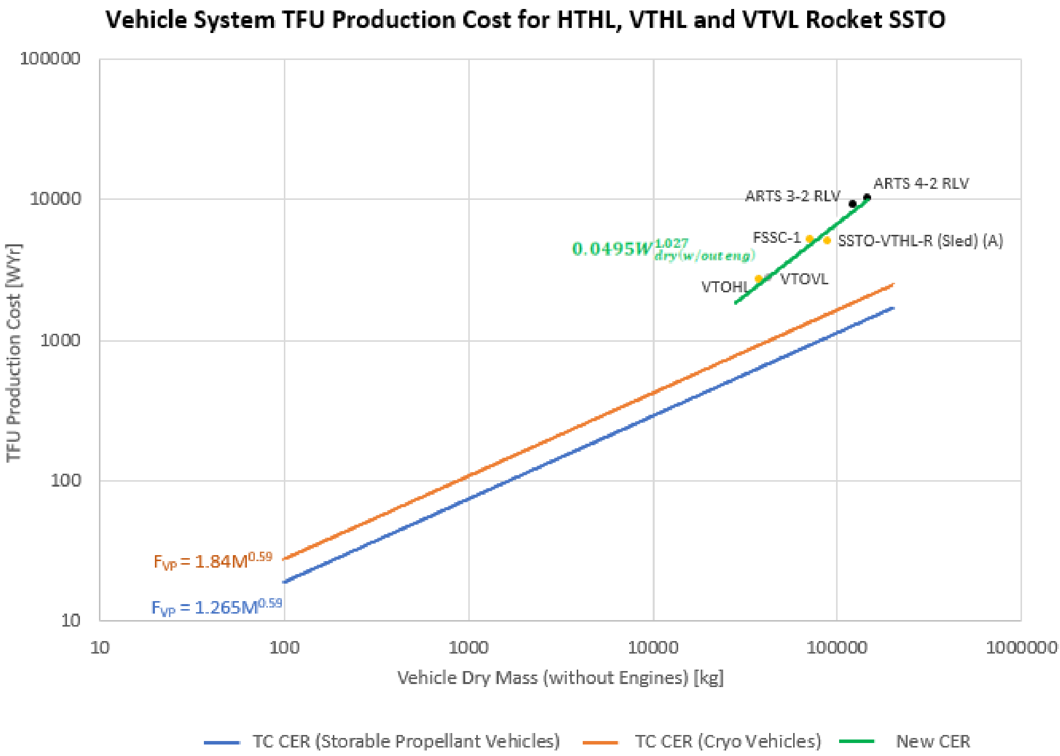


Figure 54: New CER for Vehicle System TFU Production Cost of HTHL, VTHL and VTVL Rocket SSTO with comparison with TC CERs

Figure 55 shows the datapoints available from Table 23 for this cost item, also and including Horus and Hermes as additional concepts using information from (Koelle, 2013). Even if based on very few reference points, the present analysis lays the foundation for an upgrade of original TC CER for Winged Orbital Rocket Vehicles (Eq.(50)) since the cost contribution of a specific vehicle category, i.e., Rocket 2° Stage with HL, is isolated, excluding the impact of SSTO Vehicles. Therefore, considering Vehicle Dry Mass (without Engines) as cost driver (in line with Eq. Eq.(50)), Table 31 collects results from regression analysis. Obtained CERs are characterized by high R^2 and %Std. Error. The latter is mainly related to the scatter of data in Figure 55. Considering statistical performance of Linear Eq.(127) and Power CERs Eq.(128) are quite similar, Eq.(128) plotted in Figure 55 is here preliminary suggested to be added to HyCost model since it is associated to slightly lower %Std. Error. Please, notice that due to the poor amount of data available the analysis with Staging Mach as additional driver is not performed.

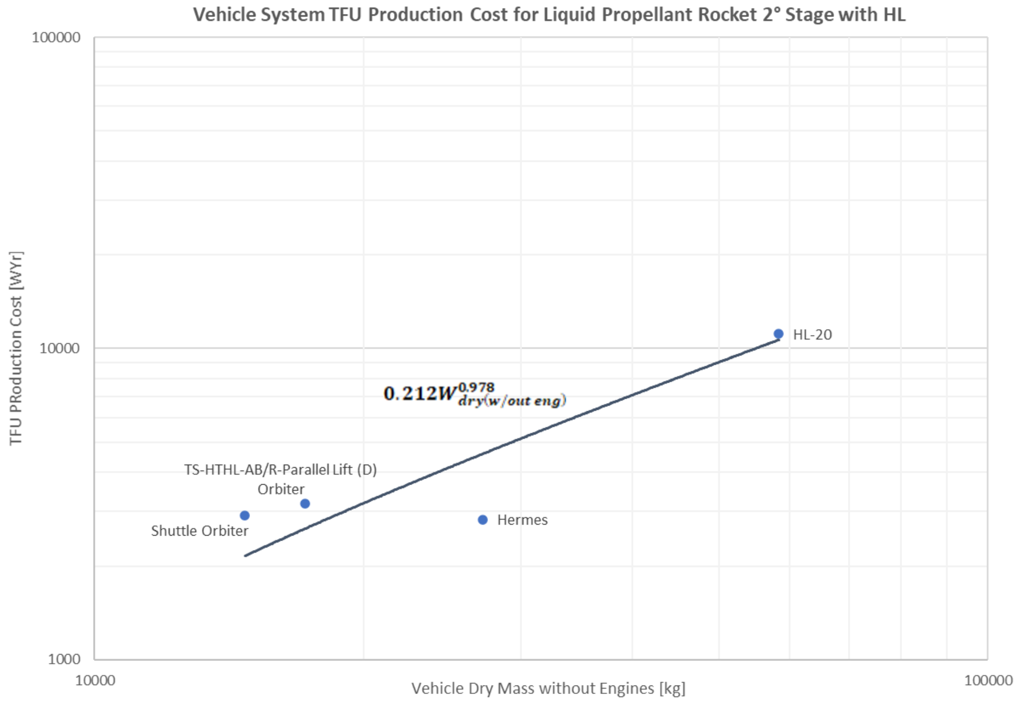


Figure 55: New CER for Vehicle System TFU Production Cost of Liquid Propellant Rocket Second Stage with HL

Table 31: Liquid Propellant Rocket Second Stage with HL TFU Production CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$12.76 + 0.168W_{dry(w/out\ eng)}$	Linear	31.73	0.916	(127)
$0.212W^{0.978}_{dry(w/out\ eng)}$	Power	31.71	0.914	(128)
$0.00013 + 0.212W^{0.978}_{dry(w/out\ eng)}$	Triad	44.843	0.914	(129)

VTVL Liquid Propellant Rocket First Stage. As reported, Eq.(48) and Eq.(49) from TC allow to estimate Vehicle System TFU Production Cost for both reusable expendable VTVL rocket first stages (respectively, with storable and cryo propellant). However, in line with the discussion provided for the corresponding RDTE CER (Eq.(32)), Eq.(48) and Eq.(49) are not actually based on reusable concepts data but their applicability is expended to RLVs by TC. In addition, to the RDTE case, no additional cost data for TFU Production cost of VTVL Liquid

Propellant Rocket First Stages emerged from the extensive literature review performed in this work. As such, the same strategy already adopted to obtain the CERs in Table 21 has been followed. Notably, the original dataset used by TC to derived Eq.(48) and Eq.(49) has been merged, including available data for semi-reusable first stages from Table 23 (i.e., Falcon 9 and HyperNova). Next, regression analysis has been performed basing on this extended database. Results of this study are collected in Table 32, where it can be noticed that %Std in in general higher than 35% in all cases due to the data dispersion. Therefore, the Power CER (Eq.(131)) is selected since it is associated to the lowest %Std and the difference in terms of R^2 with respect to the Linear CER is negligible. Eventually, Eq.(131) is plotted in Figure 56 highlighting the datapoints included in this analysis.

Table 32: VTVL Liquid Propellant Rocket First Stage TFU Production CERs – Dry Mass (without Engines) dependency

CER	Category	%Std Error	R^2	Eq.
$93.20 + 0.024W_{dry(w/out\ eng)}$	Linear	37.79	0.566	(130)
$1.786W_{dry(w/out\ eng)}^{0.584}$	Power	35.26	0.848	(131)
$15.53 + 1.186W_{dry(w/out\ eng)}^{0.622}$	Triad	36.38	0.849	(132)

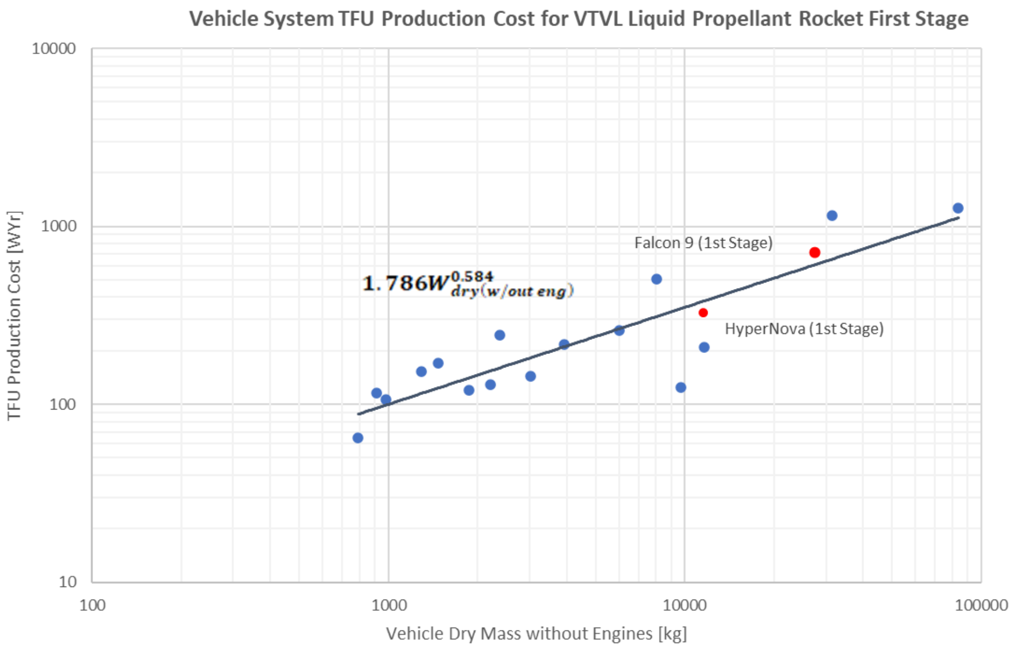


Figure 56: New CER for Vehicle System TFU Production Cost of VTVL Liquid Propellant Rocket First Stage

3.2.3 Operating Cost

3.2.3.1 Summary of HyCost Operating Cost Model

As far as DOC is concerned, as shown in Figure 39, the NASA-modified ATA CERs (Repic et al., 1973) reported in Section 3.1.2.4 can be adopted for High-Speed Transportation (HST), while the TC operations cost model summarized in Section 3.1.2.3 is advised for RLVs. As far as TC model is concerned, suggested figures for propellant price (e.g., fuel/oxidizer and gases cost per kilo) should be updated. In this context, the prices for FY2021 reported in (Sninsky, 2020) should be used. Moreover, for LH_2 price, the exploitation of values suggested by (Fusaro, Vercella, et al., 2020) and mentioned in Section 3.1.2.4 is advised. Concerning Refurbishment and Spares Cost (RSC), TC model is adopted for rocket RLVs, while NASA-modified ATA CERs are again suggested for maintenance cost of advanced airbreathing engines envisaged for both HSTs and RLVs. In addition, it is worth recalling that, due to lack of actual data, only preliminary guidelines are provided in TC for Fees and Insurance Cost. However, thanks to the extensive state-of-the-art analysis carried out in this work, Section 3.2.3.2 will report additional information for Launch Site User Fee found in literature. In addition, a strategy to estimate Insurance Cost for RLVs will be proposed. Eventually, lacking more detailed models for IOC, guidelines from IATA and ICAO reported by (Ferretto, 2020) are suggested for HST vehicles operating in an aircraft-like perspective and the IOC model by TC depicted in Figure 37 is adopted for RLVs.

3.2.3.2 Guidelines for Fees and Insurance Assessment

As described in Section 3.1.2.3, according to TC, main contributions to fees and insurance costs are 1) Launch Site User Fee Cost per Launch, 2) Public Damage Insurance (Third Party Liability), 3) Launch Vehicle Insurance (i.e., Vehicle Loss Charge) and 4) Surcharge for Mission Abort.
Surcharge for Mission Abort is strictly connected to a failure in payload delivering, hence it has to be covered by the launch provider, which should guarantee a free re-launch to the user (Koelle, 2013). Assuming an initial abort rate of 1 out of 30 to 50 flights, then 6 to 3% of the Cost per Flight (CpF) should be taken into account as an add-on charge due to mission abort for each flight (Koelle, 2013). Please, notice that a full definition of CpF is provided in Section 3.2.3.2. Launch Vehicle Insurance strongly depends on RLVs reliability. As such, thanks to the achievement of low failure rates (ideally, 1 failure out 10,000 flights similarly to military aircraft (Koelle, 2013)), this cost item can be drastically reduced in the future. Preliminarily, a Vehicle Loss Charge in the order of 0.1% to 0.2% of Vehicle Recurring Cost (VRC) can be assumed (Koelle, 2013). As defined by (Koelle, 2013), for RLVs VRC includes Vehicle Production Cost Amortization per Flight and RSC per flight. For Launch Site User Fee (applicable only to commercial launches), more recent data (with respect to TC) for Mid-Atlantic Regional Spaceport (i.e., Virginia Spaceport) and Commercial Florida Spaceport is available from literature. In particular, according to (Browder & Newman, 2019), Virginia Spaceport charged about $1.5 million (FY2019) as a launch fee for a medium-class rocket (or about 2% of the total launch vehicle price), while Table 33 refers to “small” orbital flight the “low” and “high” costs per flight for Commercial Florida Spaceport (Futron, 2005). As a result, for Launch Site User Fee cost per Launch assessment it is suggested to assume:

- $1.5 million (FY2019) for medium class vehicle, in line with Virginia Spaceport data;
- 450 k$ (FY2005) for small class vehicle, in line with Commercial Florida Spaceport data.

Table 33: Typical Launch Site User Fees (Low vs High values) at Commercial Florida Spaceport (Futron, 2005)

	Low Cost	**High Cost5**
Suborbital Flights	$50,000	$100,000
Orbital Flights	$200,000	$450,000

In addition, as stated in TC, Launch Vehicle Insurance (also referred as Vehicle Loss Charge) depends on the type of reusable vehicle and the degree of redundancy and advanced technology used. Referring to (Koelle, 2013), it should be in the order of 0.1 to 0.2% of VRC. Basing on the definition of VRC reported above and using a mean value for Vehicle Production Cost, Production Cost Amortization per Flight can be calculated by defining a certain LpA as well as the number of reuses for the vehicle. Then, by adding Refurbishment Cost per flight it is possible to assess VRC per flight and, from that, Vehicle Loss Charge can be calculated as 0.1 to 0.2% of VRC. For Public Damage Insurance, applicable only to commercial launches, the following data from TC (Koelle, 2013) can be used to suggest a preliminary approach for cost assessment:

- For a 100 M$ coverage, the insurance cost is typically in the 100000 $ range per flight;
- For PROTON launches in Kazakhstan, a minimum coverage of 300 M$ is required plus 40M$ for potential damage to launch facility (i.e.,200000 $ per flight);
- For SOYUZ and ZENIT launches the coverage required is 200M$ plus 25M$ for launch facilities and for the smaller Russian launch vehicles 150 M$ plus 5 M$ for launch facilities

The same information is also collected in Table 34, including launch mass data from literature. Values to be assessed in order to derive a complete model are highlighted in yellow.

Table 34: Refence data for Public Damage Insurance (Koelle, 2013)

	Initial Input Available		Final Output Required	
Vehicle	Launch Mass [ton]	Total Insurance Coverage [M$]	Insurance Cost [$/flight]	Insurance Cost per Flight as a % of Total Insurance Coverage
Unknown 1		100	100000	0,1%
PROTON	700	340	200000	0,06%
SOYUZ/ZENIT	480	225		
Unknown 2 (smaller than SOYUZ/ZENIT)		155		

As first step, Launch Mass and Total Insurance Coverage data available for SOYUZ/ZENIT and PROTON can be used to obtain a preliminary correlation between Launch Mass and Total Insurance Coverage as in Figure 57. Using this correlation and the available data for Total Insurance Coverage, it is possible to estimate Launch mass value for Unknown 1 Vehicle (i.e., the vehicle with unknown Launch Mass but characterized by a Total Insurance Coverage of 100M$) and for Unknown 2 Vehicle (i.e., a launch vehicle smaller that SOYUZ/ZENIT vehicle with unknown Launch Mass but characterized by a Total Insurance Coverage of 155M$). Launch mass values estimated for Unknown 1 and Unknown 2 are highlighted in orange in Table 35.

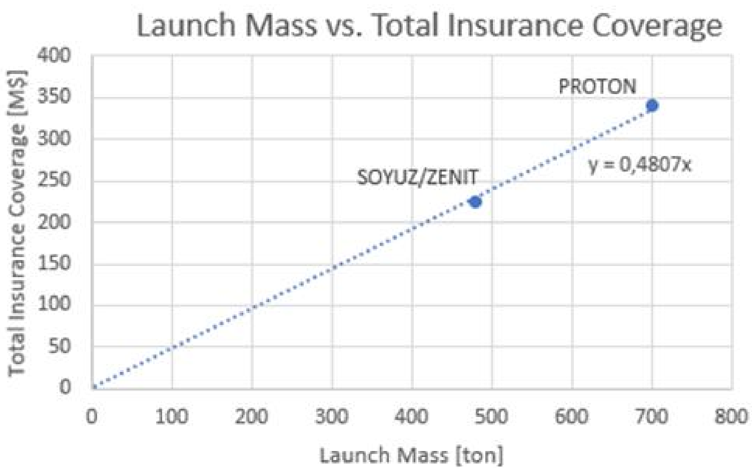


Figure 57: Reference Data used to derive correlation between Launch Mass and Total Insurance Coverage

Table 35: Initial estimation of missing data for Public Damage Insurance Cost Model

			Final Output Required	
Vehicle	Launch Mass [ton]	Total Insurance Coverage [M$]	Insurance Cost [$/flight]	Insurance Cost per Flight as a % of Total Insurance
Unknown 1	208	100	100000	0,1%
PROTON	700	340	200000	0,06%
SOYUZ/ZENIT	480	225		
Unknown 2 (smaller than SOYUZ/ZENIT)	322	155		

Then, thanks to available data for Total Insurance Coverage and Insurance Cost per Flight as a % of Total Insurance Coverage related to Unknown 1 vehicle and PROTON, a correlation between Total Insurance Coverage and Insurance Cost per Flight as a % of Total Insurance Coverage can be derived as shown in Figure 58.

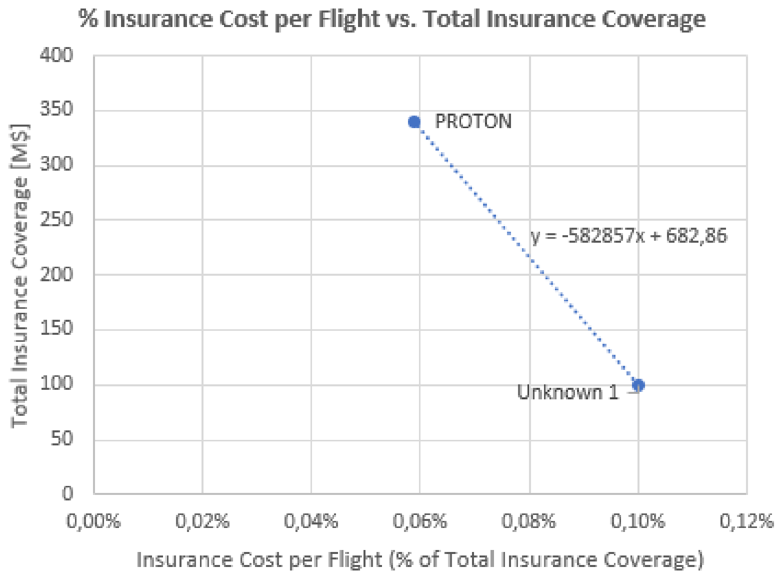


Figure 58: Reference Data used to derive correlation between Total Insurance Coverage and Insurance Cost per Flight as a % of Total Insurance Coverage

Using this correlation and the available data for Total Insurance Coverage, the Insurance Cost per Flight as a % of Total Insurance Coverage for SOYUZ/ZENIT and Unknown 2 can be obtained. The full set of estimated values is highlighted in orange in Table 36. Eventually, considering the generic case in which it is required to assess Insurance Cost per Flight starting from Launch Mass, the flowchart in Figure 59 can be used. Notably: starting from Vehicle Launch Mass, Total Insurance Coverage can be estimated using the correlation in Figure 57. The latter can be then used to estimate Insurance Cost per Flight as a % of Total Insurance Coverage using the correlation in Figure 58 and, eventually, the value for Insurance Cost per Flight.

Table 36: Final estimation of missing data for Public Damage Insurance Cost Model

			Final Output Required	
Vehicle	**Launch Mass [ton]**	**Total Insurance Coverage [M$]**	**Insurance Cost [$/flight]**	**Insurance Cost per Flight as a % of Total Insurance Coverage**
Unknown 1	208	100	100000	0,1%
PROTON	700	340	200000	0,06%
SOYUZ/ZENIT	480	225	176747	0,08%
Unknown 2 (smaller than SOYUZ/ZENIT)	322	155	140375	0,09%

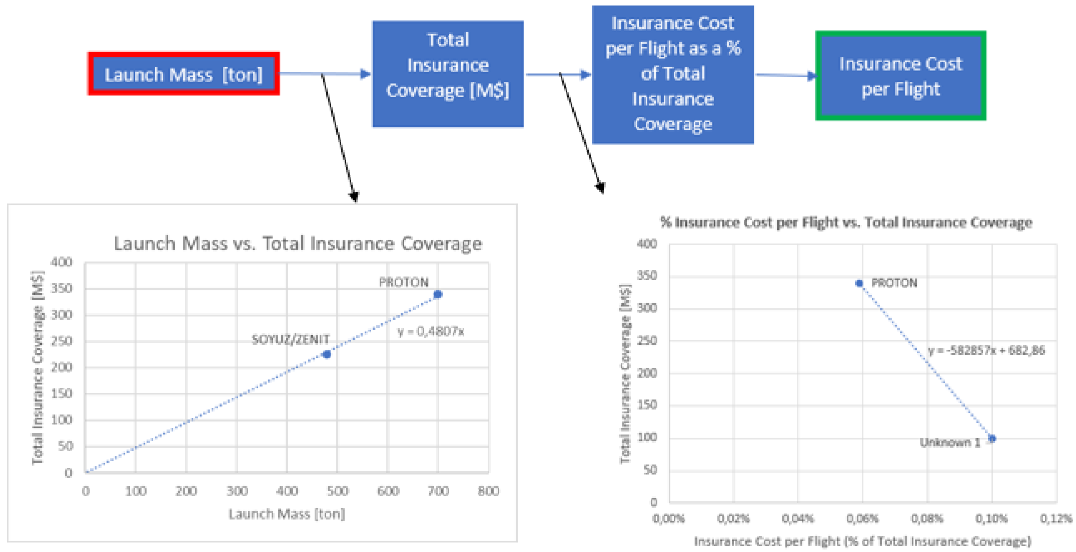


Figure 59: Flowchart for the estimation of Insurance Cost per Flight for a Launch Vehicle with known Launch Mass

3.2.4 CpF, PpF, cost per unit mass of payload and Final LCC Assessment

To complete the description of the cost model proposed in this Dissertation it is important to discuss how obtained cost estimation results can be collected in such a way to ease their subsequent evaluation. At this purpose, the exploitation of the Cost per Flight (CpF) scheme proposed by (Koelle, 2013) is recommended. Please, notice that the CpF is the overall cost sustained by the launch provider to develop, produce, and operate the vehicle. As such, it includes five key elements, i.e., VRC (already mentioned in Section 3.2.3.2), DOC, IOC, business charges and payload insurance. A detailed definition of the cost items included within the CpF scheme is provided in Table 37. Modifications introduced with respect to the original CpF scheme by (Koelle, 2013) are highlighted hereafter. For completeness, Table 37 suggests, for each cost item, the references to be used.

Notably, in order to assess the amortization share of vehicle production cost (cost item [1] in Table 37) a mean value for Vehicle Production Cost should be calculated. This can be performed by applying Eq.(46) and dividing by the total number of vehicle units produced. Then, the obtained mean production cost should be further divided by the number of vehicle reuses to finally obtain the amortization share per flight. Additional guidelines for production cost amortization for RLVs and engines can be found in (Koelle, 2013). As far as far

HSTs are concerned, recalling the definition of depreciation cost provided in Section 3.1.2.4, Eq.(65) can be used to calculate cost item [1] for this vehicle category. Moreover, cost item [2] (i.e., Expendable elements' cost) should be carefully evaluated depending on the specific case study, whilst cost item [3] can be determined using the TC RSC model along with the NASA-ATA equations (Section 3.1.2.3) in order to deal with maintenance cost of high-speed airbreathing engines. The exploitation of NASA-ATA equations was not originally envisaged in the original CpF scheme (Koelle, 2013). Another novelty of the CpF scheme in Table 37 is the inclusion of cost item [7] to take into account the contribution of flight crew cost to CpF (this seems particularly useful for aircraft-like RLVs like the STRATOFLY TSTO introduced in Section 2.2.1). As far as insurance cost is concerned, it is handled by cost items [10] and [11] for RLVs: in this case, guidelines discussed in See Section 3.2.3.2 apply, whilst for HSTs Eq.(64) can be used for a comprehensive insurance cost estimation. For sake of clarity, cost item [12] is not directly tackled in this Dissertation and further studies might focus on the additional fees and taxes expected to impact onto RLVs CpF such as emissions-related fees currently sustained by civil aircraft. Moreover, considering the simple IOC model suggested within this Dissertation (based on Figure 37), the IOC contribution within the proposed CpF scheme is limited to cost items [13] and [14]. In particular, cost item [14] (out of the scope of this Dissertation) represents an annual fee to be further split per each flight. A preliminary estimation of this cost contribution can be derived using (Ebeling, 1993b) and additional guidelines can be found in (Koelle, 2013). Eventually, RDTE cost amortization charge is applicable only in case of commercial development and it aims at recovering the RDTE expenses sustained by the launch provider (no recover of development effort is envisaged in case of governmental funding). Notably, cost item [15] can be determined as a percentage of RDTE as shown in Figure 60 (Koelle, 2013), depending on the total number of launches performed during vehicle life cycle

Table 37: CpF scheme based on (Koelle, 2013)

Major CpF/PpF Element	Cost Item	Cost Item ID	Ref.
VRC	Amortization share of vehicle production cost	[1]	Guidelines in (Koelle, 2013)
	Expendable elements' cost	[2]	Not considered
	RSC/Maintenance	[3]	Eq.(61), (69)-(72)
DOC	Ground Operations cost	[4]	Eq.(59)
	Flight and Mission Operations cost	[5]	Eq.(60)
	Propellants, gases, and consumables	[6]	Eq.(62) + (Fusaro, Vercella, et al., 2020; Sninsky, 2020)
	Flight crew cost	[7]	Eq. (63)
	Ground transportation and recovery cost	[8]	CER from (Koelle, 2013) (not considered)
	Launch site user fee	[9]	See Section 3.2.3.2
	Public damage insurance	[10]	See Section 3.2.3.2
	Mission abort and vehicle loss charge	[11]	See Section 3.2.3.2
	Other charges (taxes fees)	[12]	Not considered
IOC	Commercialization cost	[13]	Figure 37
	Launch site infrastructure O&S (Annual Fee)	[14]	(Ebeling, 1993b)
BUSINESS CHARGES	RDTE cost amortization charge	[15]	Figure 60
	Profit	[16]	To be defined

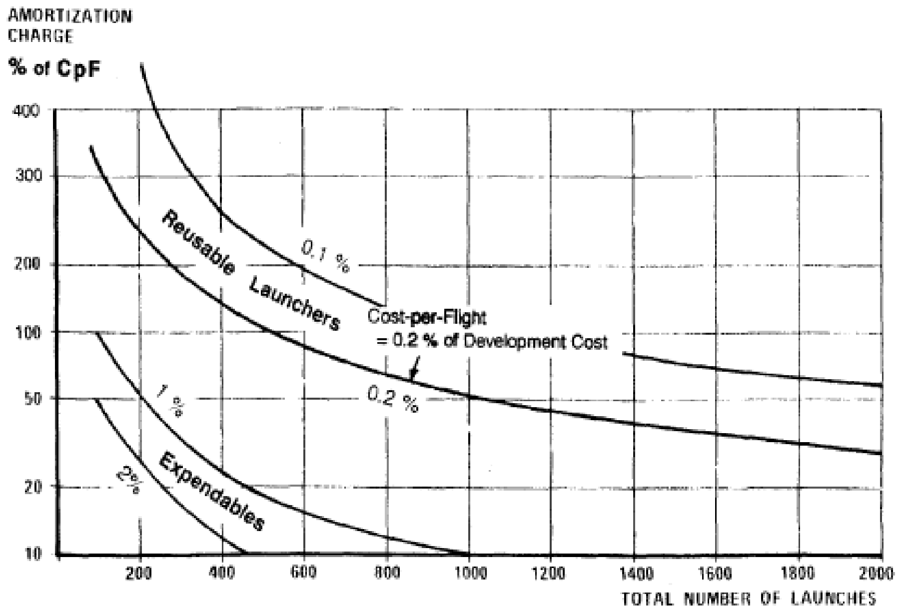


Figure 60: RDTE Cost Amortization Charge per launch as a function of total launches (Koelle, 2013)

Basing on the CpF scheme in Table 37, the total CpF can be derived by summing up all VRC, DOC and IOC contributions as summarized by Eq.(133). By adding business charges to CpF, it is possible to obtain the Price per Flight (PpF) charged by the launch provider to the customer (Eq.134).

$$\text{CpF} = \sum [1]\ to\ [14] \tag{133}$$

$$\text{PpF} = \sum [1]\ to\ [16] \tag{134}$$

In this context, it is also worth highlighting that by dividing the CpF by the payload mass delivered to LEO during each launch, it is possible to obtain the cost per kilo (or per lb) associated to the specific RLV design. This is a cost figure of great interest in the RLV context since it quantifies the cost benefits achieved with respect to ELVs. Past studies (Andrews & Andrews, 2000) established a target of 500 \$/lb (almost 1000 \$/kg) for future RLVs. Nowadays, the achievement of this goal is fast approaching thanks to the development of semi-reusable commercial launch system like Falcon 9 and Falcon Heavy. Indeed, as shown in Figure 61, the shift towards a more "commercial" access to space has allowed significantly reduce launch costs with respect to ELVs. The effective capability of the proposed cost model to reproduce current RLVs CpF will be assessed thanks to the application to the case studies in Section 3.4.

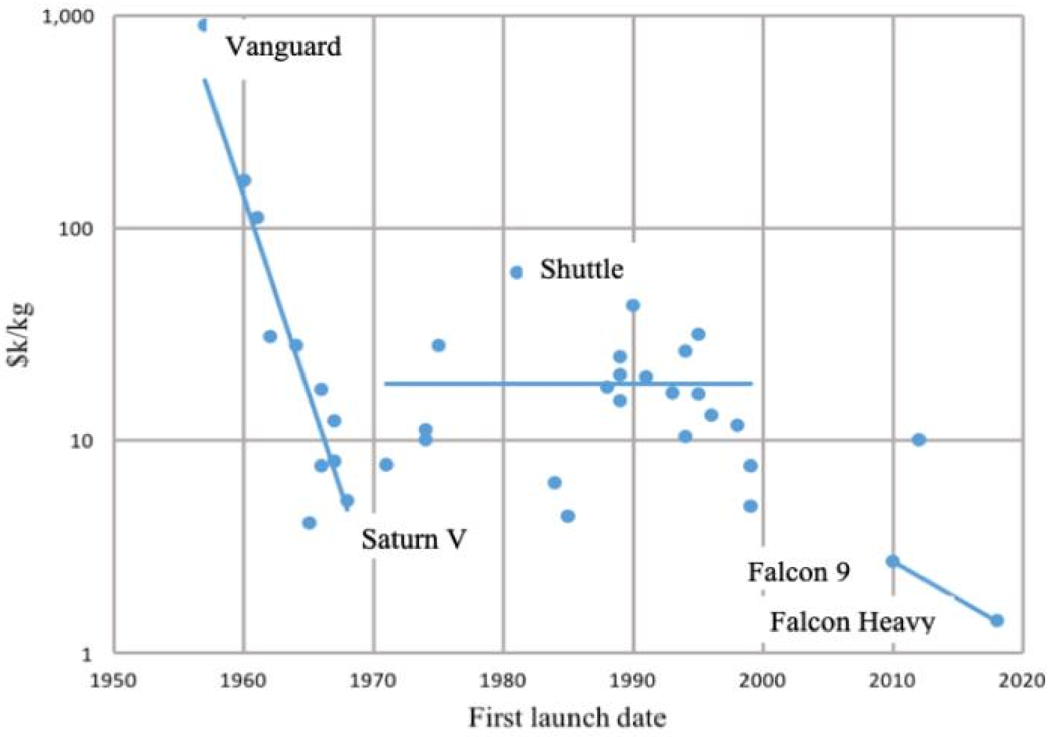


Figure 61:Charge per launch as a function of total Launch cost per kilogram to LEO versus first launch date (Jones, 2018)

Along with the CpF and the cost per kilo, another important output of the cost model is the estimation of the LCC. The latter, as discussed in Chapter 5, will be a fundamental input for final Cost-Effectiveness assessment. Notably, basing on the definitions provided in Section 3.1.1, LCC entails all the costs sustained to develop, produce, and operate a certain system during the overall life cycle. Therefore, as expressed by Eq.(136), LCC is the sum of total RDTE cost ($Total\ RDTE$), total production cost ($Total\ Prod$) and total operating cost ($Total\ Ops$). Please, notice that disposal cost is not considered in the present Dissertation since they are considered negligible compared to the other LCC components.

$$LCC = Total\ RDTE + Total\ Prod + Total\ Ops \tag{135}$$

Please, notice that $Total\ RDTE$ and $Total\ Prod$ can be determined by using, respectively, Eq.(21) and Eq.(46). Moreover, $Total\ Ops$ is the overall DOC and IOC contribution (from the Operating Cost model described in Section 3.2.3) during the overall RLV life-cycle (i.e., all flights performed by all the vehicles produced).

3.2.5 Uncertainty in cost estimation

Section 3.2.4 has focused on the most widespread strategies used to collect the outputs of the cost model. To complete the discussion, it is deemed important to highlight that that these outcomes are highly affected by the uncertainties that characterize the cost estimating process (Fusaro, Viola, et al., 2020; W. Hammond, 1999). As specified in Section 1.3, the cost model described in this Dissertation exploits the results of preliminary and conceptual design activities. In particular, design variables such as vehicle dry mass and Staging Mach are used as cost drivers within the CERs. Recalling the CER forms collected in Table 4, the other major constituents of a CER are the semi-empirical coefficients (also referred as "parameters" in (Fusaro, Viola, et al., 2020)). On these premises, as shown in Figure 62, the uncertainties onto the cost items can be related to (1) uncertainties onto the cost drivers and (ii) uncertainties onto the cost parameters (Fusaro, Viola, et al., 2020). Notably, uncertainties on cost drivers can be easily determined based on the design margins associated to each cost driver. Conversely, the evaluation of uncertainties related to the variation of cost parameters is not straightforward. Indeed, at conceptual design stage, cost parameters are stem from regression analysis performed on a well-defined statistical population. As emerged during the derivation of Vehicle System CERs for Development and Production (respectively, in Section 3.2.1.1 and Section 3.2.2), the statistical population for RLVs (and for HSTs as well) is very limited and, sometimes, already affected by some uncertainties. Therefore, the resulting semi-empirical formulation shall consider not only the nominal trend but also its neighborhood, by defining proper prediction intervals.

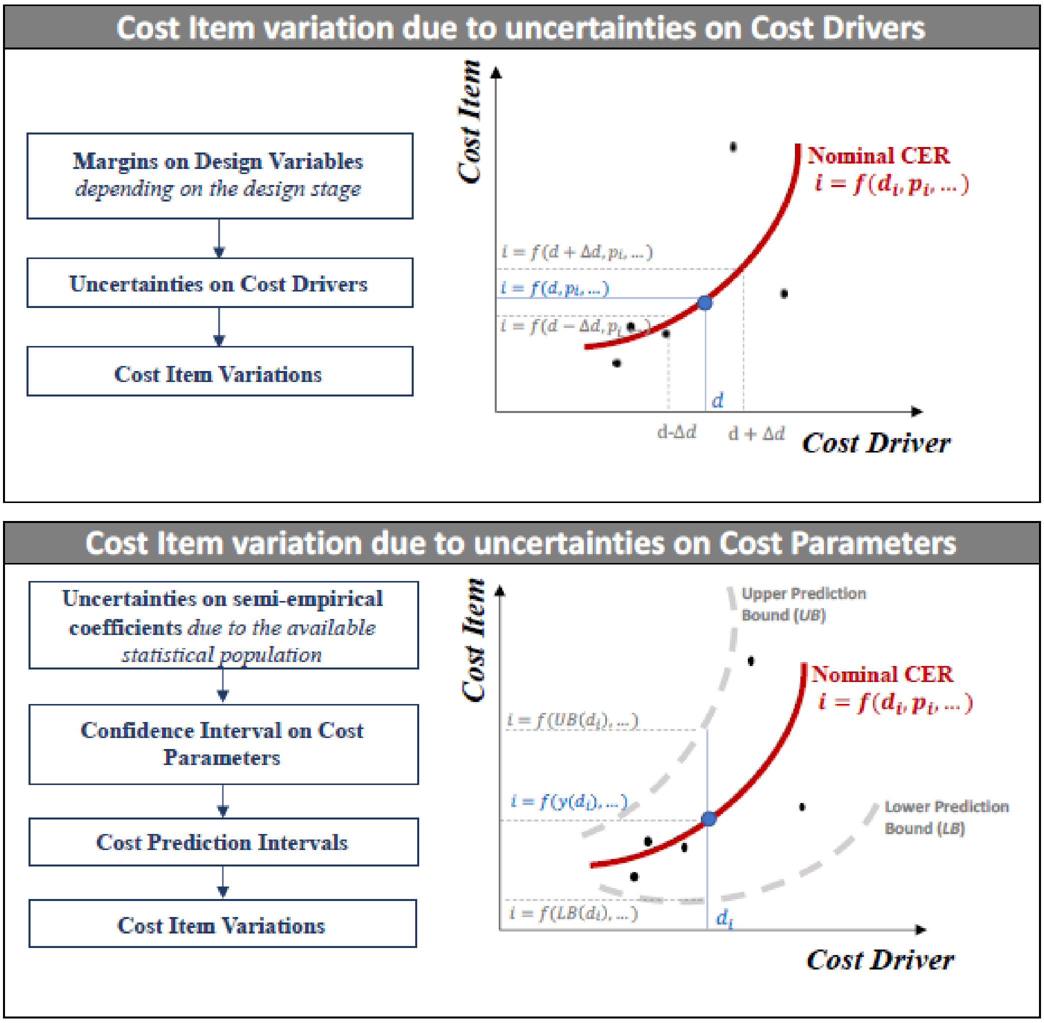


Figure 62: Cost Items variations due to uncertainties on Cost Drivers and on Cost Parameters (Fusaro, Viola, et al., 2020)

As depicted in Figure 62, confidence and prediction bounds set the lower and upper values of an associated prediction interval as well as the width of the interval itself. "*A very wide interval for the fitted coefficients (i.e. a very wide confidence bound) can indicate that more data shall be used during fitting [i.e. regression analysis] to properly definite the set of semi-empirical coefficients*". (Fusaro, Viola, et al., 2020). Please, notice that a noteworthy application of these concepts can be found in (Fusaro, Viola, et al., 2020), providing a thorough analysis of confidence and prediction bounds for a set of HST CERs (similar to those provided by (Ferretto, 2020) and mentioned in Section 3.1.2.3). A similar study can be performed in the future also for the new CERs for RLVs proposed in Section 3.2.1 and in Section 3.2.2.

An alternative (and easier) approach to evaluate the impact of uncertainties onto cost is based on the exploitation of the SE (Section 3.1.1). In this context, it is worth adding that Standard Error (SE or %Std. Error) "*is important in evaluating the ever-present uncertainty in cost estimates and should be applied to CER cost estimates*" (Hammond, 1999). Considering that all the new CERs discussed in this Dissertation have been provided with the %Std. Error, this information can be easily exploited for an initial uncertainty analysis.

3.3 Software implementation

The cost model described in Section 3.2. has been implemented within the open-source Python Qt environment by means of a Graphical User Interface (GUI). The resulting tool (called HyCost) aims at supporting engineers in performing LCC estimation during the conceptual and preliminary design phases. HyCost is based on a tab-oriented architecture, i.e., it consists of several "tabs" or sections enclosed in the same window. Thanks to this well-structured architecture, the tool is compact, straightforward, flexible, and user-friendly. The tab-oriented tool also provides high modularity since it is possible, at any time, to insert a new tab to provide an additional feature. Figure 63, Figure 64 and Figure 65 provide an overview of the key features of the HyCost tool, showing the main tabs to be filled by the user. Please, notice that the tool screenshots provided hereafter show the exploitation of HyCost to the Space Shuttle. The latter was a noteworthy test case used to validate the tool after implementation.

As shown at the top of Figure 63, HyCost implements HST and RLV routines summarized in Figure 39. Please, notice that as mentioned in Section 3.2 only airbreathing HSTs are tackled by the proposed cost model. Therefore, in case of a vehicle concept conceived both as a HST and a RLV (such as the STRATOFLY TSTO described in Section 2.2.1), it is possible to easily switch from a HST to a RLV mission scenario.

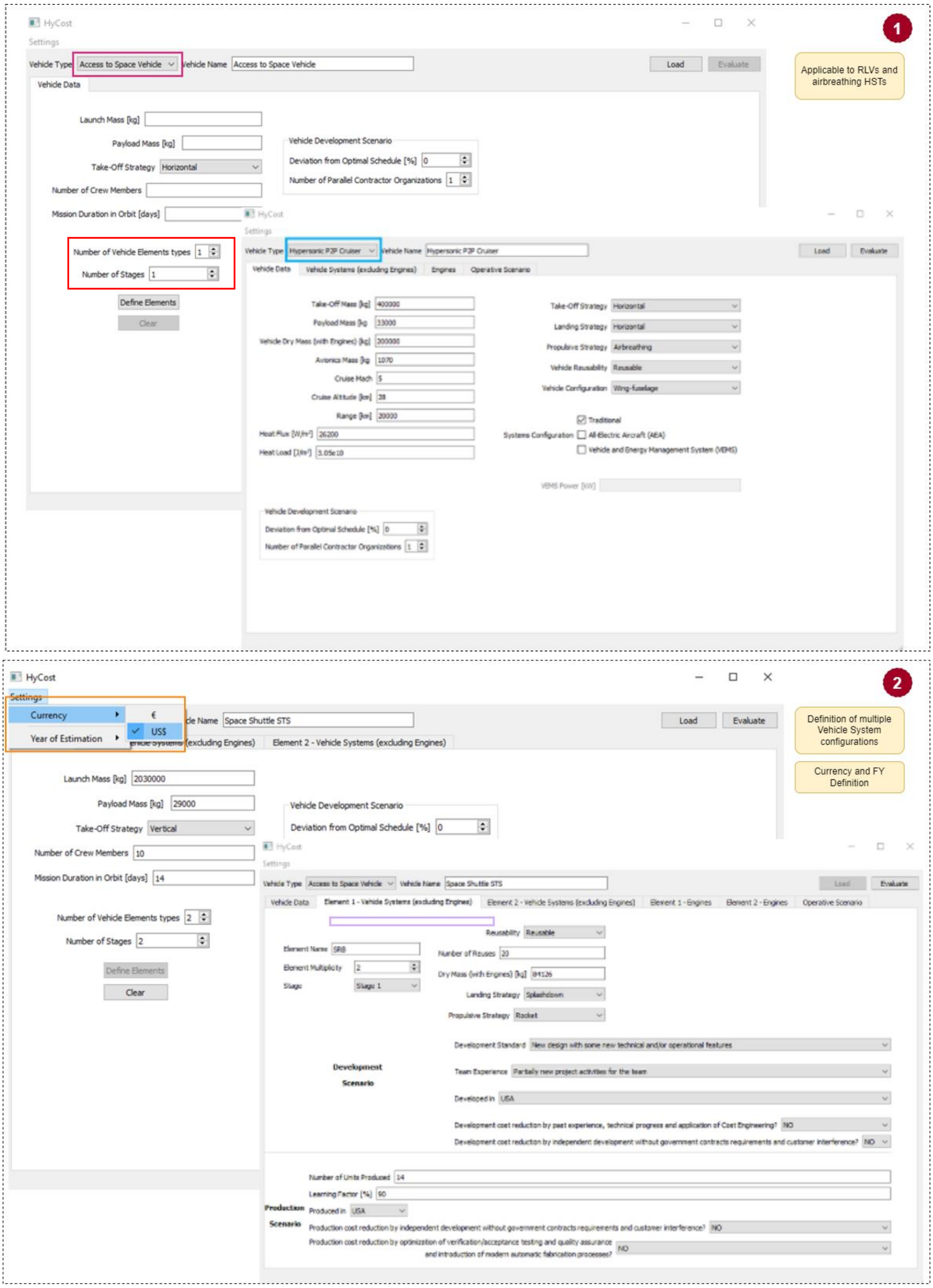
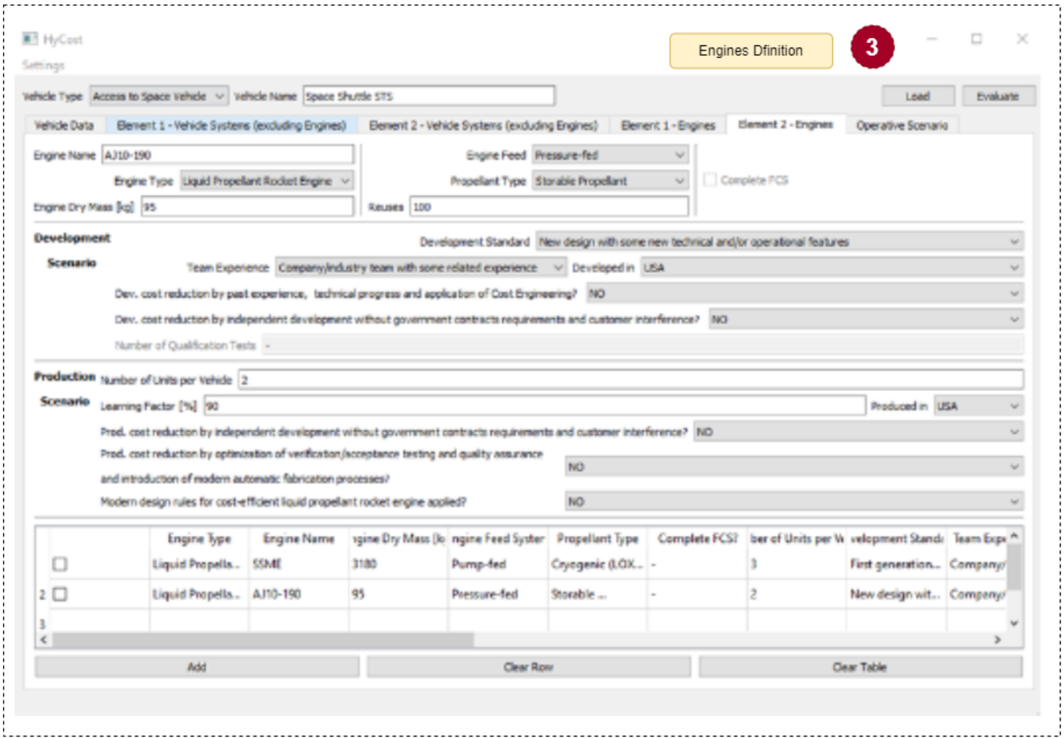


Figure 63: HyCost Tool (1)

Dealing with a RLV, a noteworthy feature of the tool is the possibility to define a vehicle in terms of “Number of Vehicle Elements types” and “Number of Stages” as shown at the bottom of Figure 63. The former allows to preliminary specify the overall vehicle configuration, defining the number of different type of elements constituting the vehicle. Complementary, the input “Number of Stages” allows to define the number of “groups” in which the specific element types are gathered. Please, notice that this feature has been introduced within the tool to model complex RLV systems like the Space Shuttle as well as more conventional SSTO and TSTO designs. Indeed, excluding the External tank (indeed, it is a one-of-a-kind system which cannot be handled with available CERs), the Space Shuttle can be modeled as constituted by two element types, the SRB (x2) and the Orbiter (i.e., three elements in total). These elements are supposed to be grouped in two stages (i.e., SRBs constitute the first stage and the Orbiter the second stage). This distinction is fundamental for the tool to determine, for example, the exact number of units (for each element type) to be produced. However, in case of SSTO and TSTO vehicles, the definition of elements and stages is more straightforward since they are constituted by one (or two) elements coinciding with the stages. Thanks to this preliminary description, it is possible to appreciate its great flexibility of the tool in terms of vehicle configuration definition. Moreover, as depicted in Figure 64, HyCost allows to define the engines types installed on each vehicle element with related characteristics (entailing both airbreathing and rocket engines) as well as all the inputs required by the Operating Cost Model (Section 3.2.3) to define the Operative Scenario of the RLV.

Eventually, after running the tool with the inputs specified in the previous tabs, additional tabs are generated to show the final outputs of the cost estimation. Notably, as shown in Figure 65, along with summary tables with RDTE, Production, DOC and IOC, a graphical summary of the main outputs is also provided.



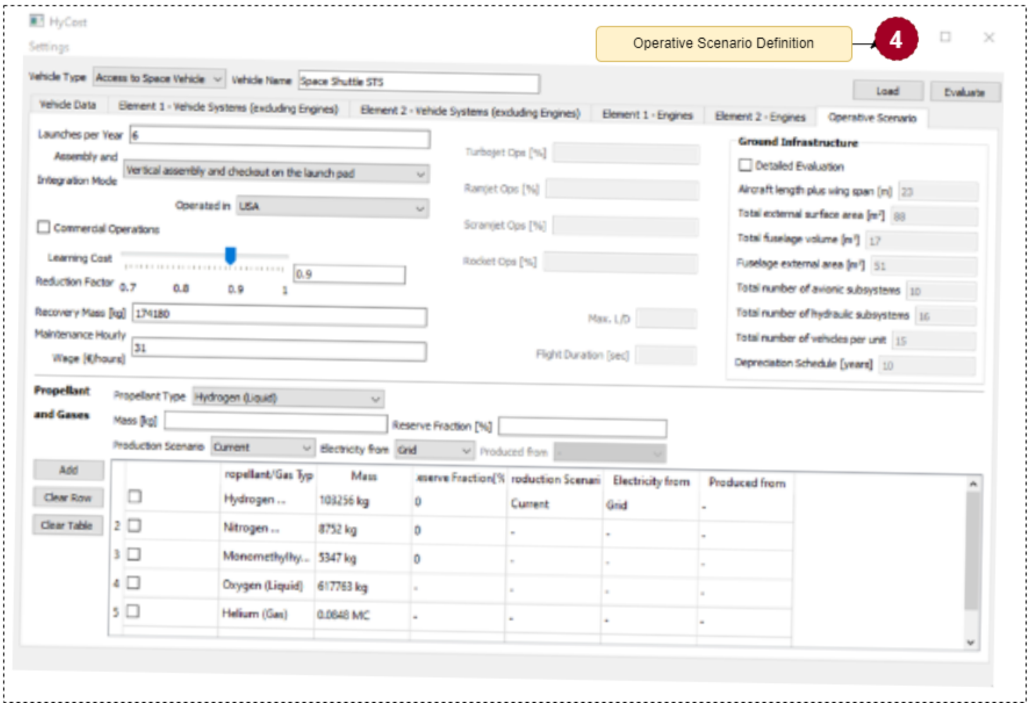


Figure 64:: HyCost Tool (2)

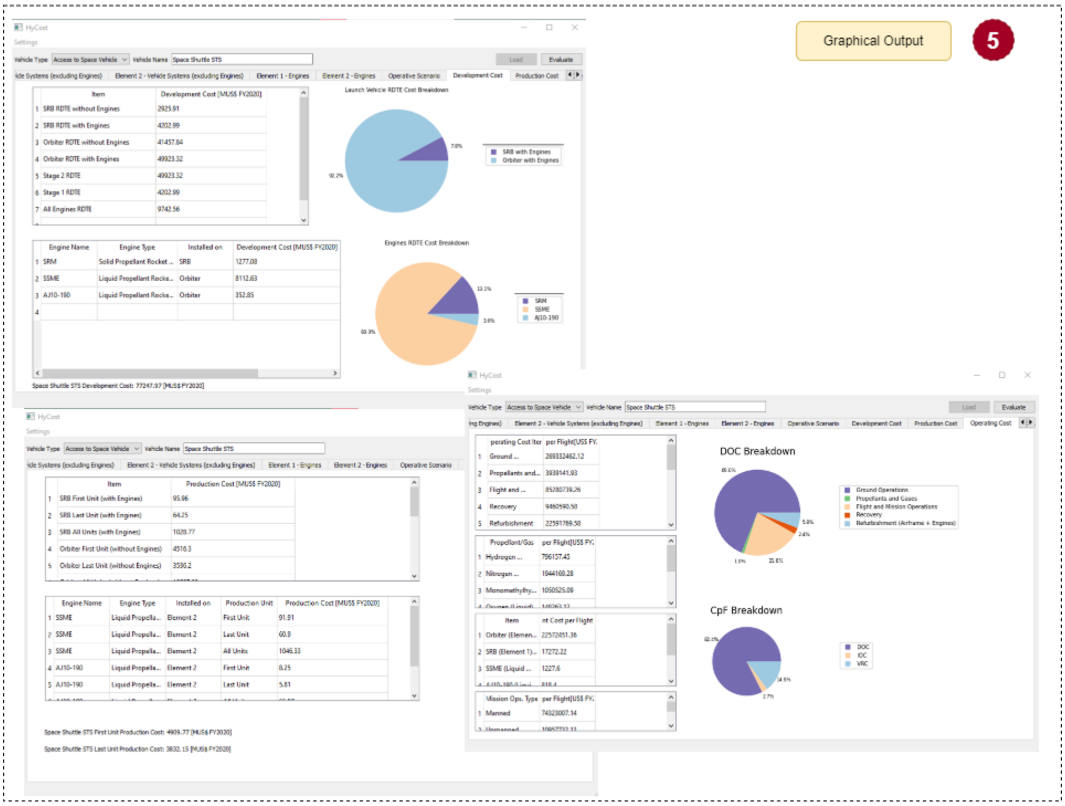


Figure 65: HyCost Tool (3)

3.4 Application to the Case Studies

This Section describes the application of the cost model presented in Section 3.2 to the case studies described in Section 2.2. Notably, RDTE, Production and Operating Costs are assessed and then compared to available cost estimations to validate the proposed CERs. Moreover, an overall LCC analysis for each case study is performed with the aim to derive all the inputs required the final Cost-Effectiveness assessment presented in Section 5.5. In particular, Section 3.4.1 deals with the STRATOFLY TSTO vehicle (i.e., Case Study 1), whilst Section 3.4.2 provides a cost assessment for SpaceX Starship (i.e., Case Study 2).

3.4.1 Case Study 1

As discussed in Section 2.2.1, the STRATOFLY TSTO is a new air-launched vehicle concept preliminary investigated within this Dissertation. Notably, it is based on a slightly modified version of the STRATOFLY MR3 (Viola et al., 2021) for the first stage, whilst the CARGUS expendable rocket already proposed for the Sänger II (Koelle & Kuczera, 1989) is envisaged as upper stage. Therefore, recalling the RDTE and Production Costs subdivision previously discussed, the following elements are herein tackled:

- Vehicle Systems (without engines): modified version of STRATOFLY MR3 (referred as STRATOFLY MR3-modified) and CARGUS;
- Engines: ATR and DMR (on-board the STRATOFLY MR3 Cruiser) and HM/60 Vulcain Engine (for CARGUS).

Notably, STRATOFLY MR3-modified is modelled as a fully reusable HTHL airbreathing first stage vehicle, while CARGUS as an expendable rocket vehicle.

On this basis, Section 3.4.1.1 and Section 3.4.1.2, respectively, deal with RDTE and Production Cost assessment, whilst Section 3.4.1.3 tackles Operating Cost. Eventually, Section 3.4.1.4 provides a summary of CpF, cost per kilo and LCC for the vehicle. For sake of clarity, with reference to the f_8 coefficient defined in Section 3.1.2.3 (and identifying the region in which development and production activities related to the vehicle are performed), a European scenario is assumed taking into account that STRATOFLY TSTO is based on a European concept. Therefore, for all CERs entailing f_8, a value of 0.86 (as in (Koelle, 2013)) is used.

3.4.1.1 Development Cost

As far as RDTE cost is concerned, the CERs collected in Table 38 are exploited. For sake of clarity, no RDTE effort is envisaged for the HM 60 Vulcain engine installed on the CARGUS since its development was already pursued in the framework of the ARIANE 5 activities (Borromee & Thevenot, 1986).

Table 38: Summary of RDTE CERs for STRATOFLY TSTO

Element	**Equation**
STRATOFLY MR3-modified	(84)
CARGUS	(32)
ATR	(36)
DMR	(35)
HM 60 Vulcain	N/A
Vehicle with Engines	(21)

Main inputs required by the CERs for Vehicle Systems in Table 38 are summarized in Table 39. Notably, values for design parameter (i.e., dry masses and Staging Mach) are the same already reported in Section 2.2.1. Lacking specific data about the CARGUS dry mass, it has been assumed equal to the net mass provided in Figure 19 as a first approximation. In addition, the f_i factors have been assumed considering the guidelines provided by (Koelle, 2013). Further details about the definition of the f_9 factor shown in Table 39 are provided in Section 3.4.2, while the value for f_2 derives from Eq.(26) assuming $\varepsilon = 0.0857$ from CARGUS characteristics and $\varepsilon^* = 0.1027$ using a dedicated chart with a reference statistical population from (Koelle, 2013) (see Section 3.1.2.3 for further details). The high f_2 value obtained indicates that a development cost increase (with respect to similar state-of-the-art concepts) is expected for CARGUS since it is more technologically advanced. Notably, the lower net mass fraction (ε^*) with respect to state-of-the-art (ε^*) allows to carry more payload but requires more advanced (and costly) technologies.

Table 39: Inputs for Vehicle System RDTE CERs - STRATOFLY TSTO

	Input Value for	
Input	**Modified STRATOFLY MR3**	**CARGUS**
Dry Mass with Engines [ton]	186	6
Dry Mass without Engines [ton]	-	4.8
Staging Mach	7.38	-
		-
f_1	1.3	0.8
f_2	N/A	1.436
f_3	0.9	
f_9	0.86	
f_{10}	0.75	
f_{11}	0.45	

In addition, inputs for engine-related CERs are gathered in Table 40. Please, notice that design data for ATR and DMR engines derive from (Ferretto, 2020). For sake of clarity, the maximum speed associated to ATR in Table 40 corresponds to Mach 8 (i.e., the maximum Mach achieved by the original

STRATOFLY MR3). As clarified below, this assumption will allow to better align the cost estimation performed in this work with previous results by (Ferretto, 2020). In addition, the values for f_i factors are based on the definitions from (Koelle, 2013). Furthermore, Table 41 collects the inputs required to assess total RDTE cost by means of Eq.(21). For simplicity, no deviation for optimal schedule (f_6) and one major contractor (f_7) are assumed.

Table 40: Inputs for ATR and DMR Engines

Input	Input Value	
	ATR	**DMR**
(One) Engine Dry Mass [kg]	4000	1400
Maximum Speed [m/s]	2487	-
f_1	1.2	1.4
f_3	0.9	1.4
f_9	1	
f_{10}	0.75	
f_{11}	0.45	

Table 41: Inputs for total RDTE cost

Input	Input Value
N	2
f_0	1.0816
f_6	1
f_7	1

Eventually, Table 42 collects the results from the application of the RDTE CERs in Table 38. For sake of clarity, both governmental and commercial scenarios are reported for all Vehicle Systems and engines under consideration. Notably, the lower costs expected for the commercial scenario (confirmed in (Jones, 2018; D. E. Koelle, 2013) are obtained from the governmental scenario by applying the f_{10} and f_{11} factors reported in Table 39 and in Table 40.

Table 42: RDTE cost results for STRATOFLY TSTO

	Governmental Scenario		Commercial Scenario	
Element	**WYr**	**B€ [FY2021]**	**WYr**	**B€ [FY2021]**
STRATOFLY MR3 -modified (without engines)	55,096.23	21.27	18,594.98	7.18
CARGUS (without engines)	8,315.51	3.21	2,806.48	1.08
ATR	17,296.92	6.68	5,837.71	2.25
DMR	5070.96	1.96	1711.45	0.66
HM 60 Vulcain	0	0	0	0
Total	**92,779.25**	**35.82**	**31,312.10**	**12.09**

In Figure 66 obtained results for the first stage of the STRATOFLY TSTO are compared with the costs for the STRATOFLY MR3 (in its original version) reported by (Ferretto, 2020) for a governmental scenario. To exclude the effect of inflation, the comparison is performed using WYr costs. At this purpose, cost values from (Ferretto, 2020) (originally reported in M€ for FY 2017) are converted to WYr. From Figure 66 it can be noticed that results are basically in line with the reference. The small deviation for ATR and DMR costs (even if Eq. (35) and Eq. (36) were applied also by (Ferretto, 2020)) is probably due to the fact that in the original reference the exact values used for the f_i factors are not reported, so that the values assumed in this work have been tuned to align results. To further decrease the deviation from the reference, as mentioned, the maximum velocity achieved by the STRATOFLY MR3 (not modified) at Mach 8 has been used in Eq. (36) (instead of the value associated to Mach 7.38) It is also worth mentioning that another potential source of deviation could lie in the WYr conversion factors adopted. Indeed, a conversion factor from WYr to € FY2017 is not reported in (Ferretto, 2020), so that the conversion factor reported in Section 7.1 (derived in this work) has been used. Apart from this, it is interesting to notice that also the RDTE result for the STRATOFLY MR3-modified (without engines) derived from Eq.(84) slightly deviates from the value for STRATOFLY MR3 by (Ferretto, 2020) stemming from Eq.(29). Therefore, thanks to the newly developed CER specifically tailored for airbreathing first stage vehicles it is possible to derive the delta RDTE cost required to convert an airbreathing HST into a RLV first stage (almost 1 B€).

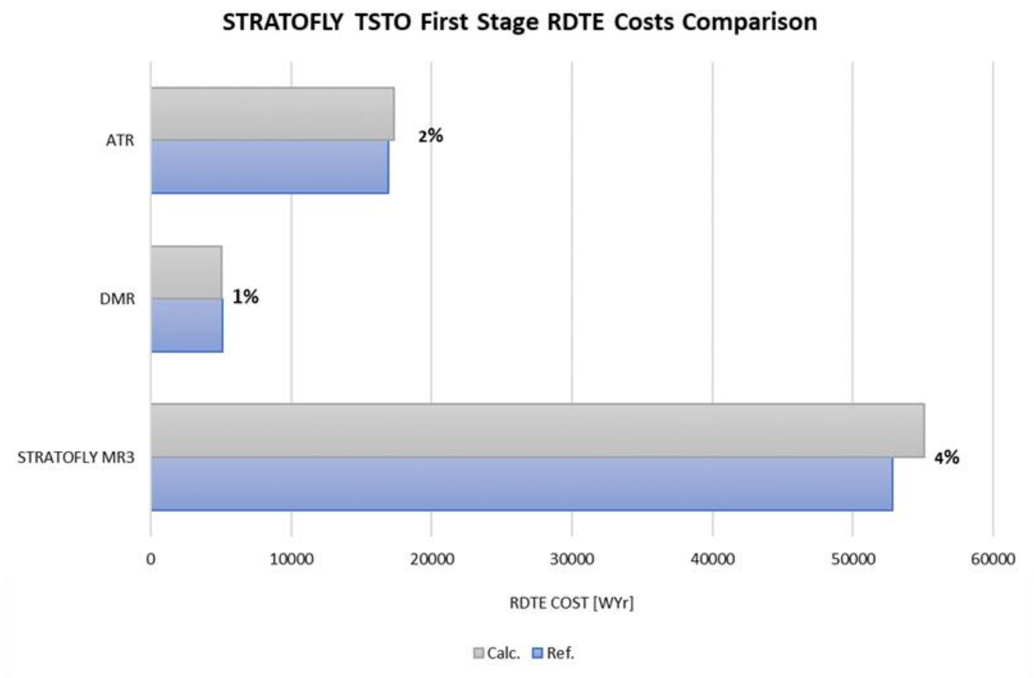


Figure 66: RDTE results comparison with reference for STRATOFLY TSTO First Stage

As far as CARGUS is concerned, a RDTE cost estimation is not available from literature. Indeed, available cost data for Sänger focuses on the configuration with HORUS. However, a preliminary comparison of results for CARGUS with available data for expendable stages is provided in Figure 67. In particular, the dataset used in TC to derive Eq. (32) along with CARGUS predicted RDTE cost. From results, it can be noticed that the CARGUS estimated cost is slightly lower than the cost of state-of-the-art expendable stages. This might be strictly related to the assumption that CARGUS development could highly benefit of the heritage from ARIANE (through $f_1$and f_3 factors).

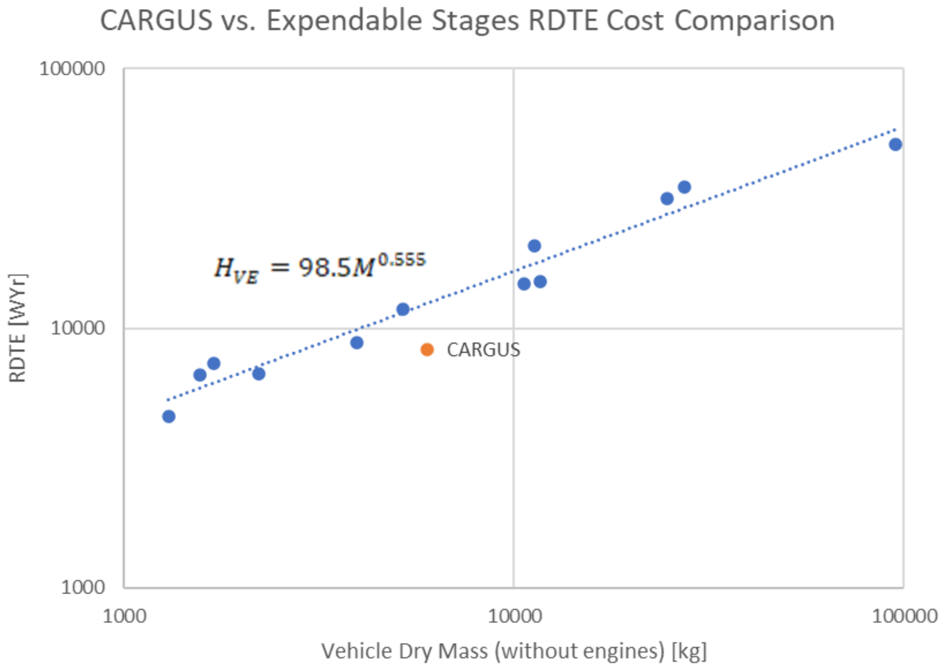


Figure 67: RDTE results comparison with reference for STRATOFLY TSTO Second Stage

3.4.1.2 Production Cost

For TFU Production Cost assessment, the CERs collected in Table 43 are used. Required inputs can be found in Table 39 and Table 40. Additional inputs are also collected in Table 44.

Table 43: Summary of TFU Production CERs for STRATOFLY TSTO

Element	**Equation**
STRATOFLY MR3-modified	(121)
CARGUS	(49)
ATR	(54)
DMR	(55)
HM 60 Vulcain	(56)

Table 44: Additional inputs required for TFU Production CERs

Input	Value
Modified STRATOFLY MR3 Maximum Altitude [km]	31
Modified STRATOFLY MR3 Maximum Speed [m/s]	2265
Number of ATR Engines per Vehicle (First Stage)	6
Number of DMR Engines per Vehicle (First Stage)	1
Vulcain Engine Dry Mass [kg]	1200
Number of Vulcain Engines per Vehicle (Second Stage)	1
DMR Engine Thrust [kN]	5000
f_{10}'	0.7
f_{11}'	0.5

Eventually, Table 45 gathers the results from the application of the TFU Production CERs in Table 43 to both governmental and commercial scenarios for all Vehicle Systems and engines under consideration. In analogy with RDTE costs, the f_{10}' and f_{11}' factors defined in Table 7 are used to model a commercial scenario. Assumed values are collected in Table 44.

Table 45: TFU Production cost results for STRATOFLY TSTO

	Governmental Scenario		Commercial Scenario	
Element	WYr	M€ [FY2021]	WYr	M€ [FY2021]
STRATOFLY MR3 - modified (without engines)	3564.22	1375.97	1247.48	481.59
CARGUS (without engines)	235.10	90.76	70.76	27.32
ATR	206.61	79.76	72.31	27.92
DMR	95.42	36.83	33.40	12.89
HM 60 Vulcain	45.82	17.69	22.91	8.85
First Stage (First Unit)	4595.54	1774.12	1608.44	620.94
Second Stage (First Unit)	280.92	108.45	93.67	36.16
TSTO Vehicle (First Unit)	5173.44	1997.21	1805.77	697.12

For completeness, Table 45 also shows TFU Production Costs for First, Second Stage and for the overall TSTO vehicle. These values derive from the application of Eq.(46) considering only first units' costs. Please, notice that the First Stage TFU includes the first batch of six ATRs produced.
As performed for RDTE cost results, Figure 68 compares obtained results for the first stage of the STRATOFLY TSTO with the costs for the STRATOFLY MR3 (original) reported by (Ferretto, 2020) for a governmental scenario. From comparison, good alignment of results for ATR and DMR can be observed. In this case, the deviation is merely associated to the WYr conversion factor adopted (see the discussion in Section 3.4.1.1 on this topic). The higher percent difference with respect to the reference is also because TFU Production costs are much lower in absolute value than RDTE costs, so that small deviations have a higher impact. For the second stage, data from (Koelle, 1989) can be used to evaluate obtained results considering the governmental scenario. Notably, Figure 69(a) and Figure 69(b) highlight, respectively, the TFU Production Cost for CARGUS and for the HM 60 Vulcain engine. For CARGUS, a TFU Production cost of almost 200 Man-Years (MY) (i.e., WYr) is suggested. This is perfectly in line with the 235.10 WYr from Table 45. For the Vulcain engine, around 90 WYr are envisaged for TFU Production, almost twice the value provided in Table 45. This huge difference can be explained by considering that the TFU Production of H 60 Vulcain engine has been calculated using Eq. (56), which is specifically tailored for modern rocket engines, while a state-of-the-art production approach is assumed in Figure 69(b). However, the exploitation of Eq. (56) in this work seems more appropriate since the present application refers to a rocket engine produced in the future, so that improvements with respect to the original H 60 Vulcain can be expected.

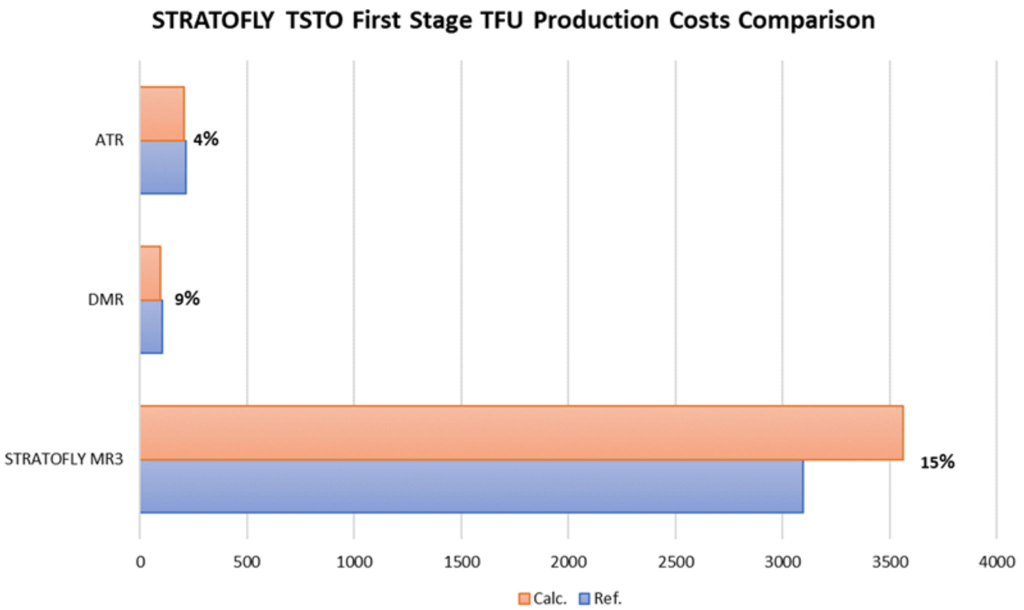
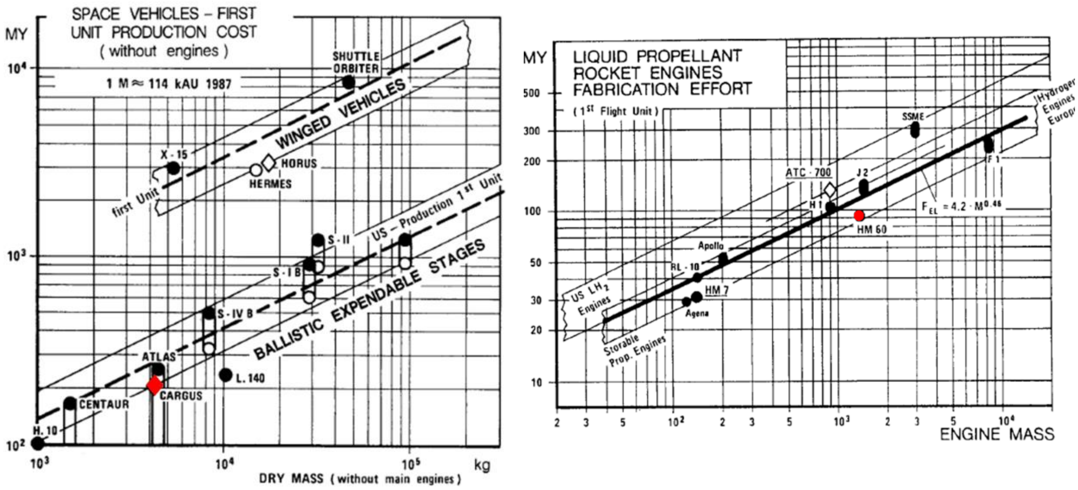


Figure 68: TFU Production results comparison with reference for STRATOFLY TSTO First Stage



(a) (b)

Figure 69:(a) Space vehicle unit production cost model; (b) Liquid propellant rocket engine cost model (Koelle, 1989)

To complete the analysis of Production Costs, an estimation of Total and Average Production Costs is provided. The latter, as described in Section 3.2.4, allows to determine the contribution of production cost amortization onto the CpF. In order to apply Eq. (46) and, thus, calculate total Total Production Cost to be sustained during the overall life-cycle of the STRATOFLY TSTO, it is important to define the total number of units to be produced. In this context, adopting the same assumptions of (Ferretto, 2020), it is hypothesized that 200 units of the STRATOFLY MR3-modified are produced along with 1200 ATR units and 200 DMR units. This also implies that 200 CARGUS units are produced. Moreover, to derive the Total Production Cost, a learning curve should be defined (Section 3.2.2). In line with (Ferretto, 2020), it is assumed a 83% learning curve for all Vehicle Systems and engines composing the TSTO. As a result, a summary of Total Production Cost is provided in Table 46 for both governmental and commercial scenarios. Exploiting these results, Eq. (46) provides the Total Production Cost for the TSTO (Table 46).

Table 46: Total Production costs summary for STRATOFLY TSTO

	Total Production Cost			
	Governmental		**Commercial**	
	WYr	**M€ FY2021**	**WYr**	**M€ FY2021**
ATR	50,257.36	19,401.94	17,590.07	6790.68
DMR	6212.698	2398.43	2174.44	839.45
Rocket	2983.153	1151.651	1491.58	575.82
First Stage (without engines)	232,059.2	89,586.85	81,220.72	31,355.40
Second Stage (without engines)	15,306.73	5909.19	4607.326	1778.66
TSTO Vehicle	**325,504.41**	**125,661.54**	**113,605.56**	**43,857.62**

In addition, taking into account the number of units produced for each Vehicle System, engine and for the overall TSTO, an estimation of the Average Production Cost can be derived (Table 47). For completeness, Figure 70 and Figure 71 show the detailed learning curves, respectively, for Vehicle Systems and engines, thus providing an insight onto the decreasing trend of Production Cost starting from the TFU up to the last unit produced. Notably, Total Production Cost results in Table 46 have been obtained by summing up all the cost contributions shown within these learning curves.

Table 47: Average Production costs summary for STRATOFLY TSTO

	Average Production Cost			
	Governmental		**Commercial**	
	WYr	**M€ FY2021**	**WYr**	**M€ FY2021**
ATR	41.88	16.17	14.61	5.66
DMR	31.06	11.99	10.87	4.20
Rocket	14.9	5.76	7.458	2.88
First Stage (without engines)	1160.29	447.93	406.10	156.78
Second Stage (without engines)	76.53	29.55	23.04	8.89
TSTO Vehicle	**1627.52**	**628.31**	**568.03**	**219.29**

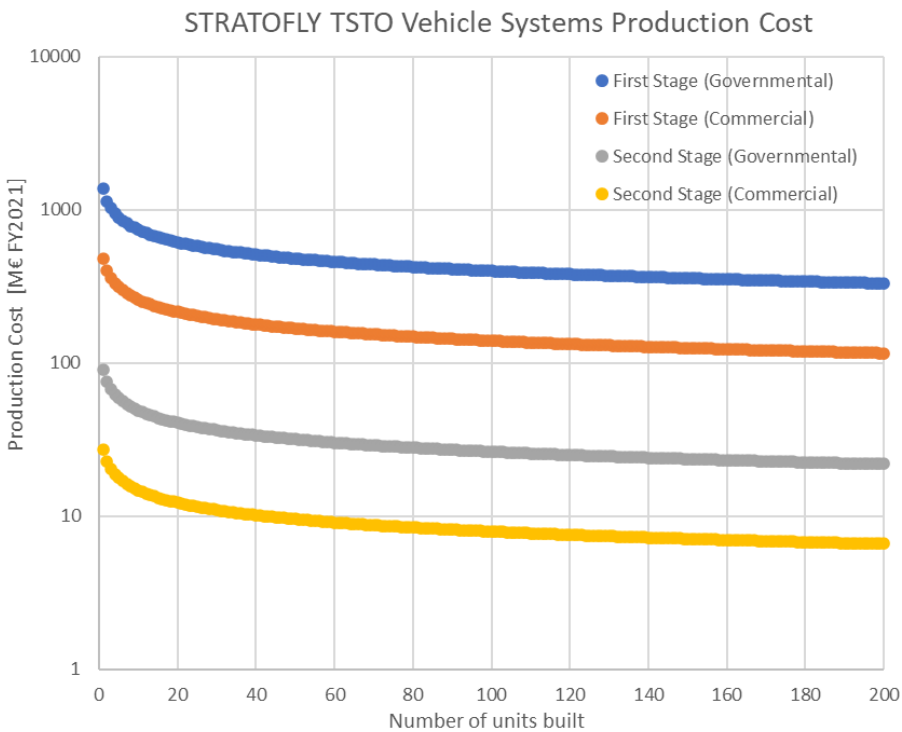
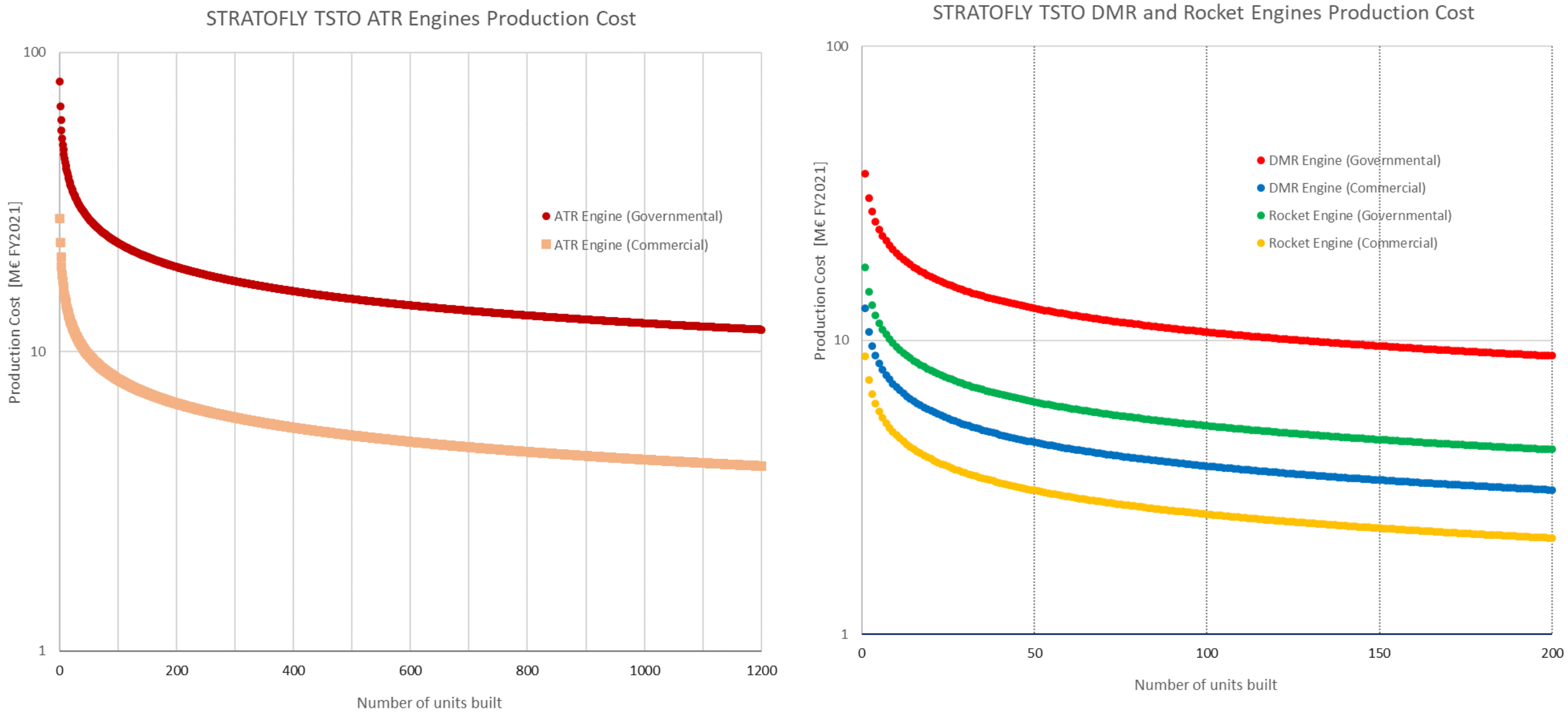


Figure 70: Production cost reduction due to learning curve effect for STRATOFLY TSTO Vehicle System



(a) (b)

Figure 71: Production cost reduction due to learning curve effect for (a) ATR Engines and (b) DMR and Rocket Engines

3.4.1.3 Operating Cost

Table 48 collects all the CERs used to perform Operating Cost assessment for STRATOFLY TSTO basing on the Operating Cost Model described in Section 3.2.3. Table 49 gathers all the inputs required. For LpA, the same value assumed for SKYLON (Hempsell et al., 2009) has been adopted. LH_2 cost has been assumed considering a long-term scenario with high share of electricity coming from renewables as in (Fusaro, Vercella, et al., 2020), while LOX cost stems from (Sninsky, 2020). Fuel and oxidizer masses for the second stage, not available from (Koelle & Kuczera, 1989), have been derived using the guidelines from (Czysz & Vandenkerckhovet, 2001) (already mentioned in Section 2.2.1.6) assuming a mass ratio of 3.619 for CARGUS and a bulk density of 360 kg/m^3. For sake of clarity, no reserve fuel fractions are considered, taking into account that the proposed STRATOFLY TSTO design (Section 2.2.1) is only at an initial stage (i.e. the 30 ton fuel reserve emerging from the preliminary mission analysis needs further validation). Moreover, values for K_{LTJ}, K_{LRJ}, K_{MTJ} and K_{MRJ} are the same suggested by (Repic et al., 1973). Final cost results are summarized in Table 50 following the CpF scheme (Section 3.2.4). Further comments are provided in Section 3.4.1.4.

Table 48: Summary of Operating CERs for STRATOFLY TSTO

Operating Cost Item		**Eq./Section**
DOC	Ground Operations	(58)
	Propellants	(62)
	Launch, Flight, and Mission Operations	(60)
	Launch Site User Fee	Section 3.2.3.2
	Public Damage Insurance	Section 3.2.3.2
	Mission Abort	Section 3.2.3.2
	Flight Crew	(63)
RSC/Maintenance		(61),(69)-(72)
IOC		Figure 37

Table 49: Inputs for Operating Cost assessment for STRATOFLY TSTO

Input	**Value**
LpA	70
Number of Stages	2
f_v	1.8
f_c	0.7
f_4	0.7
f_{11}	0.5
M_0 [ton]	400
Cost of LH2 Propellant [€/kg]	2
Cost of LOX Propellant [$/TN]	219.27
Cost of LOX Propellant [€/TN]	185.35
Total LH2 Propellant per trip to LEO (First Stage) [kg]	138,000
Total LH2 Propellant per trip to LEO (Second Stage) [kg]	152.35
Total LOX Propellant per trip to LEO (Second Stage) [kg]	54,846.65
Total LOX Propellant per trip to LEO (Second Stage) [TN]	53.98
Q First Stage	1
Q Second Stage	1.04
First Stage Flight Time [hours] (from preliminary mission profile)	1.88
r_L	25
k_{TJ}	20%
k_{RJ}	52%
L/D (from preliminary mission analysis)	5.395
K_{LTJ}	2
K_{LRJ}	2
K_{MTJ}	2
K_{MRJ}	3
f_5 (First Stage) (Figure 36)	0.05%
Number of Flight crew Members	3
Crew wage [€/hour]	754.84

Table 50: Results – CpF Scheme for STRATOFLY TSTO

		Governmental		Commercial	
		WYr	**M€**	**WYr**	**M€**
VRC	Amortization share of vehicle prod. cost	98.66	38.0889	33.0191	12.7471
	Turbojet Engine Maintenance Labor		0.0009		0.0009
	Turbojet Engine Maintenance Material		0.0057		0.0020
	Ramjet Engine Maintenance Labor		0.0004		0.0004
	Ramjet Engine Maintenance Material		0.0016		0.0006
	First Stage RSC	1.7821	0.6880	0.6237	0.2408
	Total RSC		**0.6966**		**0.2446**
DOC	Ground Operations	11.928	4.6048	5.9640	2.3024
	Launch, Flight, Mission Operations	1.0652	0.4112	1.0652	0.4112
	Propellants (LH2) Cost		0.2763		0.2763
	Propellants (LOX) Cost		0.0100		0.0100
	Propellants (Total) Cost		0.2863		0.2863
	Crew Cost		0.000000004832		0.000000004832
	Launch Site User Fee		0		0.1691
	Public Damage Insurance		0.1368		0.1368
	Mission Abort		1.5129		0.9528
	Vehicle Loss Charge		0.0388		0.0130
IOC	**Commercialization cost**	12.053	4.6531	6.2346	2.4069
BUSINESS CHARGES	**RDTE cost amortization charge**	0	0	31.31	12.0884

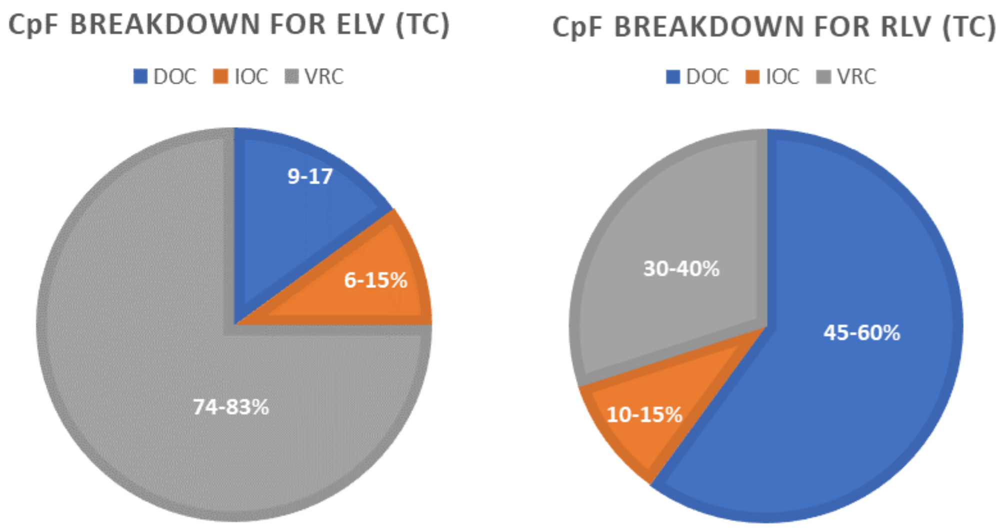
3.4.1.4 CpF, cost per kilo and LCC Summary

As far as the CpF scheme in Table 50 is concerned, it collects all the meaningful results from cost analysis considering both a governmental and a commercial scenario. Notably, to derive the Amortization share of vehicle production cost the results of production cost assessment gathered in Table 47 have been used. Firstly, the average cost for the First Stage (with engines) has been calculated from the average costs for First stage (without engines) and from ATR and DMR engines average costs (taking into account the total number of engines for each type installed on the stage). Then, the calculated average cost for the First Stage (with engines) has been divided by the total number of reuses (i.e. 200 as in (Ferretto, 2020)) to obtain the Amortization share of vehicle production cost. A similar procedure has been followed for the Second Stage to derive the average cost for the Second Stage (with engines). The latter coincides with the Amortization share of vehicle production since CARGUS is expendable. For sake of clarity, in Table 50, Launch Site User Fee has been assessed assuming an Orbital "Low Cost" Scenario (Table 33), while Public Damage Insurance has been calculated by applying the model proposed in Section 3.2.3.2 (Figure 59). Moreover, Mission Abort Charges have been estimated as 3% of CpF, while Vehicle Loss Charge as 0.1% of VRC (basing on the guidelines in Section 3.2.3.2). In addition, RDTE cost amortization charge is 0.1% of total RDTE cost in line with Figure 60. Eventually, IOC derives from the application of Figure 37, assuming CASE A (worst case) for the governmental scenario and CASE C (best case) for the commercial scenario.

Eventually, Table 51 collects the final CpF assessment for the case study, showing the detailed summary of main CpF components (i.e., DOC, IOC, VRC) obtained from Table 50. For comparison, Figure 72 shows the typical CpF breakdown for ELVs and the expected subdivision for RLVs. As it can be noticed, CpF results for STRATOFLY MR3 lie in-between the ELV and RLV breakdown with more tendency to ELVs values. This might be related to the fact that the expendable Second Stage highly impacts onto the VRC, thus shifting the overall CpF breakdown towards this component. Moreover, Table 51 shows the final cost per kilo calculated for the STRATOFLY TSTO. From results, it can be observed that, even if the estimated cost per kilo is above the 1000 €/kg projected for future RLVs, it is in the same order of magnitude. Results envisaged for governmental and commercial scenarios are in the same order of magnitude mainly due to the application of the RDTE amortization surcharge in the commercial scenario. To summarize, by applying the HyCost methodology to Case Study 1, its potential to model the low costs per kilo expected for future RLVs has been verified.

Table 51: CpF Summary and cost per kilo for STRATOFLY TSTO

	Governmental	**Commercial**
DOC per flight	7.69 M€ (15%)	4.52 M€ (22%)
IOC per flight	4.65 M€ (9%)	2.41 M€ (12%)
VRC per flight	38.79 M€ (76%)	12.99 M€ (66%)
CpF	50.43 M€	31.76 M€
cost per kg	**3361.96 €/kg**	**2117.24 €/kg**



(a) (b)

Figure 72: Reference CpF breakdown for ELVs and RLVs suggested by (Koelle, 2013)

For completeness, Table 52 provides the final LCC estimated for Case Study 1 assuming an overall life cycle spanning a timeframe of 50 years. These results will be exploited in Section 5.5 for the Cost-Effectiveness assessment.

Table 52: LCC Summary for STRATOFLY TSTO

	Governmental [M€]	**Commercial [M€]**
Total RDTE	35,817.59	12,088.44
Total Production	118,448.06	41,340.02
Total Operations	43,801.69	24,230.75
LCC	**198,067.34**	**77,659.21**

3.4.2 Case Study 2

Basing on Section 2.2, Space X Starship TSTO is the second case study on which the proposed cost model described in Section 3.2 is verified. Key characteristics of this concept have been provided in Section 2.2.2. As performed for STRATOFLY TSTO, recalling the RDTE and Production Costs subdivision at the basis of this work (Figure 39), it can be stated that Space X Starship TSTO is composed by the following elements:

- Vehicle Systems (without engines): Super Heavy and Starship;
- Engines: Raptor;

Notably, the Super Heavy is modelled as a fully reusable VTVL first stage rocket vehicle, while Starship is a fully reusable rocket second stage with HL.

On this basis, Section 3.4.2.1 and Section 3.4.2.2, respectively, describe RDTE and Production Cost assessment, whilst Section 3.4.2.3 deals with Operating Cost. Moreover, Section 3.4.2.4 provides a final summary in terms of CpF, cost per kilo and LCC for the vehicle. Eventually, Section 3.4.2.5 shows a comparison of obtained results with SpaceX projections (Musk, 2017b).

For sake of clarity, in contrast to Case Study 1 (Section 3.4.1), a f_8 coefficient (Section 3.1.2.3) equal to 1 is assumed for Case Study 2 (i.e., US Scenario) since the SpaceX Starship is a US concept.

3.4.2.1 Development Cost

The CERs collected in Table 53 are used to assess RDTE cost of the SpaceX Starship TSTO. For sake of clarity, Eq. (85) is used instead of Eq.(89) since no detailed staging information about SpaceX Starship TSTO is provided in literature (i.e., a precise Staging Mach value is not available).

Table 53: Summary of RDTE CERs for SpaceX Starship TSTO

Element	Equation
Super Heavy	(100)
Starship	(85)
Raptor	(37)
Vehicle with Engines	(21)

Main inputs required by the CERs in Table 53 can be found in Table 3 (Section 2.2.2). In addition, the values assumed for the f_i factors are gathered in Table 54. The latter have been defined considering the guidelines provided by (Koelle, 2013). Considering the Super Heavy, the value for f_2 derives from Eq.(26) assuming $\varepsilon = 0.06$ (using Net mass data from Table 3) and $\varepsilon^* = 0.046$ from (Koelle, 2013). The low f_2 value (< 1) obtained indicates that a development cost decrease (with respect to similar state-of-the-art concepts) can be expected for the Super Heavy. Notably, the concept is characterized by advanced technologies which, instead of increasing costs, contribute to their decrease. For the Raptor engine, f_2 is calculated through Eq.(39) with N_Q = 300. This value is below the average value of 500 tests suggested by (Koelle, 2013) taking into account the heritage from the testing campaign of the Merlin engine at Space X. Moreover, the value of f_9 for Super Heavy and Starship is the same proposed by (Koelle, 2013) for the Falcon 9. In that case, consistent cost saving was achieved by performing in-house great part of the RDTE effort and by reducing the number on subcontractors. As mentioned in Section 3.4.1.1, the same optimized subcontracting scenario was assumed for the STRATOFLY TSTO to provide an additional means of RDTE costs reduction. For total RDTE (Eq.(21)), values for f_6 and f_7 are the same reported in Table 41.

Eventually, Table 55 collects the results from the application of the RDTE CERs in Table 38. For sake of clarity, both governmental and commercial scenarios are reported for all Vehicle Systems and engines under consideration. Despite the SpaceX Starship TSTO is a purely commercial concept, such complete analysis allows to appreciate the great cost difference in case of governmental funding. Notably, the lower costs expected for the commercial scenario (confirmed in

(Jones, 2018; D. E. Koelle, 2013) are obtained from the governmental scenario by applying the f_{10} and f_{11} factors reported in Table 39 and in Table 40.

Table 54: Inputs for Vehicle System RDTE CERs – SpaceX Starship TSTO

	Input Value for		
Input	**Super Heavy**	**Starship**	**Raptor**
f_1	1.2	1.3	1.1
f_2	0.769	N/A	0.846
f_3	0.7	1	0.5
f_9	0.86	0.86	1
f_{10}	0.75		
f_{11}	0.45		

Table 55: RDTE cost results for SpaceX Starship TSTO

	Governmental Scenario		**Commercial Scenario**	
Element	**WYr**	**B€ [FY2021]**	**WYr**	**B€ [FY2021]**
Super Heavy	50,248.85	19.40	16,958.99	6.55
Starship	127,820.47	49.34	43,139.41	16.65
Raptor	4596.19	1.77	1551.21	0.60
Total	**197,571**	**76.27**	**66,680.22**	**25.74**

3.4.2.2 Production Cost

TFU Production Cost assessment is performed using the CERs collected in Table 56. Required inputs are gathered in Table 3. Results for all Vehicle Systems and engines under consideration are gathered in Table 57 for both governmental and commercial scenarios. Please, notice that values for f_{10}' and f_{11}' factors are the same used for STARTOFLY TSTO (Table 44).

Table 56: Summary of TFU Production CERs for SpaceX Starship TSTO

Element	Equation
Super Heavy	(131)
Starship	(128)
Raptor	(56)

Table 57: TFU Production cost results for SpaceX Starship TSTO

	Governmental Scenario		Commercial Scenario	
Element	**WYr**	**M€ [FY2021]**	**WYr**	**M€ [FY2021]**
Super Heavy	2237.21	18.36	783.02	302.29
Starship	22,002.70	8494.18	7700.94	2972.96
Raptor	64.46	24.89	22.56	9.03
First Stage (First Unit)	3550.17	1370.55	1242.56	479.69
Second Stage (First Unit)	22,208.89	8573.78	7773.11	3000.82
TSTO Vehicle (First Unit)	27,327.79	10,549.94	9564.73	3692.48

As performed for the STRATOFLY TSTO in Section 3.4.1.2, the analysis of Production Costs should be completed with an estimation of Total and Average Production Costs. Indeed, as described in Section 3.2.4, this information is required to determine the contribution of Production Cost Amortization onto the CpF. In order to apply Eq. (46) for Total Production Cost assessment, the total number of units to be produced should be defined. In this context, no detailed information about SpaceX Starship production scenario for a LEO mission is available from literature. Indeed, the LEO mission is considered as an additional potential of the vehicle, whose main purpose is to provide interplanetary transport (Musk, 2017b). In account of this, as mentioned in Section 2.2.2, many details are available for the Mars mission depicted in Figure 73.

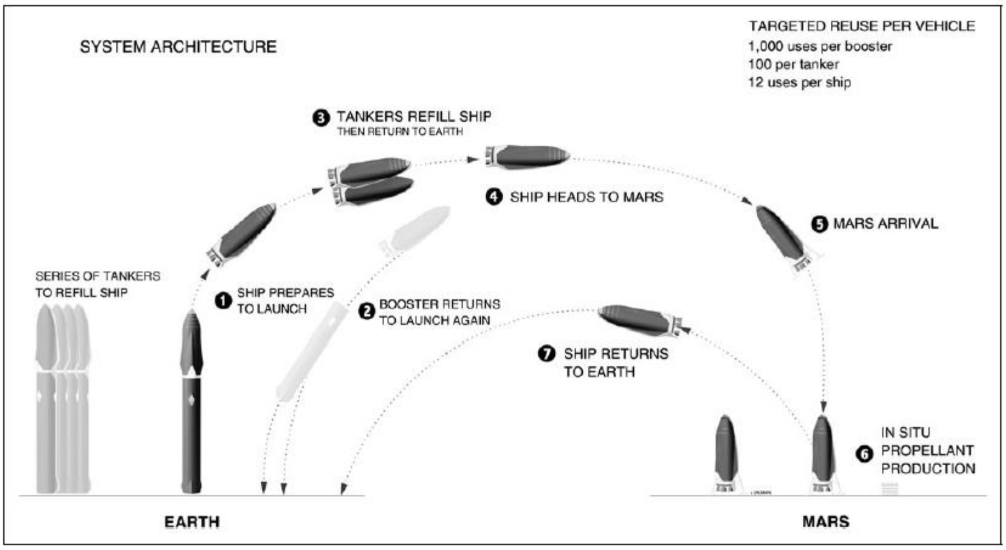


Figure 73:Reference Mars Mission for Space X Starship TSTO (Musk, 2017b)

The Mars mission envisages the exploitation of a Tanker vehicle (very similar to the Starship) able to refill the Starship in LEO and providing enough propellant for the trip to Mars. Data available for this mission will be used in this Dissertation to define the production scenario and to verify calculated costs as reported in Section 3.4.2.5. Notably, it is assumed that the same number vehicles produced for the Mars mission can be also used for LEO in-between each launch window to Mars (indeed, the Earth–Mars rendezvous only occurs every 26 months (Musk, 2017b)). Specifically, according to (Musk, 2017b), "*the threshold for a self-sustaining city on Mars or a civilization would be a million people. If you can only go every 2 years and if you have 100 people per ship, that is 10,000 trips. [...] However, 10,000 flights is a lot of flights, so ultimately you would really want in the order of 1,000 ships.*" (Musk, 2017b)). More precisely, considering 12 reuses for each Starship (see Table 3 and Figure 73), 834 second stage vehicles are required. Moreover, assuming a lifetime of 1000 lunches for each Super Heavy and, per each Mars mission, 6 launches (to allow the refill), a total number of 60,000 Super Heavy launches are envisaged during the whole SpaceX Starship TSTO program to Mars. This means that at least 60 Super Heavy Boosters are needed (probably more in case of a LEO scenario, but the exact number cannot be determined). Similarly, taking into account that 5 Tankers should be launched to support each Mars trip and that each Tanker can be reused up to 100 times, at least 500 Tankers should be produced. At this point, taking into account the number of Raptor engines installed on each Super Heavy and Starship from Table 3 (for the Tanker, the same number envisaged for the Starship applies), a total number of 10,200 Raptor engines should be produced in order to equip all the vehicles involved in the Mars scenario. As mentioned, the same production numbers are preliminary assumed for the LEO scenario. Please, notice that the Tanker vehicle, envisaged only for the Mars mission, is not specifically tackled in this analysis. As far as learning curve is concerned, the values collected in Table 58 are used. As described in Section 3.4.2.5, these values have been optimized in order to align estimated production costs with reference data from SpaceX.

Table 58: Learning Factors assumed for SpaceX Starship TSTO

Element	**Learning Factor**
Super Heavy	0.9
Starship	0.7
Raptor	0.83

As a result, Table 59 provides a summary of Total Production Cost for both governmental and commercial scenarios. Thanks to these results, Eq. (46) provides the Total Production Cost for the TSTO.

Table 59: Total Production costs summary for SpaceX Starship TSTO

	Total Production Cost			
	Governmental		**Commercial**	
	WYr	**M€ FY2021**	**WYr**	**M€ FY2021**
Raptor	75,269.37	29,057.87	26,344.28	10,170.25
First Stage (without engines)	84,060.89	32,451.85	29,421.31	11,358.15
Second Stage (without engines)	1,153,682	445,380.87	403,788.6	155,883.30
TSTO Vehicle	**1,392,974**	**487,541**	**537,760**	**188,216**

In addition, basing the number of units to be produced for each Vehicle System and for the engine discussed above, an estimation of the Average Production Cost can be derived (Table 60).

Table 60: Average Production costs summary for SpaceX Starship TSTO

	Average Production Cost			
	Governmental		Commercial	
	WYr	**M€ FY2021**	**WYr**	**M€ FY2021**
Raptor	7.36	2.84	2.578	0.995
First Stage (without engines)	1401.01	540.86	490.35	189.30
Second Stage (without engines)	1383.31	534.03	484.16	186.91
First Stage (with engines)	1710.34	660.28	598.62	231.10
Second Stage (with engines)	1449.60	559.62	507.36	195.87
TSTO Vehicle	**3159.94**	**1219.90**	**1105.98**	**426.96**

3.4.2.3 Operating Cost

All the CERs used for Operating Cost assessment for SpaceX Starship TSTO are gathered in Table 61. Please, notice that no flight crew cost is calculated since an unmanned mission to LEO is considered (Section 2.2.2). As far as RSC is concerned, Eq. (61) is used for the Vehicle System contributions, while Rocket engine RSC is determined thanks to the guidelines provided by TC (Section 3.1.2.3), i.e., 240 Wh every 20 flights plus 10% spares.

Inputs required for Operating Cost assessment can be found in Table 3 and in Table 62. For LpA, the same value assumed for STRATOFLY TSTO (Section 3.4.1.3) (i.e., 70 LpA) is used in order to consider the same operational scenario. Considering the current trend of SpaceX launches, this LpA can be presumably achieved around 2030 (Figure 74). Moreover, Propellant cost is the same suggested by (Musk, 2017b). For f_5 factors, final values have been obtained by tuning the values for the "Mach 7 Hypersonic Booster" and "Orbital Winged Rocket Vehicle" in Figure 39 (respectively, for the Heavy Booster and the Starship) in order to align with SpaceX projections (see Section 3.4.2.3). On this basis, final cost results are summarized in Table 63 following the CpF scheme (Section 3.2.4). Further comments are provided in Section 3.4.2.4.

Table 61: Summary of Operating CERs for SpaceX Starship TSTO

Operating Cost Item		**Eq./Section**
DOC	Ground Operations	(58)
	Propellants	(62)
	Launch, Flight, and Mission Operations	(60)
	Launch Site User Fee	Section 3.2.3.2
	Public Damage Insurance	Section 3.2.3.2
	Mission Abort	Section 3.2.3.2
RSC		(61)*
IOC		Figure 37

Table 62: Inputs for Operating Cost assessment for SpaceX Starship

Input	Value
Number of Stages	2
f_v	1.8
f_c	1
f_4	0.7
f_{11}	0.5
Cost of Propellant [$/ton]	168
Q First Stage	1
Q Second Stage	3
f_5 (First Stage)	0.4%
f_5 (Second Stage)	0.08%

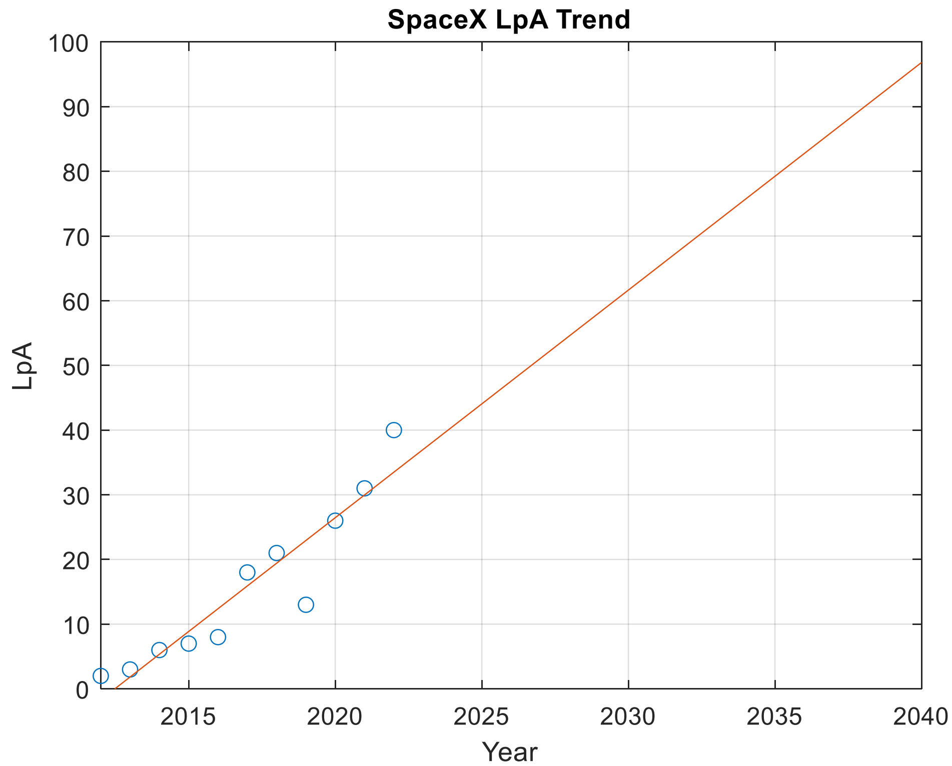


Figure 74: Current trend of SpaceX LpA

Table 63: Results – CpF Scheme for SpaceX Starship TSTO

		Governmental		**Commercial**	
		WYr	**M€**	**WYr**	**M€**
VRC	Amortization share of vehicle prod. cost	122.51	47.30	42.88	16.55
	Rocket Engine RSC	0.0505	0.0195	0.0505	0.0195
	First Stage RSC	88.01	33.98	30.80	11.89
	Second Stage RSC	1.79	0.69	0.63	0.24
	Total RSC	**89.85**	**34.69**	**31.48**	**12.15**
DOC	Ground Operations	119.08	45.97	59.54	22.99
	Launch, Flight, Mission Operations	3.54	1.37	3.54	1.37
	Propellant Cost		0.76		0.76
	Launch Site User Fee		0		0.17
	Public Damage Insurance		1.42		1.42
	Mission Abort		4.21		2.59
	Vehicle Loss Charge		0.0820		0.0287
IOC	Commercialization cost	12.05	4.65	6.42	2.48
BUSINESS CHARGES	**RDTE cost amortization charge**	**0.00**	**0**	**66.68**	**25.74**

3.4.2.4 CpF, cost per kilo and LCC Summary

The CpF scheme in Table 63 collects all the noteworthy results from cost analysis considering both a governmental and a commercial scenario. Notably, to derive the Amortization share of vehicle production cost the results of production cost assessment gathered in Table 60 have been used. In particular, the average cost for the First Stage (with engines) has been divided by a total number of reuses (see Section 3.4.2.2) to obtain the Amortization share of vehicle production cost. A similar procedure has been followed to derive the average cost for the Second Stage (with engines). Eventually, the two contributions have been summed up to derive the total amortization of Production Cost per flight for the vehicle. Moreover, Launch Site User Fee has been assessed by assuming an Orbital "Low Cost" Scenario (as for STRATOFLY TSTO). This is also in line with SpaceX assumptions (Musk, 2017b). In addition, Public Damage Cost derives from the model proposed in Section 3.2.3.2 (Figure 59). However, since the launch mass of the SpaceX Starship TSTO (Table 3) is far above the range covered by Figure 57, the exploitation the chart might lead to underestimate the percent insurance cost per flight. In account of this, a 6% insurance cost per flight has been conservatively assumed (the lowest value in the data range of Figure 57). In line with STRATOFLY TSTO, Mission Abort Charges have been estimated as 3% of CpF, while Vehicle Loss Charge as 0.1% of VRC (basing on the guidelines in Section 3.2.3.2). Furthermore, RDTE cost amortization charge is 0.1% of total RDTE cost (Figure 60.) Eventually, IOC stems from the application of Figure 37, assuming CASE A (worst case) for the governmental scenario and CASE C (best case) for the commercial scenario.

Eventually, Table 64 collects the key outcomes of CpF assessment for the case study (i.e., DOC, IOC, VRC) obtained from Table 63. By comparing these results with the CpF subdivisions expected by TC (Figure 72) it can be noticed that CpF results for Case Study 2 are more in line with the RLV breakdown compared to the STRATOFLY TSTO (see Section 3.4.1.4). This is probably related to the fact that the both stages of the SpaceX Starship TSTO are reusable. In addition, Table 64 shows the calculated cost per kilo. Interestingly, the obtained values are quite in line with the cost per kilo previously introduced for STRATOFLY TSTO (Table 51). Also in this case, even if the estimated cost per kilo lies above the 1000 €/kg projected for future RLVs, results are in the same order of magnitude. Therefore, thanks to the application of HyCost methodology to Case Study 2, it has been possible to verify even more the potential of the approach to provide results in line with typical costs expectations for future RLVs.

Table 64: CpF Summary and cost per kilo for SpaceX Starship TSTO

	Governmental	**Commercial**
DOC per flight	88.50 M€ (50%)	41.47 M€ (57%)
IOC per flight	4.65 M€ (3%)	2.48 M€ (3%)
VRC per flight	81.98 M€ (47%)	28.71 M€ (40%)
CpF	**140.45 M€**	**86.24 M€**
cost per kg	**3511.15 €/kg**	**2156.00 €/kg**

For completeness, Table 65 provides the final LCC estimated for Case Study 2 assuming the same life-cycle timeframe of STRATOFLY TSTO (i.e., 50 years) to allow comparison of results in Section 5.5 within the Cost-Effectiveness assessment.

Table 65: LCC Summary for SpaceX Starship TSTO

	Governmental [M€]	**Commercial [M€]**
Total RDTE	76,272.63	25,742.01
Total Production	118,448.06	41,340.02
Total Operations	326,027.13	153,806.47
LCC	**520,747.82**	**220,888.50**

3.4.2.5 Comparison with SpaceX Projections

As introduced in the previous Section, the costs estimated for Case Study 2 have been compared with available data from SpaceX. Lacking specific cost data for a LEO mission, cost information for the Mars Mission reported in Figure 75 has been considered. Notably, Fabrication Cost, Average Maintenance Cost per Use and Total Cost per one trip to Mars for the Booster (Super Heavy) and the Ship (Starship) have been verified. As already mentioned, the costs for the Tanker vehicle have been excluded from the present analysis. Please, notice that the cost data in Figure 75, originally referred to FY2017, has been converted to FY2021

COSTS

With full reuse, our overall architecture enables significant reduction in cost to Mars

	BOOSTER	TANKER	SHIP
FABRICATION COST	$230M	$130M	$200M
LIFETIME LAUNCHES	1,000	100	12
LAUNCHES PER MARS TRIP	6	5	1
AVERAGE MAINTENANCE COST PER USE	$0.2M	$0.5M	$10M
TOTAL COST PER ONE MARS TRIP (Amortization, Propellant, Maintenance)	$11M	$8M	$43M

Cost Of Propellant: $168/t
Launch Site Costs: $200,000/launch
Discount Rate: 5%

Sum Of Costs: $62 M
Cargo Delivered: 450 T
Cost/ton to Mars: <$140,000

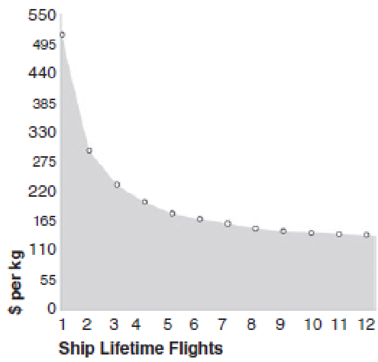


Figure 75: Estimated cost of SpaceX Starship for the Mission to Mars (Musk, 2017b)

Results of comparison between estimated costs and reference Space X data are provided from Figure 76 to Figure 78 for the cost items under interest. As it can be noticed, estimated values are in good accordance with SpaceX projections. As mentioned, this has been possible thanks to a proper tuning of the f_i factors within the CERs. Notably, for Fabrication (i.e. Production) cost, the f_4 factors for engine and Vehicle Systems previously reported in Table 58 have been properly modified also taking into account the guidelines from (Koelle & Huber, 1961). For sake of clarity, calculated Fabrication Costs in Figure 76 coincide with the Average Production Costs for the First and the Second Stage (with engines) in Table 60. Specifically, calculated values for the commercial scenario have been converted to M$ for FY2021 to allow comparison with SpaceX data. As far as Average Maintenance Cost per use is concerned, the f_5 factors for the Booster and the Ship in Table 62 have been tuned to match results with the reference. Notably, the First Stage and Second Stage RSC in Table 63 (for commercial scenario) have been used for comparison in Figure 77 after proper conversion to M$ for FY2021.

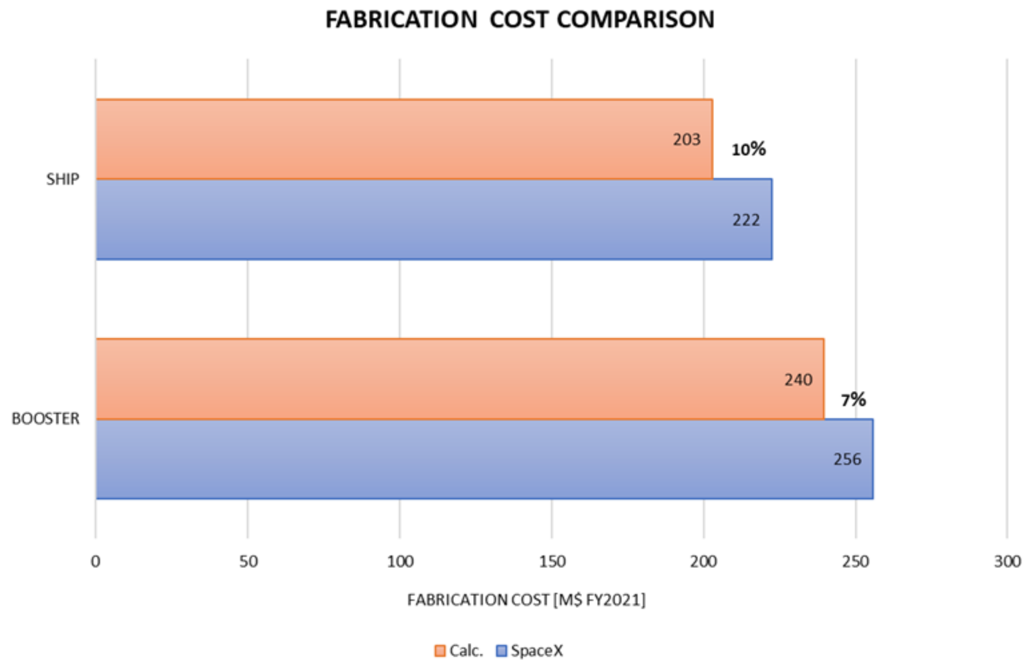


Figure 76: SpaceX Starship TSTO Fabrication Cost Comparison

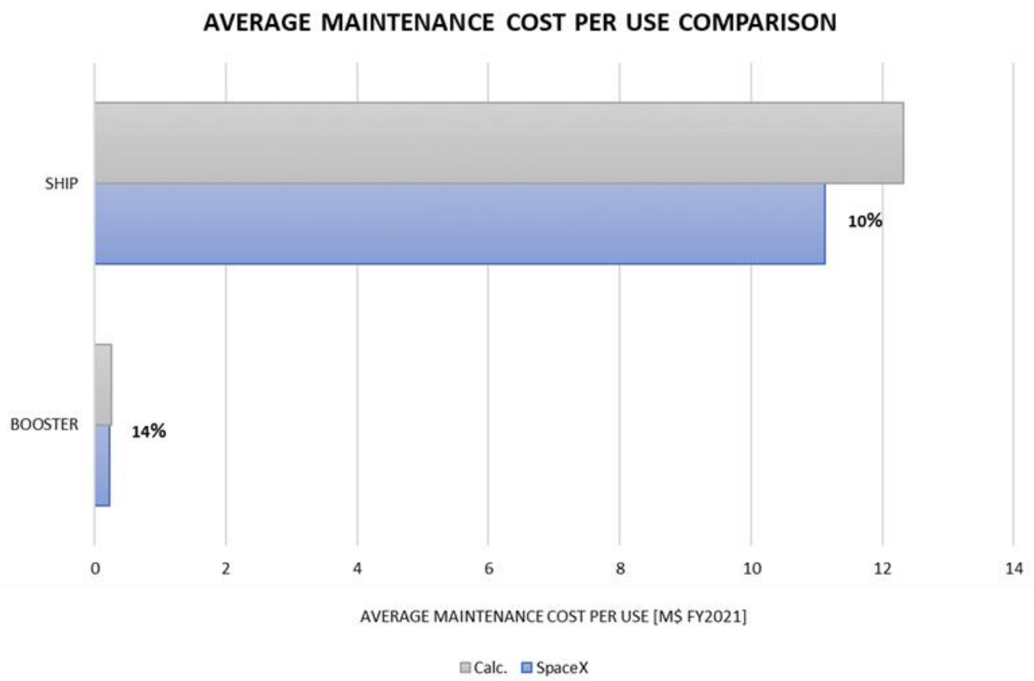


Figure 77: SpaceX Starship TSTO Average Maintenance Cost per use Comparison

Taking into account that a RDTE estimation is not available from Space X, the comparison of results in terms of Total Cost per one Mars Trip (Figure 75) allows a preliminary verification calculated RDTE costs. Indeed, basing this cost item entails Amortization, Propellant, and Maintenance. In this context, considering that SpaceX Starship development is performed within a commercial scenario, basing on (Koelle & Huber, 1961), both Production and RDTE costs are included into amortization expenses. Notably, an amortization cost per flight equal to 0.1% of RDTE (Figure 60) is considered for both First Stage and Second Stage. For sake of clarity, RDTE cost amortization of Raptor engine has not been included since it is negligible with respect to Vehicle Systems contribution. However, in principle, the Raptor RDTE amortization should be properly allocated to both the Booster and Ship in Figure 78. For the remaining components of the Total Cost per one Mars Trip, the previous discussions about production and maintenance apply. Moreover, the propellant cost in Table 63 (converted to M$) is included.

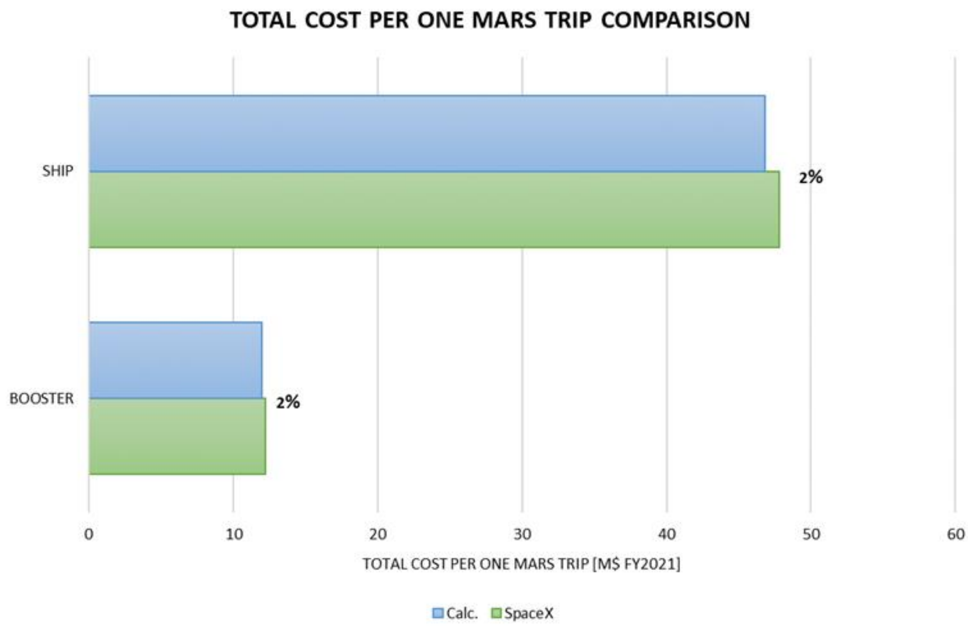


Figure 78: SpaceX Starship TSTO Total Cost per One Mars Trip Comparison

3.5 Chapter 3 Abbreviations

ATA	Air Transport Association of America
ATR	Air Turbo Rocket
BaU	Business-as-Usual
BH	Block Hour
CC	Combined Cycle
C-E	Cost-Effectiveness
CER	Cost Estimation Relationship
CpF	Cost per Flight
CPI	Consumer Price Index
CSM	Command and Service Module
DLR	Deutsches Zentrum für Luft- und Raumfahrt
DMR	Dual Mode Ramjet
DOC	Direct Operating Cost
ELV	Expendable Launch Vehicle
FAA	Federal Aviation Administration
FESTIP	Future European Space Transportation Investigations Programme
FY	Fiscal Year
GUI	Graphical User Interface
HL	Horizontal Landing
HST	High-Speed Transportation
HTHL	Horizontal Take-Off Horizontal Landing
HTO	Horizontal Take-Off
IATA	International Air Transport Association
ICAO	International Civil Aviation Organization
IOC	Indirect Operating Cost
ISPA	International Society of Parametric Analysts
ISS	International Space Station
LCC	Life-Cycle Cost
LEO	Low Earth Orbit
LND	Landing
LpA	Launches per Annuum
MPE-ZPB	Minimum-Percentage-Error Zero-Percentage-Bias
MS	Microsoft
MY	Man-Year
NMF	Net Mass Fraction
O&S	Operations & Support
PpF	Price per Flight
RDTE	Research, Development, Test and Evaluation
RLV	Reusable Launch Vehicle
RMS	Root-mean-square

RSC	Refurbishment and Spares Cost
SE	Standard Error
SoA	State-of-the-Art
SRB	Solid Rocket Booster
SSTO	Single Stage to Orbit
STRATOFLY	Stratospheric Flying Opportunities for High-Speed Propulsion Concepts
TC	TransCost
TFU	Theoretical First Unit
TO	Take-Off
TOC	Total Operating Cost
TPS	Thermal Protection System
TSTO	Two Stage to Orbit
US	United States
VRC	Vehicle Recurring Cost
VT	Vertical Take-off
VTHL	Vertical Take-off Horizontal Landing
VTO	Vertical Take-Off
VTVL	Vertical Take-off Vertical Landing
Wh	Work hour
WYr	Work-Year

Chapter 4

Technology Roadmap for Future Reusable Space Transportation and Re-Entry Systems

This Chapter aims at describing the exploitation of Technology Roadmapping to assess the technological sustainability of future RLVs. In particular, after an introduction to Technology Roadmapping and major State-of-the-Art (SoA) approaches in Section 4.1.1, Section 4.1.2 describes the key features of the reference methodology for Technology Roadmapping adopted in this Dissertation called Technology RoadmappIng Strategy (TRIS). Basing on the SoA version of TRIS (herein referred as SoA TRIS) available at the beginning of this work, Section 4.1.3 highlights the strengths as well as the key limitations of the approach to be tackled in order to apply TRIS to RLVs. Then, with the aim to highlight the strict connection between the cost estimation results (obtained from the Cost Model presented in Chapter 3) and the Technology Roadmapping process, Section 4.2. describes two ways to exploit the outcomes of RDTE cost assessment to estimate the cost required for technology development (or Technology Development Cost). Subsequently, starting from the gaps in SoA TRIS highlighted in Section 4.1.2, Section 4.3 describes step by step the enhanced version of TRIS methodology specifically tailored for future RLVs proposed in this work. In addition, Section 4.4 summarizes the key features of the software implementation of the enhanced TRIS aimed at supporting the overall Technology

Roadmapping process. Eventually, Section 4.5 describes the exploitation of TRIS to perform Technology Roadmapping analysis for the case studies discussed in Section 2.2. As far as Case Study 1 is concerned, thanks to the great data availability from the H2020 STRATOFLY Project (Section 1.2.2), a thorough application of TRIS is carried out. A preliminary Technology Roadmap for the propulsive technologies installed on STRATOFLY MR3 (and on STRATOFLY MR3-modified) is proposed taking into account their key role in the overall success of the concept. For Case Study 2, lacking detailed information about the technologies installed on the vehicle, the proposed Technology Roadmapping exercise focuses on the verification of the development timeline envisaged by SpaceX using the planning routine available in TRIS. At the end of the Chapter, a summary table collects all abbreviations used.

Please, notice that the enhancement of TRIS methodology as well as its application to Case Study 1 are mostly based on (Viola et al., 2022). These topics, covered in Sections 4.2, 4.3 and 4.5.1 of this Dissertation are original part of Author research.

4.1 Literature Review

4.1.1 Introduction to Technology Roadmapping

The mastering of enabling technologies for RLVs is a mandatory step towards the establishment of such advanced concepts in the future (Section 1.1). In this context, Technology Roadmapping can represent a crucial support towards the development of innovative solutions in a sustainable and competitive way. The starting point is a deep understanding of the current technological status, from which possible paths for future improvements are suggested in a structured way. The main outcome of the process is the Technology Roadmap, able to collect and show in a graphical way multiple and heterogeneous aspects related to technology development (Carvalho et al., 2013). A key concept at the basis of Technology Roadmapping is the Technology Readiness Level (TRL) scale already introduced in Section 1.3. It is a classification originally introduced by NASA in the 1970s and further specified by (Mankins, 2009) as a nine-levels metric to assess technology maturity. For sake of clarity, this Dissertation is based on the TRL scale definition provided by the ECSS (ECSS (European Cooperation for Space Standardization), 2017) and currently adopted by ESA (Figure 79).

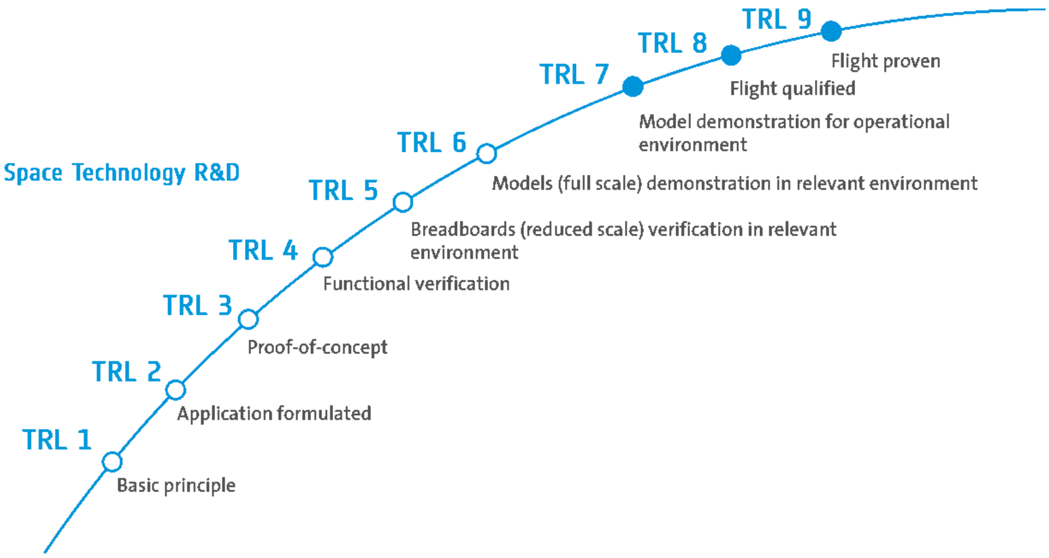


Figure 79: ESA Definitions for TRL Scale

From a historical perspective, the very first roadmapping activity was accomplished by Motorola in 1987 (Willyard & McClees, 1987) with the aim to foresee the "*technological future*" of the company thanks to a proper organization of the "*forecasting process*". Starting from this first application, Technology Roadmapping became, through the years, increasingly widespread among companies, governments and other institutions (ESA, 2020b; ISECG, 2018; NASA, 2015). The increasing of its popularity lead to the introduction of several roadmapping approaches (Moehrle, 2013):

1. *Technology-Driven View Technology Roadmapping* (Schuh et al., 2013), after defining objectives and technologies for the specific concept, it exploits plenary councils, consortiums and integration teams to review strategic options, priorities and objectives;
2. *Market-Driven View Technology Roadmapping* (Geschka & Hahnenwald, 2013), a market-driven approach proposing different scenarios for technology development taking into account non-technical requirements, such as societal and economic factors;
3. *Fast-Start Technology Roadmapping* (Phaal et al., 2013), (Phaal, Farrukh, & Probert, Fast-start technology roadmapping, 2000), based on workshops and involving different groups of stakeholders. It aims at deriving a Technology Roadmap in an interactive way using a market-driven or a technology-driven approach;

4. *TRIZ-based Technology Roadmapping* (Moehrle, 2013)*,* where TRIZ stands for Teoriya Resheniya Izobreatatelskikh Zadatch or Theory of the Resolution of Invention-Related Tasks, a forecasting tool based on a technology-driven approach to study future technological innovations but requiring specialized knowledge of the concept under analysis;
5. *Delphi-based Technology Roadmapping* (Kanama, 2013)*,* a decision technique involving independent stakeholders through rounds of interviews;
6. *Innovation Support Technology (IST) Roadmapping* (Abe, Ashiki, Suzuki, Jinno, & Sakuma, 2009)*,* a business-oriented process for normative-based technology roadmapping supported by Decision Analysis tools and workshops discussing on preferable future scenario.

For sake of clarity, technology-driven approaches allow to explore available options before identifying the future scenario, while market-driven approaches verify that required technological capability is sufficiently settled to pursue technology advancement (Moehrle, 2013). These approaches are totally or partially based on experts' opinion. Personal and political interests could significantly limit the effectiveness of the overall process, introducing subjective preferences, thus leading to non-technically justified choices. As a result, a hybrid method considering both technology-driven and market-driven approaches with a mission-oriented point of view is considered preferable for the purposes of this Dissertation. A similar approach is already proposed in (Cresto Aleina, Fusaro, Viola, Longo, et al., 2017; Cresto Aleina, Fusaro, Viola, Rimani, et al., 2017; Viola et al., 2020), in which the so-called technology RoadmappIng Strategy (TRIS) methodology is described. TRIS is a logical and objective methodology able to generate Technology Roadmaps in support of strategic decisions. In combination with traditional methods, it highlights a multiplicity of possible incremental paths towards the final goal thanks to the exploitation of common System Engineering tools and processes (Hirshorn et al., 2017; INCOSE, 2015; Viola et al., 2012) and ad-hoc developed tools. Thanks to the expertise gained in past activities (Cresto Aleina, 2018; Cresto Aleina et al., 2015, 2016, 2019; Cresto Aleina, Fusaro, Viola, Rimani, et al., 2017; Johnson & Robinson, 2005; Viola et al., 2016, 2020), TRIS has already proven to be suitable for space exploration domain as well as for hypersonic and re-entry space transportation systems, supporting ESA's technology initiatives within this field. As such, TRIS is selected as reference methodology for technology roadmapping in the present work. The main characteristics of the approach as well as the current gaps identified are discussed, respectively, in Section 4.1.2 and in Section 4.1.3.

4.1.2 SoA TRIS Methodology Summary

TRIS is a methodology for Technology Roadmap derivation and update which aims at supporting since the early design stages the identification of optimal complex systems (or Systems of Systems (SoS)) taking into account the current technological scenario as well as stakeholders' needs (Cresto Aleina, 2018) The approach is mostly based on Systems Engineering and Decision Analysis theories and tools (Hirshorn et al., 2017) and it is applicable to a generic SoS architecture with a mission-oriented approach. In this sense, it is worth highlighting that TRIS main goal is not to propose the design of a SoS architecture. Indeed, starting from well-defined system requirements, it aims at supporting and managing the overall design process by studying the social, economic and political scenario in which the design is inserted and by "*balancing all needs and constraint of the stakeholders acting in this scenario*" (Cresto Aleina, 2018). In addition, by analysing the current technological status, TRIS can provide a planning for technology development and identify possible critical issues, thus giving important feedback onto conceptual design choices. In account of this, recalling the main topics addressed in this Dissertation (Figure 14), it emerges that the relationship between conceptual design activities and Technology Roadmapping is already well established in SoA TRIS and the overall methodology is already well integrated with conceptual design routines.

As intended in TRIS (Viola et al., 2020), a Technology Roadmap is the result of complex and strictly interwoven activities aiming at identifying and selecting technologies, missions, capabilities and systems to support strategic decisions. Notably, a Technology Roadmap entails the relationships between the following elements (or pillars):

1) Operational Capability (OC), a high-level function responding to a mission statement;
2) Technology Area (TA), a set of technologies that accomplish one or more OCs and usually subject of further sub-categorizations (i.e., Technology Subject and Technology);
3) Building Block (BB), a physical element that may include several technologies combined to achieve certain functions (OCs);

4) Mission Concept (MC), defined through a mission statement and made up of BBs, in order to implement several OCs and make use of certain technologies.

Figure 80 shows the flowchart of SoA TRIS. A brief summary of each step of the methodology is provided in the following subsections.

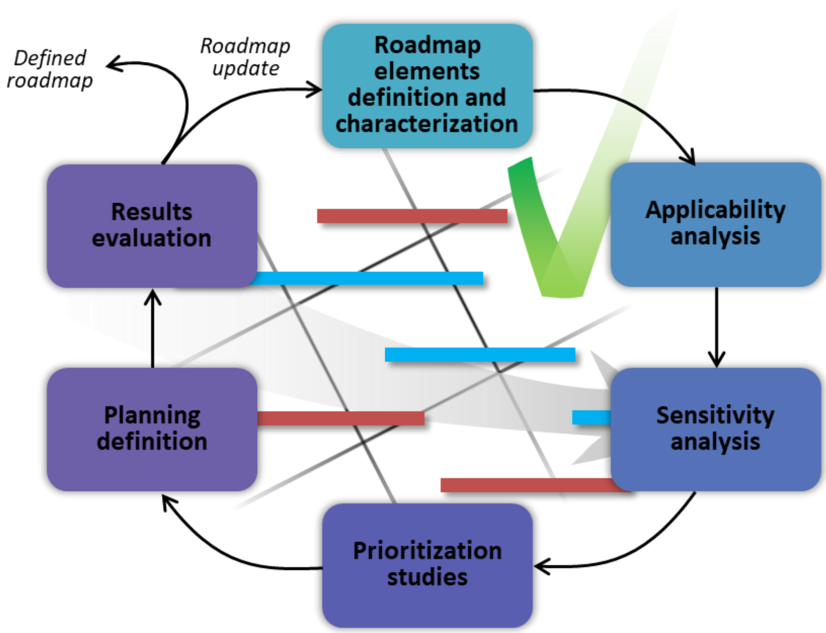


Figure 80: SoA TRIS methodology Flowchart from (Viola et al., 2020)

4.1.2.1 Roadmap elements definition and characterization (Step 1)

The process starts with the definition of lists of elements (i.e., TAs, BBs, OCs, and MCs) involved taking into account stakeholders' needs, regulations and other constraints. Considering OCs, they are strictly connected to the functions obtained from Functional Analysis (Viola et al., 2012). The latter, through the Functions/Product Matrix, can be linked to the Product Tree, which provides systems, sub-systems, and technologies for the SoS under study. As a result, the list of OCs, BBs and technologies is obtained. Eventually, Concept of Operations (ConOps) (Hirshorn et al., 2017) together with the basic definitions of TRL levels can be exploited to derive the list of MCs. To complete the elements characterization, current technology development status has to be analysed, assessing the TRL of each technology. The availability of a well-structured database containing lists of elements may significantly speed up this initial step (usually time consuming), based on the expertise of TRIS user or supported by discussions with technology experts. In this context, it is worth mentioning that the following databases can constitute a valid support to TRIS:

1. TechPort (NASA, 2022b), a public NASA tool;
2. Technology Roadmaps for space Exploration (TREx) (Saccoccia, 2012) developed by ESA and thoroughly studied by Politecnico di Torino in the past years (Cresto Aleina, 2018);
3. Hypersonic Database (HyDat) under study at Politecnico di Torino (Fusaro et al., 2017; Viola et al., 2018).

NASA TechPort is a public database that collects data about technology development projects in the fields of aeronautics, space exploration, and scientific discovery missions, providing details about the technology maturation activities carried out by NASA (NASA, 2015), while TREx is a confidential ESA database gathering data on space exploration activities performed in the European context. Benefitting of the ongoing collaboration between ESA and Politecnico di Torino, it has been possible to thoroughly analyse the contents as well as the structure of TREx and to apply this knowledge to the present research (Section 7.3). Eventually, HyDat is a database by Politecnico di Torino specifically conceived to provide all data required for TRIS analyses. In this context, (Fusaro et al., 2017) suggest a preliminary database back-end structure based on the multi-levels nested folders. Notably, each folder contains MS Office Excel® spreadsheets filled with data by the user through a Matlab® GUI as in Figure 81.

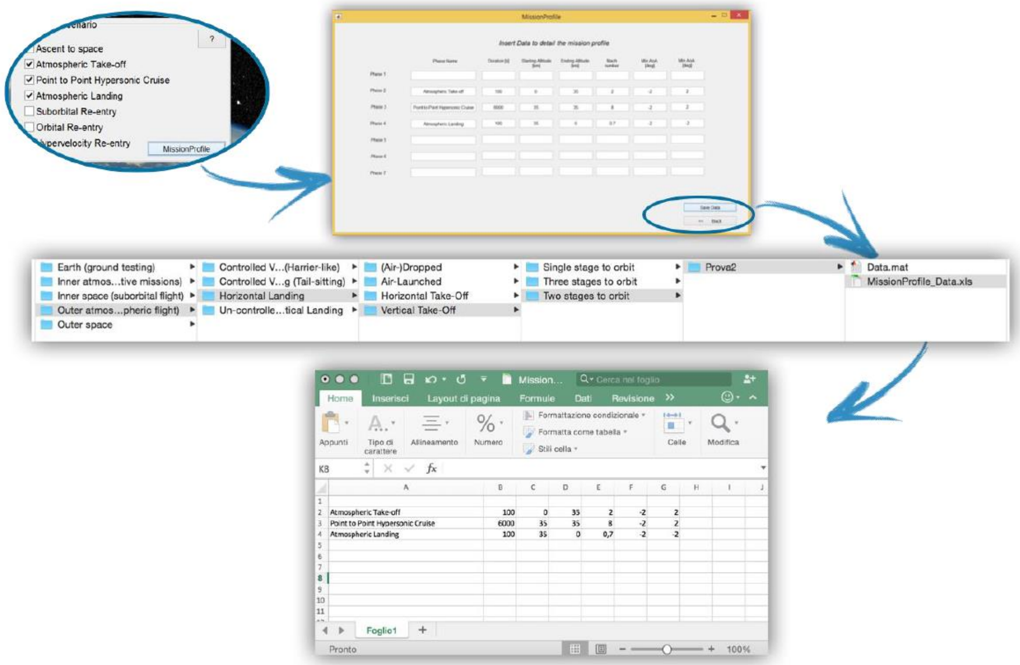


Figure 81:Example of HyDat Excel files filling using the GUI (Fusaro et al., 2017)

The activity flow diagram for HyDat backend filling implemented within the Matlab® GUI is depicted in Figure 82. The process starts with the definition of a project for technology development, which is characterized in terms of schedule (i.e. starting and ending dates), budget, status (on-going/completed or stopped) and project phase attained (from A to F, basing on the definitions provided in (Hirshorn et al., 2017) and recalled later on in Section 4.2). Then, details about the reference mission pursued within that project are specified, such as operative environment, take-off and landing mode and number of stages. Eventually, the list of technologies linked to the reference Mission Concept (MC) and to be developed during the project is defined.

Figure 82: Activity flow diagram for HyDat filling through Matlab® described in (Fusaro et al., 2017)

As mentioned, during the first step of TRIS, stakeholders' needs are also elicited. This is performed through a Stakeholders' Analysis identifying the main actors involved in the roadmapping process (i.e., the list of stakeholders) along with their main expectations and requests expressed in terms of criteria. In this context, by exploiting the concept of Strategy (or Stakeholders Grid) (Bryson, 2004), the stakeholders' categorization shown in Figure 83 is suggested.

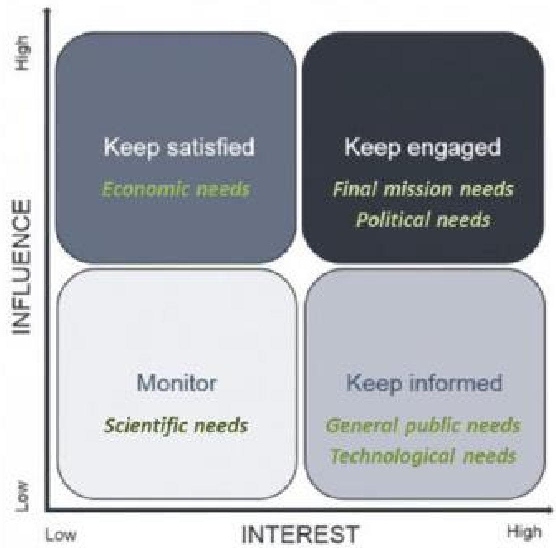


Figure 83: Stakeholders Grid (Cresto Aleina, 2018)

In the Strategy Grid, the six stakeholders' categories based on typical stakeholders' needs (e.g. economic needs, political needs, etc.) by (Kian Manaesh Rad & Sun, 2014) are allocated into the four areas of interest and influence (i.e. Monitor, Keep Informed, Keep Satisfied and Keep Engaged) of the Strategy Grid. Thanks to Stakeholders' Analysis, the criteria asked by each stakeholder are also specified. Please, notice that a list of possible criteria to be used in this phase is available from (Cresto Aleina, 2018). These criteria will be exploited in the phase of Prioritization studies (Section 4.1.2.3) in which a specified list of technologies is ordered according to stakeholders' preferences.

4.1.2.2 Applicability analysis (Step 2) and Sensitivity analysis (Step 3)

As emerged from Section 4.1.2.1, the four roadmapping elements defined in Section 4.1.2 are strictly interrelated one another. Notably, thanks to the exploitation of Function/Product Matrixes, links between lists of elements are identified during Step 1. At this point, thanks to the Applicability Analysis (TRIS second step), these links are further specified. As stated in (Cresto Aleina et al., 2018), "*this analysis highlights the importance of the connections between couples of elements, specifying if that connection is required, applicable or not applicable*". "Applicable" means that the relationship between to elements can be envisaged but not strictly required to fulfil mission requirements, “Required” is a link that highly impacts on the overall mission, while “Not applicable” is used when a specific combination of elements is not possible or envisaged. The further description and sizing of elements’ links through the labels “Required”, “Applicable” and “Not applicable” requires the exploitation of proper Decision Analysis tools such as the Decision Tree approach proposed in (Cresto Aleina, Viola, et al., 2017). The main results are the Applicability Maps (as in Figure 84), documenting the existence of a link between two elements and specifying the type of the link (i.e., required in red, applicable in blue, or not applicable in white). Applicability Analysis is followed by Sensitivity analysis, which assigns a weight to each link to represent stakeholders’ expectations (Viola et al., 2020).

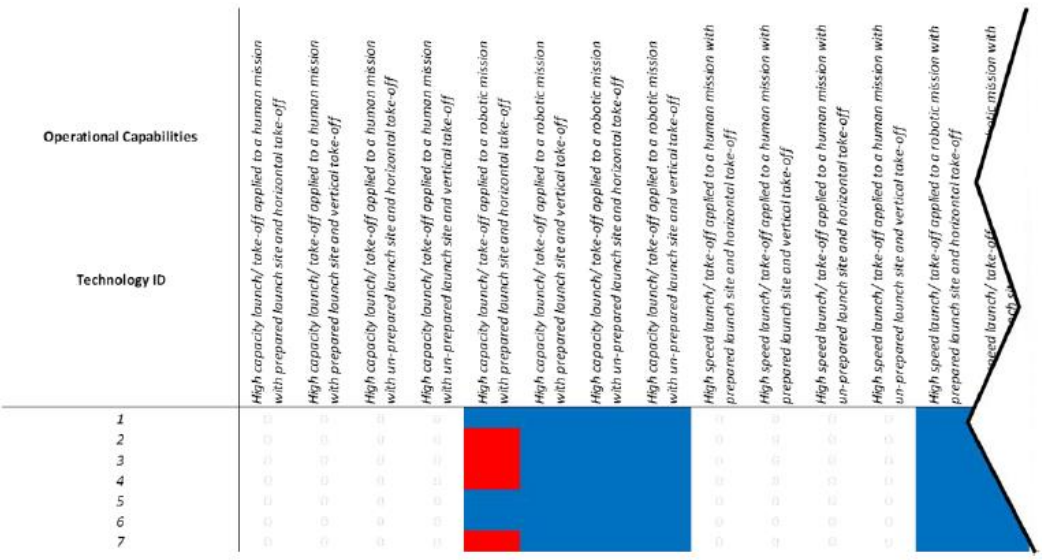


Figure 84: Example of Applicability analysis between OCs and Technologies (Cresto Aleina, 2018)

4.1.2.3 Prioritization studies (Step 4)

Proceeding towards the 4th step of TRIS, i.e. Prioritization studies, the primary objective is to rank technologies and Mission Concepts (MCs) *“in order to suggest and weight preferable paths to be followed in the roadmap definition*” (Cresto Aleina, 2018). Indeed, as a result of Step 1, technologies are listed but no ranking criterion is yet applied to order them. Therefore, proper prioritization criteria and methods must be chosen. As suggested in (Viola et al., 2020), a hybrid version of Prioritization Matrix, in which “*a decision tree is used to find every possible* *criteria combination and choose the optimal solution*" can be exploited as technology prioritization method. Specifically, several ranked lists of technologies can be obtained by applying all the available criteria combinations. Then, ranked lists of elements are evaluated thanks to proper Figures of Merit (FoMs) in order to define the optimal solution. In TRIS the following three FoMs are considered:

- TRL cost-effectiveness (FoM_1), defined as the ratio:

$$FoM_1 = \frac{\sum_i \Delta TRL_i}{\sum_i \Delta Costs_i} \tag{136}$$

  Where $\sum_i \Delta TRL_i$ is the sum for each technology (i) of the TRL increase achieved, while $\sum_i \Delta Costs_i$ is the sum for each technology (i) of the costs associated to the TRL increase;
- Average cost increase (FoM_2);
- Total Probability of failure (FoM_3).

Please, notice that FoM_2 and FoM_3 are strictly connected to the risk encountered in developing a certain technology. The three FoMs are combined in the parameter reported in Eq.(137). Then, the ranked list of technologies associated to the maximum value of TOT is chosen. In this way, the benefits deriving from FoM_1 and $(1 - FoM_3)$ are maximized, while the drawbacks associated to FoM_3 are minimized.

$$TOT = K\frac{FoM_1(1 - FoM_3)}{FoM_2} \tag{137}$$

In Eq.(137) K is a correction coefficient which considers stakeholders' influence and interest defined as:

$$K = \sum_{i=1}^{N} \frac{s_i}{p_i} \tag{138}$$

Where:

N is the number of criteria in the "optimal" combination (i is the generic criterion);

p_i is the position of the ith criterion in the selected combination of criteria;

s_i is the weight of the stakeholder asking for the ith criterion basing on his/her position on the Strategy Grid (Figure 83). s_i can be derived by associating an Impact Level to each stakeholder belonging to a specific portion of the Strategy

Grid. Considering a 4-levels scale, Level 1 is assigned to stakeholders with lowest influence and interest (i.e., Monitor), while Level 4 to stakeholders with highest influence and interest (i.e., Keep Engaged). For intermediate levels, giving more importance to stakeholders with higher influence, Level 3 is associated to Keep Satisfied and Level 4 to Keep Engaged stakeholders. As a result, after associating and Impact Level to each stakeholder under consideration, the weight of the single stakeholder can be obtained by considering his/her contribution onto the total sum of Levels.

Complementary, as far as Mission Concept (MC) prioritization is concerned, after defining the list of MCs to be considered (Step 1), a trade-off analysis (Hammond, 1999; NASA, 2016a) is carried out to rank that list according to well-defined criteria. In this case, stakeholders' needs and current market scenario are already embedded in the MC prioritization routine, which aims at proposing a ranked list of MCs able to:

1. minimize the required budget;
2. give priority to MCs that integrate several technologies or test several functionalities to minimize costs;
3. guarantee acceptable risks (in this sense, Earth surface proximity operations should be preferred and a stepwise progression from lower to higher TRL should be pursued.

These guidelines for MC prioritization can be translated into criteria to be used during the trade-off. For sake of clarity, in the trade-off analysis for MCs ranking criteria are applied progressively. Notably, the first criterion is used to derive an initial ordered list of MCs. Then, the second criterion is applied to the MCs at the same position, and so on with all the other criteria (progressively applied at MCs at the same position in the ranking).

4.1.2.4 Planning definition (Step 5)

During Planning definition, technologies and MCs' prioritization studies results are combined to derive possible TRL increase paths for the technologies under study. As discussed in (Viola et al., 2020), this step entails three main activities:

1. *Budget analysis*, to prune the list of technologies basing on the available budget;
2. *Mission Concepts (MCs) selection*, to suggest the sequence of MCs allowing to achieve the desired TRL increase path;
3. *Schedule definition*, to propose a timeline for MCs accomplishment in order to pursue technology development.

As far as Budget analysis is concerned, available budget should be compared to the costs to be sustained for technology development (i.e., required budget) and prune the list of technologies accordingly. In this context, if the total budget required to achieve TRL9 is known, Figure 85 can be used to determine the remaining costs basing on the TRL currently achieved. Notably, Figure 85 shows the Cost at Completion (CaC) fraction required to perform each TRL transit for a hypersonic and re-entry space transportation system according to experts' opinion. Please, notice that the definition of CaC is provided in Section 1.3.

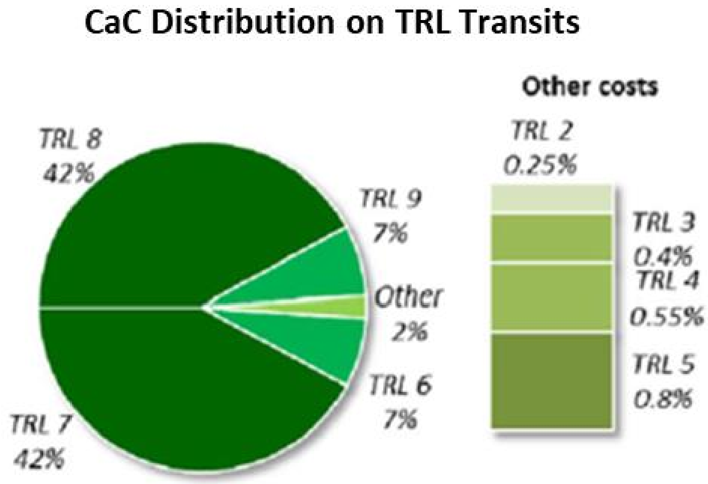


Figure 85: CaC distribution on TRL Transits in SoA TRIS (Cresto Aleina, 2018)

Concerning MCs selection, the algorithm in Figure 86, "*suggests the MCs having the highest ranking and compatible with the technology under investigation and in line with the considered TRL transit.*" (Viola et al., 2020). The output of this phase is a final ordered list of MCs which considers 1) stakeholders' requests (by means of the ranked list of technologies); 2) MCs ranking; 3) available budget and 4) as the need to propose a less risky incremental TRL path for technology development.

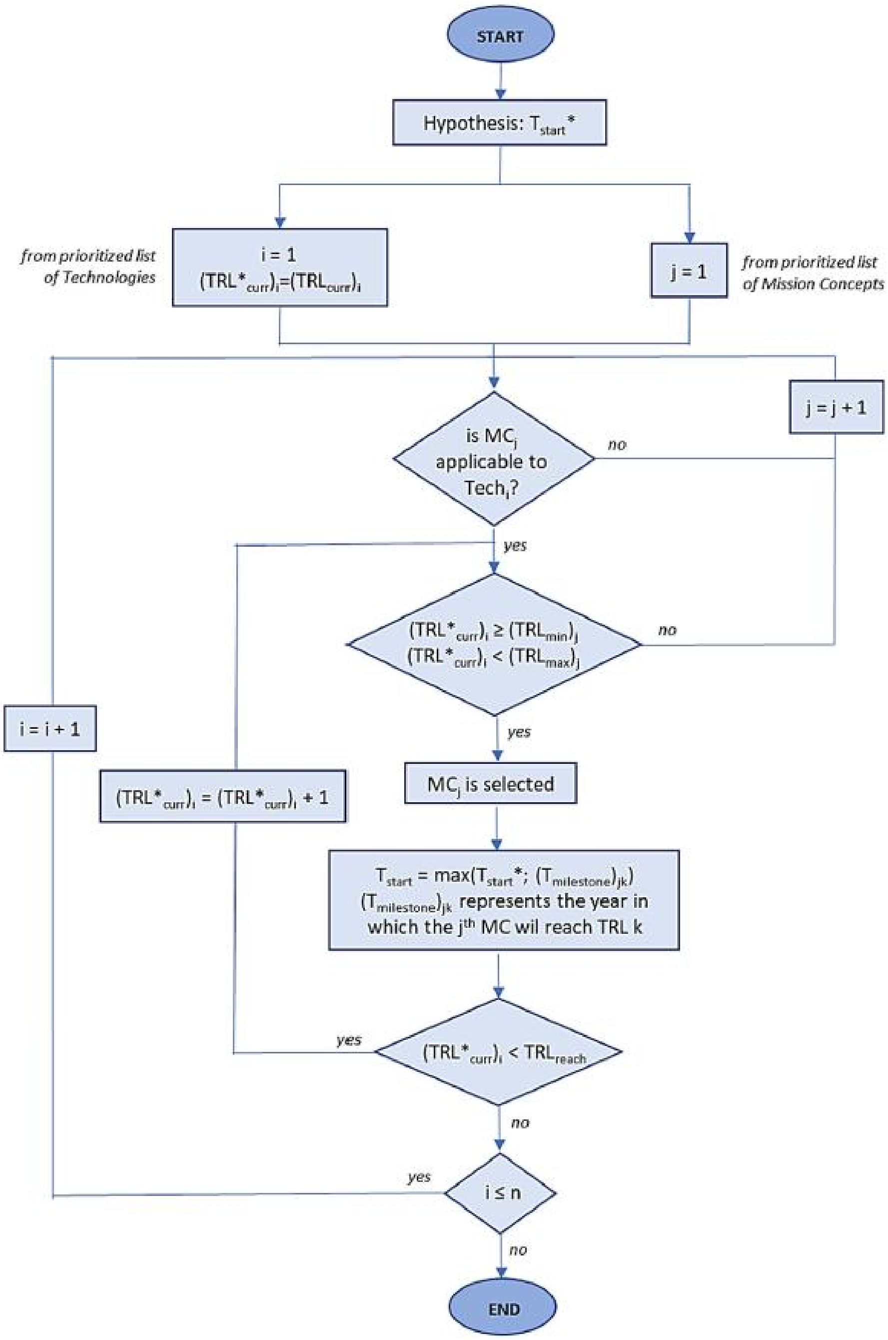


Figure 86: SoA TRIS Planning algorithm (Viola et al., 2020)

Eventually, the final list of MCs (and linked technologies) is visualized on a timeline (i.e., using a Gantt Chart) in the phase of Schedule definition. A nominal planning for technologies and MCs can be built using the Time at Completion (TaC) breakdown on TRL transits in Figure 87. In analogy with CaC, the TaC is defined as the total time required to pursue technology development starting from TRL 1 up to TRL 9. Therefore, knowing the time elapsed between two known TRL milestones, the overall TRL history for a technology can be built. For sake of clarity, a TRL milestone states the achievement of TRL level for a technology in a specific date. Moreover, the available TaC breakdown is applicable to space exploration systems as well as to hypersonic and re-entry space transportation systems.

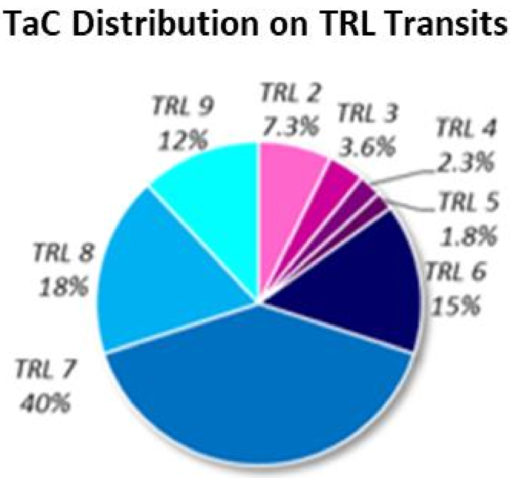


Figure 87: TaC distribution on TRL Transits in SoA TRIS (Cresto Aleina, 2018)

4.1.2.5 Results evaluation (Step 6)

In the final phase of Results evaluation, additional studies are carried out to tackle possible out-of-nominal situations through Political, Economic, Socio-cultural and Technological (PEST) analysis (Sammut-Bonnici & Galea, 2015) and preliminary risk assessment. The latter can be performed using the approach proposed in (Viola et al., 2020) and based on the concept of Advancement Degree of Difficulty (AD^2) by (Bilbro, 2008). At the end of the process., the obtained Technology Roadmap is ready to be reviewed by experts. Comments and suggestions from experts should provide the inputs for further iterations of the process also taking into account possible changes occurring in technology maturity.

4.1.3 Final comments on SoA TRIS Methodology

The SoA TRIS methodology recalled in the previous Section is surely an interesting comprehensive approach for mission-oriented Technology

Roadmapping applicable to a complex SoS. It formalizes all the main steps to pursue Technology Roadmapping in a structured way, highlighting the importance of Systems Engineering and Decision Analysis techniques into the process. In addition, it merges the requests of the main stakeholders involved with the actual technological status and the risks associated to technology development. However, starting from the thorough analysis of SoA TRIS, several improvements can be introduced to enhance the methodology. Notably, a systematic revision of the overall process is deemed required in order to deal with the case studies addressed in this Dissertation (Chapter 2). Indeed, as mentioned in Section 4.1.2, previous roadmapping analyses focused on space exploration and hypersonic and re-entry systems. From a broad perspective, the latter is already in line with the scope of the present study. However, it is worth underlying those former TRIS applications tackled only specific technologies required for the hypersonic re-entry phase (i.e., the TPS technologies on-board the IXV mentioned in Section 1.2.2). In account of this, two main enhancements to TRIS can be introduced in the present work:

1. To study other key enabling technologies applicable to RLVs, deriving proper lists of elements (i.e., technologies, MCs, BBs, and OCs);
2. To widen the perspective of Technology Roadmap by proposing suitable technology demonstrators for future RLVs. Indeed, in previous TRIS studies on IXV the target BB was a technology demonstrator and not the operational vehicle.

Starting from these generic enhancements envisaged for SoA TRIS, more specific improvements to be introduced in an enhanced version can be defined by deeply analysing each phase of the SoA methodology (Figure 80).

Step1. In Step 1, the possibility to retrieve elements' lists from HyDat is theoretically envisaged, but it is not yet practically implemented. In this context, (Fusaro et al., 2017) lays the foundation for the development of a database of roadmapping elements, introducing the type of data needed to characterize a certain project and suggesting the exploitation of a dedicated GUI to fill the database. However, the flow proposed for database backend filling (Figure 82) seems too simplistic and incomplete, being based on the definition of a single reference mission (either operative or demonstrative) addressed within the project. It seems more appropriate to leave the possibility to characterize the project specifying all the low-TRL activities leading to the final reference mission. This is particularly useful in view of using the database as source for the list of elements, since these intermediate activities may constitute the bricks of the incremental path suggested through the roadmap. In addition, the flow in Figure 82 does not entail BBs and OCs, so that it is not clear how these two pillars are involved in the database filling process. Most importantly, the nested structure proposed for HyDat in Figure 81 does not allow to fully appreciate the overall database architecture along with the interconnections among roadmapping elements. Furthermore, the data storage in MS Excel spreadsheets located at different folder levels may hamper the database accessibility as well as the updating process (with the risk to overwrite or delete files), in view of setting up in the future a common HyDat platform for sharing of knowledge as envisaged in (Fusaro et al., 2017). In this sense, a proper update of HyDat to make it suitable to interface with TRIS is judged mandatory in the present work. In account of this, great attention is paid to the formalization of a structured database architecture, which can be easily hosted on a server, accessed, and edited by the user. Notably, Section 7.3 thoroughly discusses the new database architecture proposed in this work, making benefit of the heritage coming from the exploitation of TREx. Please, notice that at this stage the focus is on the definition of a suitable database architecture able to support roadmapping activities. At this purpose, suggestions on possible ways to fill the database are also provided in Section 7.3.

Step 2 and Step 3. Moving to Applicability analysis, the elicitation of the links among elements is surely a required step towards the generation of a roadmap from different perspectives. Indeed, technologies are usually the focus of roadmapping and, specifically, of Technology Roadmapping. However, TRIS user might be interested in developing a specific set of OCs so that the focus is shifted towards OC and technologies are merely the enablers of required functions. In this sense, Applicability analysis is a fundamental tool to derive the list of technologies linked to the required set of OCs. In the framework of Applicability analysis, it is also noteworthy the possibility to provide additional information about elements and to further define their links using the labels “Required”, “Applicable”, and not “Applicable” to reflect stakeholders’ requirements. Nevertheless, the attribution of these labels is directly performed by TRIS user, which is in charge of interpreting and summarising all the multifaceted requests of stakeholders in a single label. This could lead to possible misunderstanding of stakeholders’ needs also taking into account that, in general, the same link might be intended as “Applicable” by a stakeholder or “Required” by another. As a result, the updated TRIS methodology described in Section 4.3 addresses the links among elements, but no further specifications are provided about the type of the link. This also makes the overall TRIS flow more straightforward since the exclusion of the labels “Required”, “Applicable”, and not “Applicable” from the analysis prevents from the need to weight links to quantify stakeholders’ expectations. This means that the step of Sensitivity analysis is no more required. It is also underlined that this step is by far the most intricate phase in SoA TRIS and it can be potentially awkward for an unexperienced TRIS user. As such, its removal should not be negatively intended as an oversimplification of the methodology but as an improvement in its exploitation from any user.

Step 4. In Prioritization studies, as reported in Section 4.1.2.3, the exploitation of the Prioritization Matrix as prioritization method implies the derivation of all possible criteria combinations and of many ranked lists of technologies (one per each combination). This could be excessively time consuming when several criteria are considered, leading to a huge number of criteria combinations. In addition, stakeholders’ requests are tackled only afterward during the selection of the “optimal” list thanks to the parameter K in Eq.(139). In account of this, a substantial modification of the prioritization routine is envisaged in the present work, mainly to speed up the roadmapping process and avoid the generation of a great number of ranked lists of technologies. On this basis, the present research proposes a new prioritization approach able to provide a single ranked technologies’ list already reflecting stakeholders’ requests, without the need to include them “a posteriori” in the process. Notably, the combination of criteria and, hence, the priority assigned to each criterion should reflect the importance of the stakeholder asking for that criterion and impacting on the final ranked list. This is not clearly traceable if all possible criteria combinations are considered. Basing on these considerations, the revision of the Prioritization routine is fully described in Section 4.3.3.

Step 5. As far as Planning definition is concerned, as shown in the algorithm of Figure 86, the ranked lists of technologies and missions are combined mainly checking the TRL of Mission Concepts (MCs) and considering budget availability. The main limitation of this routine lies in the fact that technologies are associated to MCs one by one, neglecting the possibility to increase the TRL of a set of technologies with a single MC. Indeed, the integration of technologies into suitable demonstrators is a crucial aspect to be considered when suggesting sustainable technology development paths. Therefore, an improved version of Planning routine is proposed in Section 4.3.4. The latter also introduces an updated version of the Time at Completion (TaC) breakdown onto TRL Transits in Figure 87 specifically tailored for future RLVs using data available from

literature. This could contribute to improve the accuracy in the estimation of time resources needed for technology development for each TRL Transit.
Furthermore, despite the strategic importance of estimating budget resources needed for technology development, SoA TRIS methodology does not provide any approach to quantify it. Indeed, recalling Figure 85, the typical distribution of technologies' Cost at Completion (CaC) onto TRL Transits is provided without any details about the order of magnitude of such costs. On this basis, remembering the activity flow at the basis of the present work (Figure 14), a fundamental objective of the overall process is to integrate of the Cost Model (Module 1) discussed in Section 3.2 with the Technology Roadmapping Methodology (Module 3) to support budget evaluation. The goal is to exploit the results from cost assessment to estimate the Technology Development Cost as well as the costs to be sustained during each TRL Transit. At this purpose, TRL Milestones are firstly mapped onto the vehicle life cycle by means of the Project Phases encountered (Hirshorn et al., 2017). Then, a link between Project Phases and LCC Phases is established. As a result, the connection between TRL Milestones achievement and LCC phases is determined (Section 4.2.1). Thanks to this result and basing on available information about the cost sustained during Space Shuttle Project Phases, an updated version of the CaC breakdown on TRL Transits in Figure 85 specific for RLVs is derived (Section 4.2.2). Benefitting of these results, as anticipated in Section 1.3, two different paths are proposed to determine Technology Development Cost, depending on the level of detail required. Notably, basing on the costs obtained from Module 1, "Path A" in Figure 14 suggests a way to preliminary assess the cost of TRL advancement at vehicle level (referred as Vehicle CaC in this work in analogy with the concept of technologies' CaC) with details on the allocation of Vehicle RDTE costs onto TRL Transits (Section 4.2.2.1). Complementary, "Path B" offers a more detailed insight onto Technology Development Cost by merging the results from cost estimation with the outcomes from Conceptual and Preliminary Design activities. Notably, information related to vehicle Product Breakdown Structure (PBS) (result of design activities) is exploited to split costs up to technology level, thus leading to a detailed assessment of technologies' CaC (Section 4.2.2.2). This discussion highlights another central point depicted within the activity flow in Figure 14, i.e., the possibility to better integrate Technology Roadmapping not only with cost estimation but also within conceptual design activity flow. As discussed in Section 4.1.2.1, this link is already provided in SoA TRIS thanks to the exploitation of Systems Engineering tools, but it is here strengthened by using

PBS data in support of Technology Roadmapping.

As a final remark, it is worth highlighting that the nomenclature adopted in SoA TRIS to define technologies subdivision (i.e. Technology Area split into Technology Subjects up to technologies) in Section 4.1.2 is based on NASA taxonomy (NASA, 2020b). However, considering the continuous collaboration with ESA experts all along this work in the framework of technology roadmapping activities, the ESA nomenclature for roadmapping elements' definition has been adopted in order to ease this interaction. Notably, the ESA Technology Tree (ESA, 2020a) is adopted for technologies, whilst the ESA Product Tree (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011) applies to BBs. More generically, the nomenclature associated to all pillars (excluding OCs) is revised considering their key role in the whole TRIS process (Section 4.3.2).

4.2 TRL, Project Phases and Technology Development Cost

4.2.1 Mapping of LCC onto Project Phases and TRL Milestones

In order to study the connection between the Technology Roadmapping methodology (discussed later on in Section 4.3 in its enhanced version) and the cost estimation model (Section 3.2) and thus assess the Technology Development Cost, it is worth recalling and enriching the definition of LCC already provided in Section 3.1. As mentioned, LCC entails all the costs sustained during vehicle lifecycle (herein labelled as Vehicle LCC), covering all the Project Phases depicted in Figure 88. The latter shows the life cycle phases applicable to a generic space project along with the major activities carried out during each phase comparing ESA and NASA nomenclature.

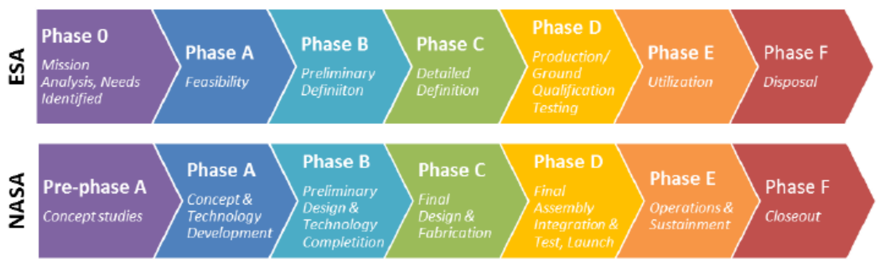


Figure 88: Phases of project life cycle according to ESA and NASA (Cotterman, H. et al., 2005)

Additional details about ESA Project Phases subdivision available from (ECSS (European Cooperation for Space Standardization), 2017) are depicted in Figure 89, highlighting the TRL Milestones typically achieved during each phase. As additional information, it also indicates the stage at which main reviews envisaged by ESA should be performed (e.g., System Readiness Review (SRR), Qualification Review (QR), etc.).

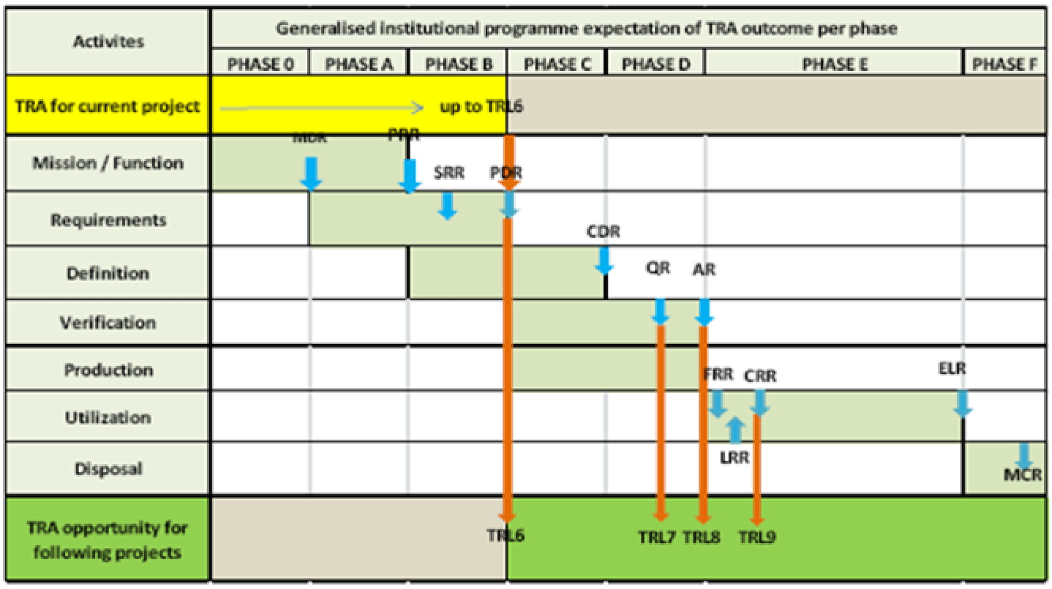


Figure 89: ESA Project Phases and related Activities (ECSS (European Cooperation for Space Standardization), 2017)

Thanks to the information provided in Figure 88 and in Figure 89 it can be inferred that Vehicle CaC, dealing with the establishment of the technological know-how related to the vehicle, represents only a portion of Vehicle LCC. More precisely, in the first instance, Vehicle CaC could be defined as equal to RDTE cost, entailing the cost of breadboards, brass-boards, prototypes, qualification and proto-flight units (Hammond, 1999). Reference to these models can also be found in Table 66 with the associated TRL Milestones achievement.

Table 66: Commonly-used models for TRL progression (ECSS (European Cooperation for Space Standardization), 2017)

Model	Potential use with respect to TRL scale
Structural model	Used, when necessary, to progress to TRL 6
Thermal model	Used, when necessary, to progress to TRL 6
Structural-thermal model	Used, when necessary, to progress to TRL 6
Engineering model (scaled)	Used, when necessary, to progress from TRL 4 to TRL 5
Development model	Used, when necessary, to progress from TRL 4 to TRL 6
Engineering model (full scale)	Used, when necessary, to progress to TRL 6
Engineering qualification model	Used to progress to TRL 7
Qualification model	Used to progress to TRL 7
Human related models	Used, when necessary, to progress to TRL 7
Life test model	Used, when necessary, to progress to TRL 7 in conjunction with model(s) used for qualification
Protoflight model	Used, when decided, to achieve TRL 7, TRL 8 and TRL 9.
Flight model	Used to progress to TRL 8 and 9.

From Table 66 it can be noticed that the most advanced models covered by RDTE, i.e., proto-flight models, can allow the progression up to TRL9. However, the final jump from TRL8 and TRL9 is guaranteed by the set-up of the flight model, whose cost by definition is not included into RDTE (Section 3.1.2). As such, RDTE cost is related to the whole TRL scale (from TRL1 to TRL9) to highlight the need to perform continuous RDTE activities, but the actual fulfillment of the final transit between TRL8 and TRL9 requires an additional cost contribution linked to the flight model. In other terms, Vehicle CaC up to TRL9 ($Vehicle\ CaC_{(TRL9)}$) can be expressed as in Eq.(139), where $Vehicle\ RDTE_{(TRL1-9)}$ is Vehicle RDTE cost covering the TRL Transit 1 to 9 and $X_{(TRL8-9)}$ is the additional cost required to effectively move from TRL 8 to TRL 9.

$$Vehicle\ CaC_{(TRL9)} = Vehicle\ RDTE_{(TRL1-9)} + X_{(TRL8-9)} \tag{139}$$

In this context, Figure 89 shows that Production and a portion of Utilization Activities (herein referred as Initial Operations) contribute to reach TRL 9 as well. Therefore, by understanding which tasks are effectively carried out during these activities, it is possible to determine the cost items involved and thus determine $X_{(TRL8-9)}$. Notably, it can be stated that Production Activities (in Figure 89) deal with the construction of the actual launch vehicle, since Utilization Activities directly follow. However, considering that Production Activities span TRL levels from 6 to 8, it can also be inferred that they also entail all intermediate technology demonstrators (basing on Table 66). As a result, their final output is the construction of a flight model coinciding with the actual vehicle, which is therefore used for final TRL 9 achievement during Utilization. As a result, the cost of Production Activities is covered by RDTE cost up to proto-flight units and by TFU Production cost for what concerns flight unit/actual vehicle cost. However, the direct switch from Production Activities to Utilization Activities is by far not representative of RLVs case. Indeed, considering that RLVs will be subject to series production similarly to current aircraft (Section 3.1.2.3), the smooth transition from Production to Operations Costs suggested by (Roskam, 1990) in Figure 90 seems more suitable. Here, Production and Operations Costs are sustained in parallel for a certain period since Operations start while series-production is still running.

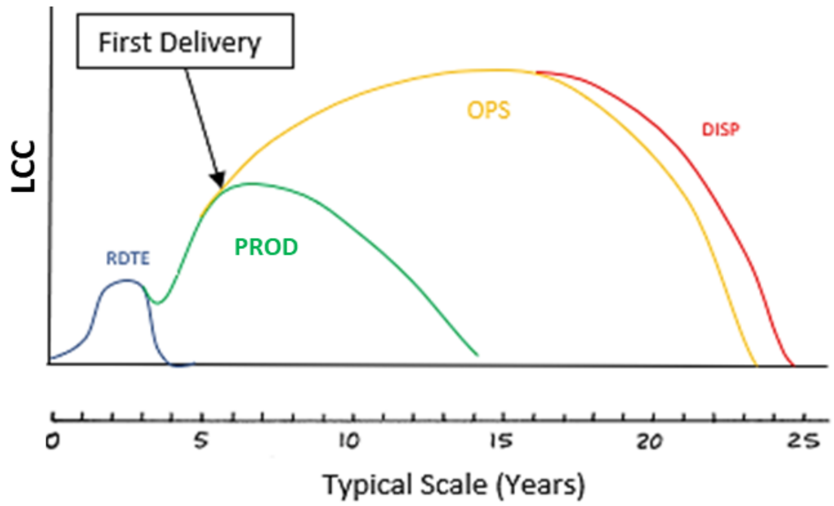


Figure 90: Typical LCC distribution over time for aircraft (Roskam, 1990)

Furthermore, taking into account the fundamental role of flight testing to guarantee the final qualification of the system (Table 66), it is judged more appropriate to extend the definition of Production Activities (as intended in Figure 89) up to TRL9. Notably, it is assumed that Production Activities for the establishment of proto-flight units (associated to RDTE costs) may lead up to TRL9 (in line with Table 66), while the tasks related to the production of the flight unit together with the flight tests accomplishment assure the final TRL Transit between 8 and 9. After that, series-production continues in parallel with routine vehicle operations. Therefore, assuming to exploit the first unit produced for flight testing, the cost of Production Activities and Initial Operations between TRL8 and TRL9 constitute the contribution $X_{(TRL8-9)}$ in Eq.(139) as expressed in Eq.(140), thus leading to the final expression for $Vehicle\ CaC_{(TRL9)}$ in Eq.(141).

$$X_{(TRL8-9)} = Vehicle\ TFU\ Production_{(TRL8-9)} + Initial\ Operations_{(TRL8-9)} \quad (140)$$

$$\begin{aligned} Vehicle\ CaC_{(TRL9)} = \\ Vehicle\ RDTE_{(TRL1-9)} + Vehicle\ TFU\ Production_{(TRL8-9)} \\ + Initial\ Operations_{(TRL8-9)} \end{aligned} \quad (141)$$

As a result, by exploiting Eq.(141) it is possible to provide an updated version of Figure 89 specifically tailored for RLVs, i.e., Figure 91. The chart shows the progression of Project Phases along with main activities performed (as in Figure 89), highlighting the extension of series production after the fulfilment of TRL9. Moreover, Project Phases are marked by TRL Milestones, partially in line with Figure 89, but also taking into account the discussion about the activities for final TR8 to TRL9 transit. The proposed Figure is also enriched with information related to LCC, reporting the subdivision of cost items (i.e., RDTE, Production, Operations) (Section 3.1.1) onto TRL transits. For sake of clarity, considering the importance of the final Transit from TRL8 to TRL9 within the present discussion, RDTE cost is split in two contributions in Figure 91, i.e., $RDTE1$ from TRL1 to TRL8 and $RDTE2$ from TRL8 to TRL9. To conclude, thanks to the present study the costs at vehicle level derived from LCC analysis (i.e., Vehicle LCC) are now related to the costs sustained to perform technology development at vehicle level (i.e., Vehicle CaC) exploiting the relationship between Project Phases and TRL milestones achievement.

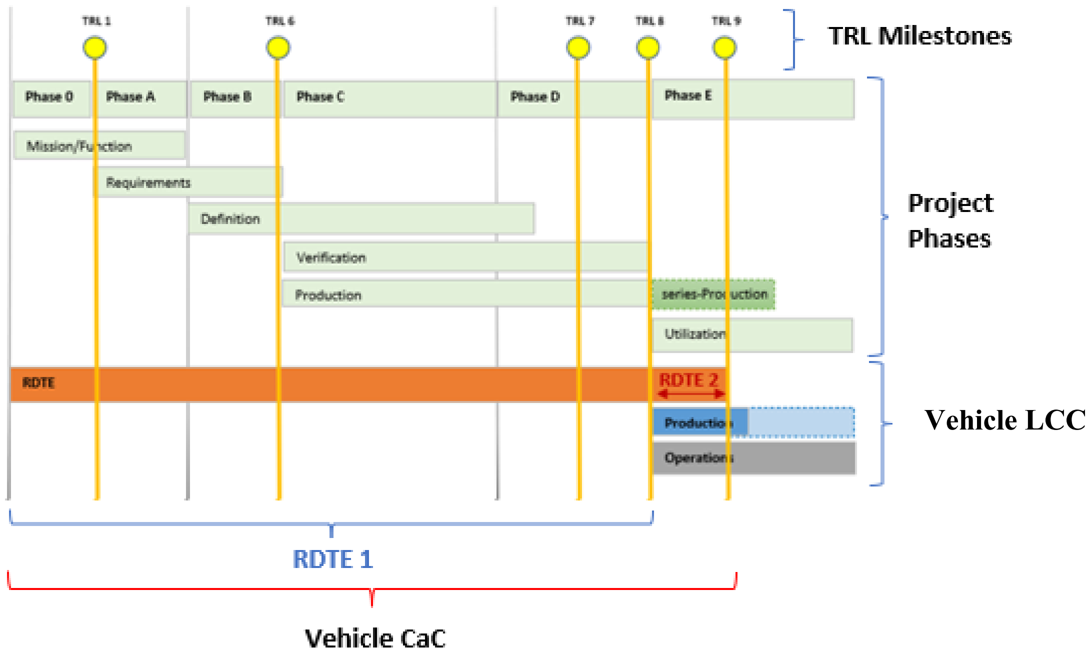


Figure 91: Location of TRL Milestones on Project Phases for hypersonic derived from original ESA subdivision (Viola et al., 2022)

4.2.2 Vehicle CaC breakdown onto TRL Transits for RLVs

As mentioned in Section 4.1.2, a purpose of the present work is to provide a new version of the Cost at Completion (CaC) breakdown onto TRL Transits previously provided in Figure 85. The new CaC subdivision should be specifically tailored to RLVs and should be used in the phase of Planning routine (Section 4.3.4) to split the required budget onto TRL Transits. At this purpose, starting from the definition of Vehicle CaC and of the specific tasks carried out to pursue technology development discussed in the Section 4.2.1, available cost data related to the activities performed during the RLVs development has been collected. However, recalling the few RLVs effectively built (Section 1.2) as well as the lack of detailed cost data associated to the TRL progression of such concepts, this analysis focuses on the Space Shuttle, for which details about the costs for Design, Development, Test and Evaluation (DDTE) are available from (Mandell, 1983). Notably, the annual DDTE expenditures from 1971 to 1982 are reported. However, in (Mandell, 1983) no detailed information about the TRL milestones achieved during Space Shuttle Program is reported so that, with the aim to obtain the breakdown of Vehicle CaC onto TRL Transits, they have been assumed in this work considering the link between Project Phases and TRL milestones in Figure

91. Specifically, thanks to the Space Shuttle Program History depicted in Figure 92, it is possible to appreciate the time distribution of Project Phases related to DDTE.

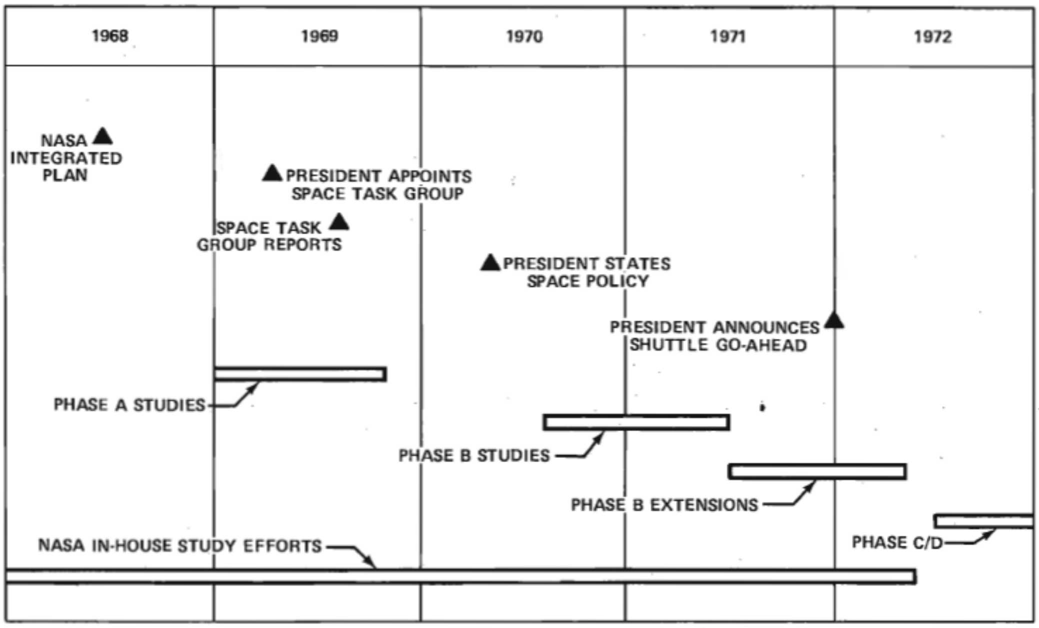


Figure 92: Space Shuttle Program History, Early Events and Program Phases (Mandell, 1983)

Please, note that the definition of Project Phases here adopted is predating the NASA subdivision in Figure 88, hence it is slightly different. For sake of clarity, in Figure 92 the following nomenclature applies:

- Phase A: Conceptual Design;
- Phase B: Program Definition & Preliminary Design;
- Phase C/D: (Detailed) Design, Development and Test.

In addition, thanks to information available in literature (Approach and Landing Test Evaluation Team, 1978; Mandell, 1983) it is possible to further characterize the Phase C/D in terms of the main milestones achieved, notably:

1. 15th February 1977: First Approach and Landing Test (ALT), i.e., ALT-1 (taxi-test);
2. 26th October 1977: Last ALT, i.e., ALT-16 (free-flight test);
3. 12th April 1981: First Orbital Manned Flight (FMOF);

4. 11th November 1982, 5th orbital flight of Space Shuttle Columbia (official end of DDTE phase according to (Mandell, 1983))

At this point, considering 1) the activities carried out in each Project Phase, 2) the specific flight tests performed during DDTE (i.e., ALTs and FMOF) and 3) the definition of TRL scale (Section 4.1.1), it is possible to place TRL milestones along Space Shuttle Program History as depicted in Figure 93. In this context, it is specified that:

- Space Shuttle technology development is assumed to start from TRL greater than 1 considering the heritage deriving from previous US space programs such as Apollo;
- No cost data is available for low TRL levels (i.e., TRL 2 and 3) because no dedicated budget was allocated by US Government but generic NASA funding was used.

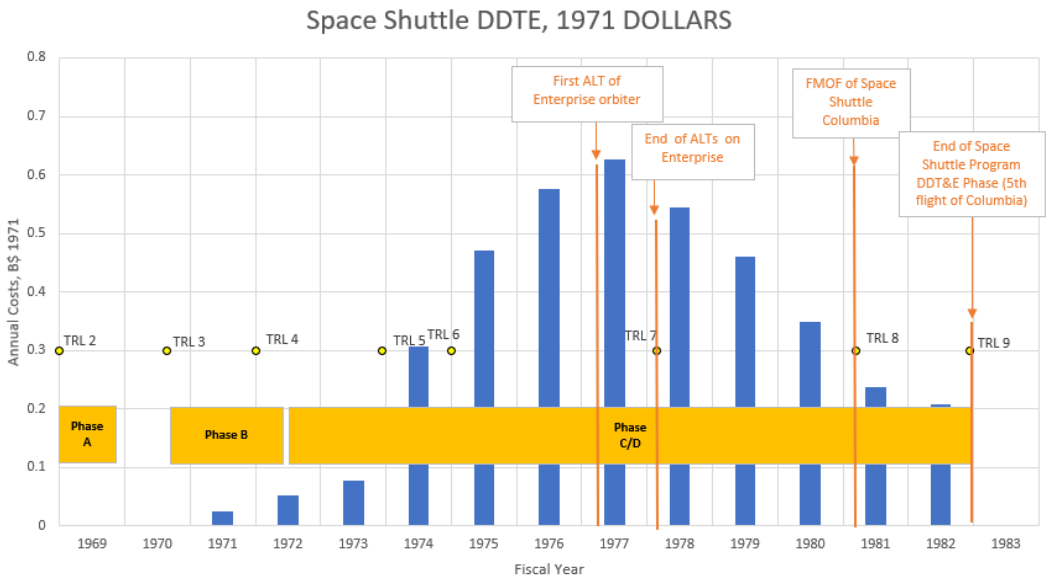


Figure 93: Space Shuttle Program History, Early Events and Program Phases (Mandell, 1983)

The association of TRL Milestones along the timeline (with related costs) provide a new Cost at Completion (CaC) distribution on TRL transits (Figure 94) at vehicle level (i.e., Vehicle CaC) which is basically in line with the former CaC breakdown for hypersonic and re-entry systems derived from experts' opinion (Figure 85). Indeed, the position of TRL 6 and TRL 7 milestones mirrors the high costs incurred for development, production, and test of flight demonstrators so that the increasing trend in annual funding depicted in Figure 93 is associated to the financing of these TRL transits. Similar considerations apply to TRL 5 milestone, which is also connected to consistent budget requirements for the development of on ground demonstrators. For sake of clarity, the CaC distribution for low TRL levels, not available from Space Shuttle data, derives from development costs effectively sustained for Sänger vehicle propulsion system (Sacher, 2010), which have been properly associated to TRL transits as performed for Space Shuttle.

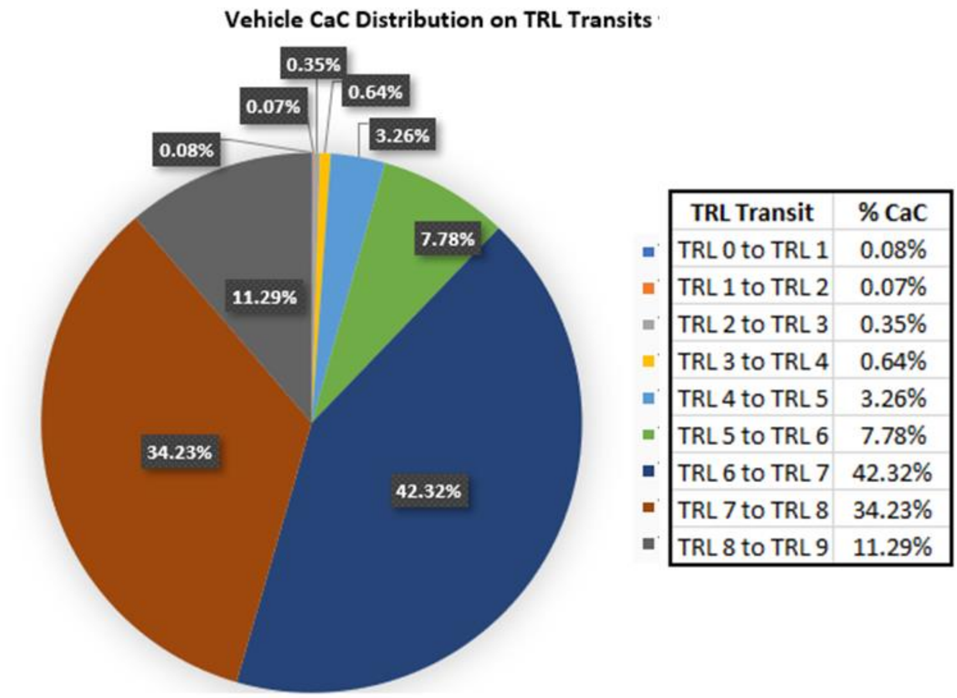


Figure 94: Newly derived Vehicle CaC distribution on TRL transits for RLVs

4.2.3 Technology Development Cost Assessment

The new CaC breakdown in Figure 94 can be exploited to perform additional studies useful for both cost analysis and Technology Roadmapping. Notably, referring to the activity flow in Figure 14, Figure 94 can be used to explore the link between Module 1 and Module 3 and derive the Technology Development Cost required for the overall vehicle (i.e., at vehicle level). At this purpose, a new expression for Vehicle RDTE costs including TRL as cost driver is suggested (Path A in Figure 14, described in Section 4.2.2.1). Complementary, the CaC subdivision in Figure 94 coupled with detailed subsystems information available from the PBS can be used to strengthen even more the relationship between Module 1 and Module 3 and provide a more detailed estimation of Technology Development Cost at technology level (i.e., technology CaC). This is accomplished through Path B (Figure 14) described in Section 4.2.2.2.

4.2.2.1 Vehicle RDTE Cost as a function of TRL (Path A)

The possibility to include TRL as additional driver onto RDTE cost estimation of future RLVs can give useful information about the resources still to be allocated in order to fulfill technology development. Indeed, cost estimation and, specifically, RDTE cost assessment evaluate the overall budget required for Technology Development Cost. However, in case of RDTE estimations related to systems already at advanced development status, it might be more useful to provide an estimation of the remaining development costs to be sustained from current TRL up to TRL9. This provides information about the technological sustainability of proposed concepts, allowing to allocate only required financial resources and avoid overestimations. In account of this, making benefit of the results in terms of Vehicle Cost at Completion (CaC) breakdown obtained in Figure 94, a general methodology to estimate Vehicle RDTE cost depending on the vehicle maturity already achieved is described. Since the proposed approach is based on the results of LCC assessment, it is deemed useful to start its description considering the cost results obtained for the case studies tackled in this Dissertation (Section 2.4). For sake of clarity the example described in detail in the remainder of this Section deals with Case Study 1 considering that it is the focus of the roadmapping activities described later on in Section 4.5. Specifically, a governmental scenario is analyzed (however, the same considerations also apply to a commercial scenario). Starting from the example, the approach is generalized in order to obtain a new expression for Vehicle RDTE cost using the cost drivers already considered within the Cost Model in Section 3.2.1 as well as current TRL. Firstly, Eq.(141) is applied using the RDTE, Production and Operating Costs obtained for Case Study 1. Notably, Total RDTE in Table 42 (i.e., 35.82 B€) and Total TFU Production Cost in Table 45 (i.e., 1997.21 M€) are considered. Moreover, Initial Operations Cost is obtained by summing up the DOC, IOC, and RSC contributions from Table 50 and then by multiplying by the number of demo flights performed. In this context, five demo flights are assumed basing on the Space Shuttle experience (Mandell, 1983). This provides an estimated $Vehicle\ CaC_{(TRL9)}$ of 37,880 M€. In addition, basing on the definitions provided in Section 4.2.1, values for $RDTE\ 1$ and $RDTE\ 2$ contributions. Specifically, as clarified in Figure 91, the percentage of Total RDTE labelled as $RDTE$ 1 (also referred as Vehicle CaC up to TRL8 (Vehicle $\mathrm{CaC}_{(\mathrm{TRL8})}$)), is defined as in Eq.(142).

$$RDTE\ 1 = Vehicle\ CaC_{(TRL8)}\ = K_1\ \cdot\ Vehicle\ CaC_{(TRL9)} \tag{142}$$

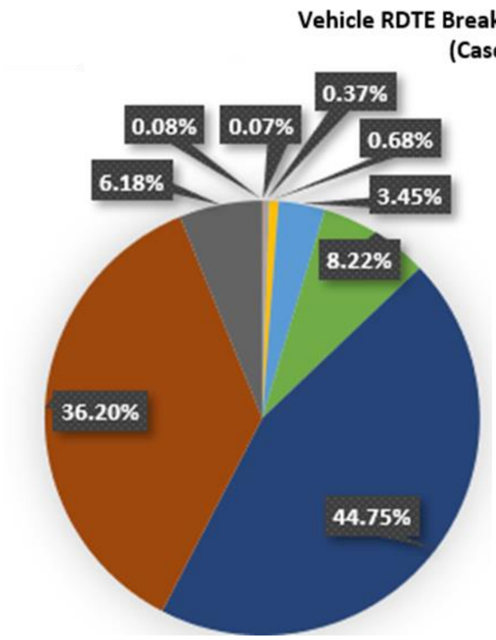
Where K_1 represents the percentage of Vehicle CaC sustained up to TRL 8. According to Figure 94, it is 88.71% of $Vehicle\ CaC_{(TRL9)}$ (i.e., 33,603 M€ for Case Study 1). As far as $RDTE$ 2 is concerned, it defined as in Eq.(143) and, basing on the results mentioned above, it is equal to 2,214 M€ for Case Study 1.

$$RDTE\ 2 =\ Vehicle\ RDTE - RDTE\ 1 \tag{143}$$

At this point, it is worth underlying that the dependence between TRL and costs has been previously expressed involving $Vehicle\ CaC_{(TRL9)}$ (Eq.(141)). However, remembering the current interest in determining the specific effect of TRL onto Vehicle RDTE cost, its contribution onto $Vehicle\ CaC_{(TRL9)}$ is now isolated. Notably, thanks to the previous results, it can be stated that:

$$RDTE\ 2 = 5.85\% \cdot\ Vehicle\ CaC_{(TRL9)} \tag{144}$$

In this way, the contributions of Vehicle TFU Production and Initial Operations costs can be excluded from the formulation of $Vehicle\ CaC_{(TRL9)}$ for Case Study 1. This allows to derive a new version of Figure 94 expressing Vehicle RDTE (and not Vehicle CaC) breakdown onto TRL Transits (Figure 95). The breakdown can also be expressed cumulatively as in Figure 96, showing the cumulative fraction of Development Cost to be sustained in order to attain a certain Vehicle Maturity. Please, notice that in Figure 96 cumulative fractions are expressed in terms of k_{TRL_x} coefficients (with x between 0 and 9).



TRL Transit	% RDTE
TRL 0 to TRL 1	0.08%
TRL 1 to TRL 2	0.07%
TRL 2 to TRL 3	0.37%
TRL 3 to TRL 4	0.68%
TRL 4 to TRL 5	3.45%
TRL 5 to TRL 6	8.22%
TRL 6 to TRL 7	44.75%
TRL 7 to TRL 8	36.20%
TRL 8 to TRL 9	6.18%

Figure 95: Vehicle RDTE distribution on TRL Transits

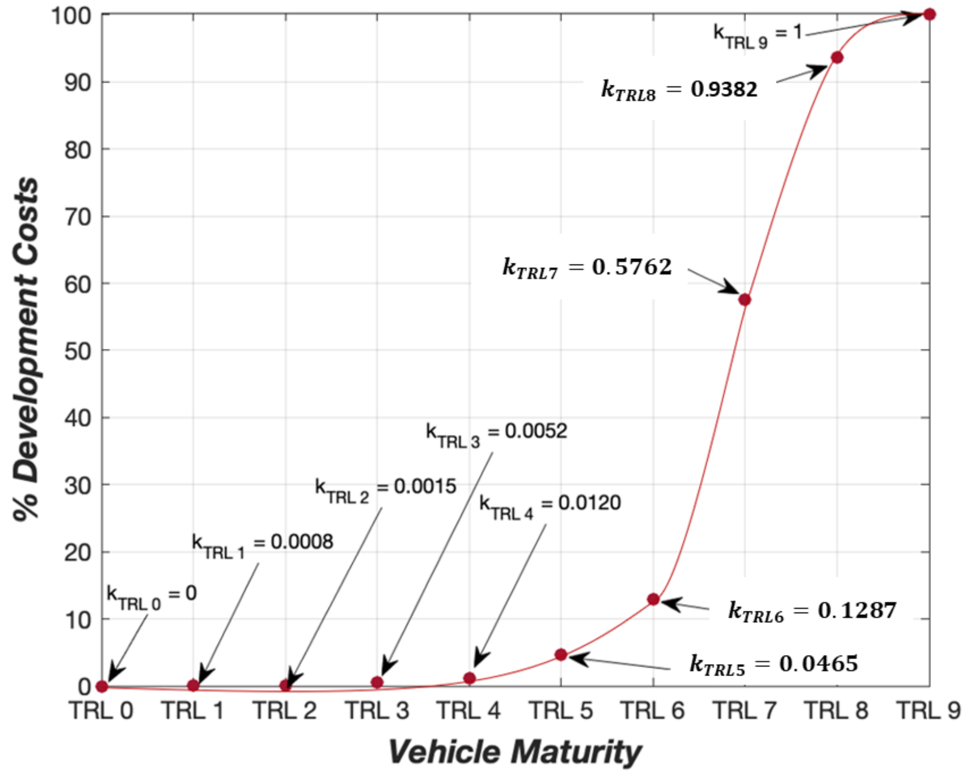


Figure 96: Cumulative Vehicle RDTE distribution on TRL Transits

As a first approximation, the values for k_{TRL_x} in Figure 96 can be considered fixed for RLVs similar to Case study 1 (i.e., HTHL Airbreathing First Stage Vehicle with Expendable Rocket Second Stage). Therefore, basing on the nomenclature defined for Eq.(21), the general formulation linking TRL and Vehicle RDTE costs reported in Eq.(145) can be derived.

$$Vehicle\ RDTE_{(TRL_x)} = \left(1 - k_{TRL_x}\right) \cdot f_0 \left(\sum H_V + \sum H_E\right) f_6 f_7 \qquad (145)$$

For sake of clarity, Eq.(145) provides $Vehicle\ RDTE_{(TRL_x)}$, which is Vehicle RDTE Cost to be sustained to move from $TRLx$ to TRL9. This expression provides Vehicle RDTE Cost as a function of the maturity currently achieved during vehicle development (by means of to k_{TRL_x}) and of the design characteristics of Vehicle Systems and Engines under study (through $\sum_i H_{VA_i}$ and $\sum_j H_{E_j}$). Please, notice that specific RDTE equations included within $\sum H_V$ and $\sum H_E$ for RLVs similar to Case Study 1 in terms of configuration are summarized in Table 38.

To summarize, the approach proposed in this Section provides a preliminary assessment of the overall budget required to sustain technology development for specific RLV categories as a function of current TRL achieved as well as of vehicle design characteristics. This allows to determine the impact of both vehicle maturity and design parameters onto required budget. As mentioned, the present analysis is highly based on the results of LCC assessment carried out for a specific Case Study tackled in this Dissertation. However, obtained results (i.e., k_{TRL_x} in Figure 96) can be preliminary used to provide budget assessment for RLV belonging to the same category. In addition, the general formulation expressed by Eq.(147) is applicable to any RLV configuration. Indeed, by applying the LCC methodology in Section 3.2 to other RLV types, specific formulations for k_{TRL_x} can be obtained and used within Eq.(145).

4.2.2.2 Technologies' CaC assessment (Path B)

Following Path A depicted in Figure14, Section 4.2.2.2 suggested a methodology to assess Technology Development Cost for the vehicle basing on the maturity effectively attained. This is certainly a useful tool to preliminary estimate the overall budget needed to pursue technology development. However, considering that this Chapter focuses on Technology Roadmapping, it is also required to provide further details about the subdivision of required budget onto technologies and thus to determine technologies' Cost at Completion (CaC). Basing on (Cresto Aleina, 2018), this parameter is usually of great interest during Stakeholders' Analysis since it used as criterion during technologies' ranking. Considering a Space Exploration Scenario, values of technologies' CaC can be retrieved from TREx (Section 4.1.2.1), but historical data for hypersonic case studies is not available (Fusaro et al., 2017). In this context, in line with Path B in Figure 14, the connection with the activities of preliminary and conceptual design can be beneficial to improve the accuracy in estimating necessary budget resources for each technology. In account of this, this Section proposes a strategy for technologies' CaC assessment that exploits the definition of Vehicle CaC provided in Section 4.2.2 and specific outcomes from conceptual design phase. Notably, as in Eq.(148), technologies' CaC can be expressed as function of Vehicle CaC (in turn evaluated knowing the Vehicle LCC as described in Section 4.2.1) and of the cost of PBS items. Please, notice that the concept of PBS has been defined in Section 1.3.

$$Technology\ CaC_i = f\{Vehicle\ CaC\ [g(Vehicle\ LCC)], Cost\ of\ PBS\ Items\} \tag{146}$$

Where $Technology\ CaC_i$ in is CaC of i[th] technology.

Differently from Vehicle CaC, technologies' CaC assessment is effectively applicable up to TRL8 instead of TRL9. Indeed, at TRL9 all technologies are physically integrated onto the actual flight vehicle. Therefore, only the costs incurred up to TRL8 can be specifically allocated onto technologies. Recalling the subdivision provided in Figure 91, these costs represent the fraction of Vehicle RDTE cost labelled as $RDTE\ 1$ (or $Vehicle\ CaC_{(TRL8)}$) and defined through Eq.(142). In addition, basing on the taxonomy defined by the ESA technology Tree (ESA, 2020a), each technology belongs to a specific Technology Domain (TD), which is strictly related to one or more PBS items. Please, notice that a thorough discussion on the ESA technology Tree is provided later on in Section 4.3.2. As such, by subdividing $Vehicle\ CaC_{(TRL8)}$ onto PBS items it is possible to determine the development cost associated to the j[th] TD. In this context, it is specified that existing commercial tools, (like the True Planning software by Price Systems) can provide an allocation of Vehicle RDTE costs onto PBS items (indeed, this level of detail is not achieved by the cost model proposed in Section 3.2). Considering the $RDTE\ 2$ contribution negligible with respect to $RDTE\ 1$

(this has been specifically verified for Case Study 1), as a first approximation, the subdivision of Vehicle RDTE costs onto PBS items (providing the RDTE cost allocation on major TDs) is very close to the allocation of $Vehicle\ CaC_{(TRL8)}$ ($RDTE$ 1) onto PBS items. At this point, to proceed with the final costs' allocation onto technologies, depending on data availability, one of the following strategies can be pursued:

1. If RDTE costs breakdown onto PBS items is available at component level (for example, from Price True Planning software), the cost of associated technologies is equal to component cost divided by the number of technologies linked to that component. In case information about the relative importance (in terms of costs) of technologies associated to the same component is available, proper weight factors might be introduced, associating more importance (i.e., cost) to certain technologies than others;
2. If PBS costs breakdown is not available at component level, an ad-hoc weighting strategy has to be adopted. An example is provided in Section 4.5.1.2.

To summarize, the CaC of i^th^ technology belonging to j^th^ TD ($Technology\ CaC_{ij}$) can be evaluated as a function of $Vehicle\ CaC_{(TRL8)}$ as in Eq.(147):

$$Technology\ CaC_{ij} = K_{Tech\ i} \cdot K_{TD j} \cdot Vehicle\ CaC_{(TRL8)} \tag{147}$$

Where K_{TDj} is the RDTE cost contribution of the jth TD and $K_{Tech\ i}$ is the cost fraction associated the ith technology relatively to other technologies in the jth TD.

4.3 Enhanced TRIS Methodology Overview

Starting from the SoA TRIS described in Section 4.1.2, a thorough revision of the Technology Roadmapping Methodology formerly proposed is performed in the present study basing on the remarks collected in Section 4.1.3. With the main purpose of increasing the flexibility of the methodology and widening its applicability to different hypersonic vehicle configurations and missions, the main phases of the SoA approach depicted in Figure 80 have been reviewed, leading to the enhanced TRIS methodology flowchart shown in Figure 97. The latter is described, step by step, in the following subsections.

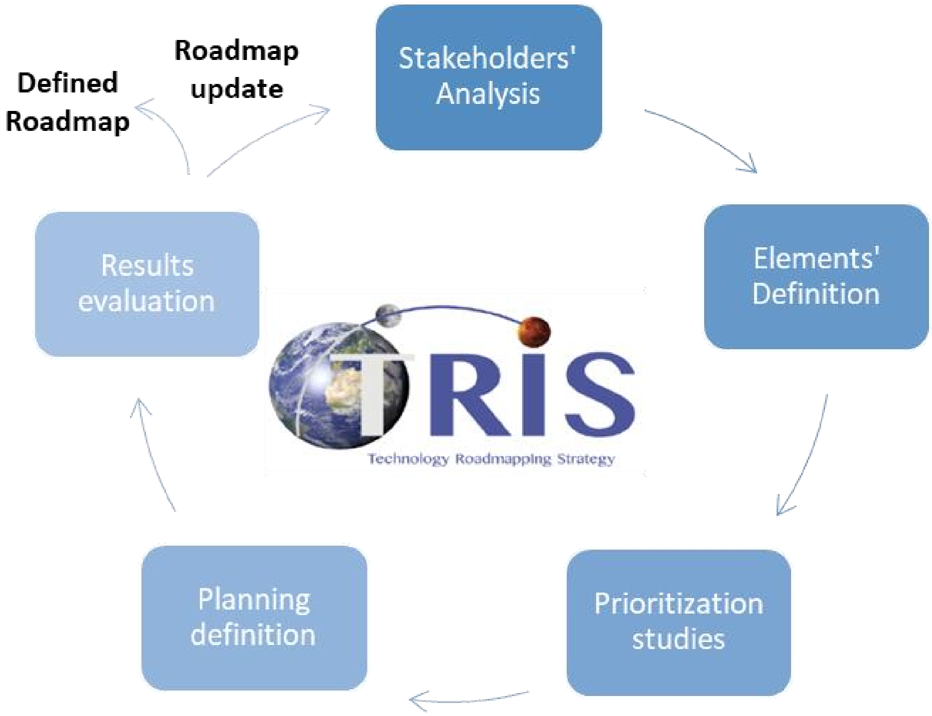


Figure 97: Enhanced TRIS Methodology Flowchart

4.3.1 Stakeholders' Analysis

With respect to the original TRIS methodology flowchart in Figure 80, the updated process (Figure 97) starts from Stakeholders' Analysis, which is now specified as an independent step considering its crucial role in any decision-making process. Indeed, it is deemed essential to identify from the very beginning of roadmapping activities all the entities involved in the process, specifying their role(s) and predicting their impact on the final decision (INCOSE, 2015). As in SoA TRIS (Section 4.1.2.1), all the actors are categorized depending on their role (Sponsor, Operator, End-user, or Customer) and characterized according to their main areas of interest in the analysis (final mission needs, political needs, general public needs, economic needs, scientific needs, or technological needs). Depending on the category and the area of interest which each stakeholder belongs to, the influence and the interest of each actor is predicted thanks to the exploitation of a Strategy Grid (Figure 83). Moreover, to quantify stakeholders' impact in the roadmapping process, the 4-levels approach described in Section 4.1.2.1 is exploited. Specifically, the importance (or weight) of the ith stakeholder within the Strategy Grid (K_{SG}, analogous to s_i in Eq.(138)) can be assessed. For sake of clarity, the goal of Stakeholders' Analysis is not only to define stakeholders but also to collect their expectations in form of parameters to be monitored and exploited during the decision-making process. Considering that these parameters are used during Prioritization Studies (i.e., Step 3 in Figure 97), it is essential to associate each of them to a prioritization order (ascending or descending). This allows to express a criterion as in Eq.(150).

$$K_{SG_i} \cdot K_{C_{ij}} \cdot (\text{Parameter } + \text{ in Ascending/Descending Order}) \tag{148}$$

This expression takes into account the weight of the stakeholder itself on the selection process (please, notice that in case of single stakeholder, K_{SG_i} is set to 1) as well as the importance of a specific criterion for that stakeholder. Indeed, in case a stakeholder expresses several criteria, it is important to identify a priority or order for them. This is mathematically expressed by $K_{C_{ij}}$ (Eq.(148)), which represents an additional weighting factor set to 1 in case of single criterion or customizable to express the relative importance of criteria asked by the same stakeholder.

During the phase of Stakeholders' Analysis, it is also important to specify the main programmatic requirements related to the technology development. Indeed, such requirements are set by the actors involved at the beginning of the overall technology development process. In particular, the timeframe spanned by the roadmap and the TRL achieved at the end of technology development should be defined. This information will be fundamental to suggest an incremental development path within the Planning Definition Phase described in Section 4.3.4.

4.3.2 Elements' Definition

Referring to Section 4.1.1, the pillars of State-of-the-Art (SoA) TRIS are 1) OC, 2) TA, 3) BB, and 4) MC. As mentioned in Section 4.1.3, this nomenclature has been revised in this study. Indeed, considering the continuous collaboration with ESA experts all along this work in the framework of Technology Roadmapping activities, the ESA nomenclature has been adopted for roadmapping elements' definition in order to ease this interaction. As a result, the following Sections introduce the definitions of Technology Roadmapping pillars as intended in this enhanced version of TRIS, highlighting differences and commonalities with respect to SoA TRIS. In addition, specifically considering the Elements' Definition step, it can be stated that it compacts the former "Roadmap elements definition and characterization" and "Applicability analysis" steps in Figure 80. Indeed, each element is characterized with properties reflecting the parameters asked by stakeholders during the previous step and links between elements are specified. As far as "Sensitivity analysis" step is concerned, it is excluded in the new TRIS methodology following the considerations reported in Section 4.1.3. As a result, along with a precise definition of each pillar, the following Sections describe the Elements' Definition process with special focus on 1) the main parameters describing each pillar and useful for the roadmapping process and 2) if available, the strategies followed to derive lists of elements suitable for the case study treated in this Dissertation. Moreover, starting from the need to formalize a proper architecture for HyDat database able to host the newly derived lists of elements with related parameters as well as links among elements (Section 4.1.3), a thorough revision of HyDat has been carried out. In account of this, basing on the initial HyDat architecture suggested by (Fusaro et al., 2017), the upgraded back-end structure is presented in Section 7.3 (Annex).

4.3.2.1 Technology (Tech)

With the aim to adjust to the ESA nomenclature, the ESA Technology Tree is considered as main reference for technologies definition in this work. The three-level structure of the Technology Tree is reported in Figure 98.

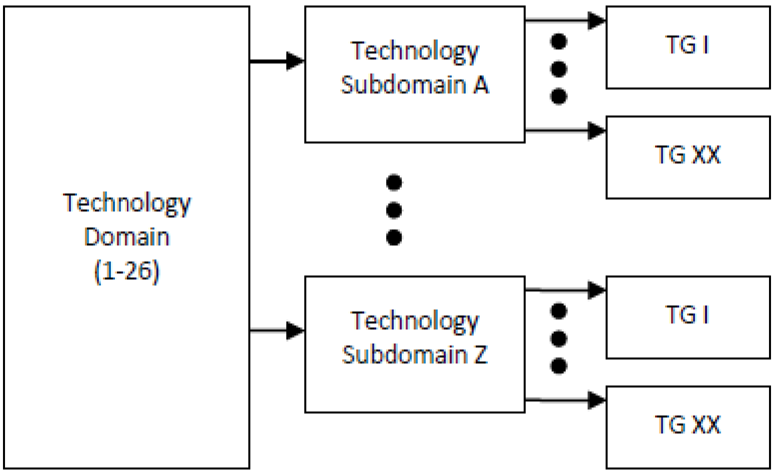


Figure 98: Structure of the ESA Technology Tree (ESA, 2020a)

By definition, Technology Domains (TDs), at the first level, refer to the "*knowhow relevant to a technical area that can be identified as being standalone and can therefore be considered independently of other TDs*" (ESA, 2020a). TDs are further split into Technology Subdomains (TSs), which "*provide a more* *accurate description*" of a TD content "*in terms of different but related technical areas*". Eventually, TSs are subdivided into Technology Groups (TGs), which "identify a technology that is relevant to a family of products but that is not the description of a product in itself". To clarify these definitions, Table 67 shows an example of TD, reporting one of the related TSs as well as some of the TGs linked to the selected TS.

Table 67: Example of TD, TS and TGs according to ESA Technology Tree (ESA, 2020a)

Technology Domain (TD)	**Technology Subdomain (TS)**	**Technology Group (TG)**
15 - Mechanisms	A - Mechanism Core Technologies	I – Actuator Technologies.
		II – Damper & Speed Regulator Technologies.
		III – Motion Transformer Technologies.
		IV - …

From Table 67, it can be inferred that TGs refer to a collection of technologies, with the same purpose (e.g., to allow actuation for Actuator Technologies) but characterized by different target application (e.g., aircraft vs. space vehicle), performance, complexity, TRL, cost, etc. As such, considering that the purpose of this Dissertation is to perform Technology Roadmapping for technologies with certain features and envisaged for specific products (i.e., RLVs), the lower-level pillar herein considered is "Technology" (Tech), which belongs to a certain TG (in turn, part of a TS and belonging to a TD). Moreover, for the purposes of Technology Roadmapping, each Tech should be characterized in terms of current TRL achieved, possibly tracking the TRL history (i.e., TRL milestones) leading to the current development status and the Cost at Completion (CaC). In this context, lacking a structured database able to store elements' data (Section 4.1.3), Functional and Product Trees can be fundamental tools to derive lists of Techs as well as links with other elements as previously suggested in State-of-the-Art (SoA) TRIS. However, the connection between design activities and technology roadmapping is even more strengthened in the new version of TRIS. Indeed, an alternative strategy to derive a list of technologies is suggested based on another fundamental outcome of conceptual design phase, i.e., PBS. As described in Section 4.2.2.2, the possibility to allocate RDTE costs onto PBS can support in the assessment of Techs CaC. However, a detailed PBS breakdown up to component level can also support in the definition of the list of technologies itself. The exploitation of a PBS can also guarantee the derivation, in a logical way, of the links existing between technologies and BBs (at different hierarchical level). An example of exploitation of PBS to derive the list of technologies required for Case Study 1 is provided in Section 4.5.1.2.

4.3.2.2 Building Block (BB)

Moving to BBs, the ESA Product Tree (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011) schematically shown in Figure 99 is used as baseline for the definition of this pillar. Further information about the specific items included in each branch of the tree can be found in (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011). The Product Tree "*provides a generic, structured and complete classification of space products*" (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011). and it is broken down into three main levels, i.e., Segments, Systems and Products. Products are further classified as:

- Equipment, i.e., "*unit at high integration level performing a high-level function or set of functions*";
- Building Blocks, "*unit at low integration level which must be utilised as part of a higher integration level to perform a high-level function, allowing re-use without major non-recurrent system adaptations*";
- EEE Components, mechanical Parts and materials (C&P), "*unit at the lowest integration level*".

By comparing the definition of BB in Section 4.1.2 with the description of Building Block now introduced within the ESA Product Tree, in the former a BB is more generically intended as a physical element that may include several technologies combined to achieve certain OCs, while the latter refers to a well-defined unit with specific objectives and characteristics. For the purposes of Technology Roadmapping, it is considered more appropriate to maintain the more generic definition of BB already adopted in SoA TRIS, also considering that is it more straightforward and intuitive. However, the classification provided in (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011) can be an interesting starting point for a more detailed characterization of the BB pillar to make it more suitable for the current application on RLVs. As a result, the BB hierarchy shown in Figure 100 is here proposed.

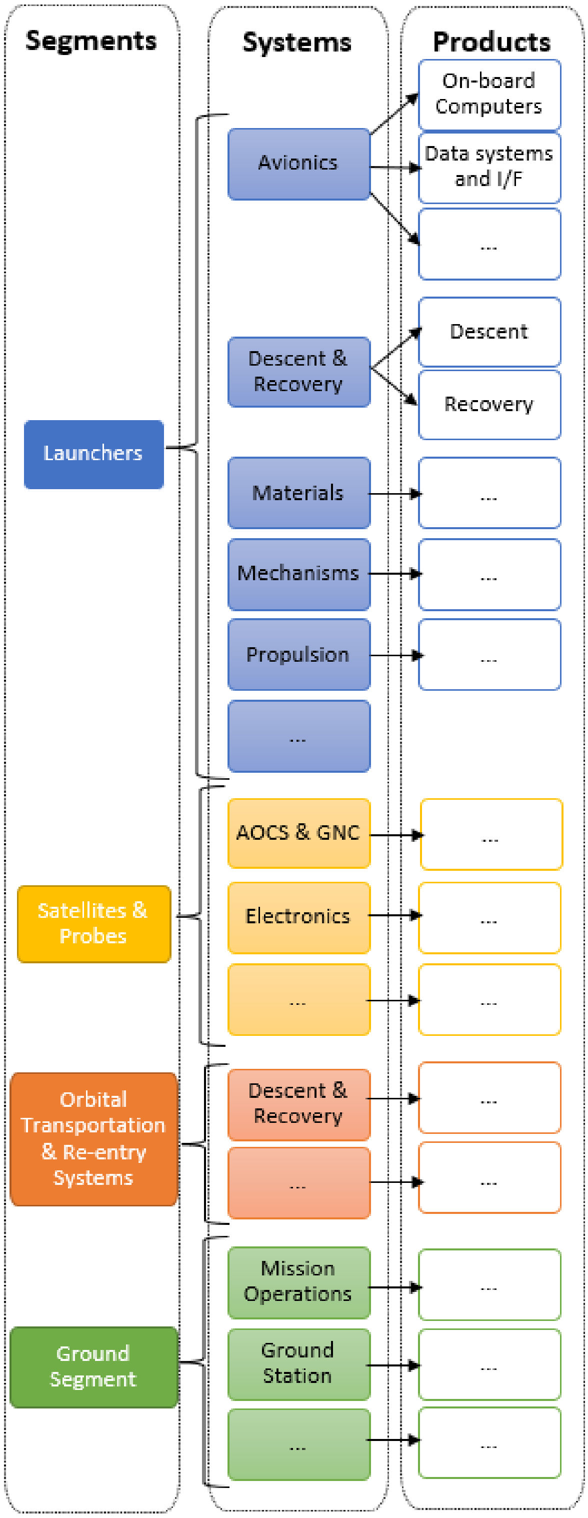


Figure 99: Overview of ESA Product Tree

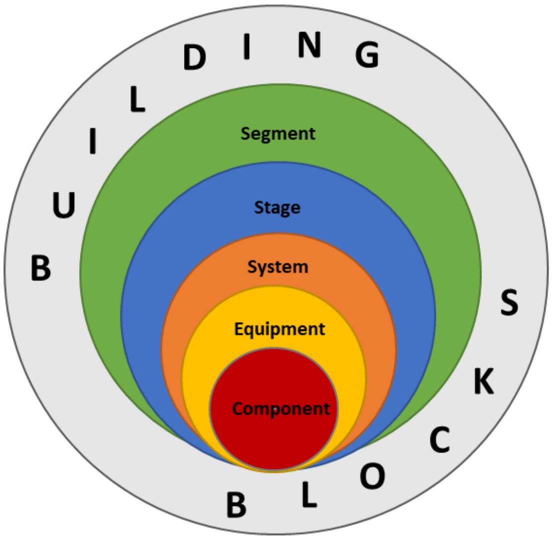


Figure 100: BBs Hierarchy based on ESA Product Tree

It is highlighted that the "Segment" Level is the same defined in ESA Product Tree, with RLVs represented both by Segment I (i.e., Launcher) and Segment III (i.e., Orbital Transportation & Re-entry System). The "Stage" Level is introduced to better represent RLV features (e.g. Airbreathing First Stage Vehicle, Rocket Second Stage, etc.), while "System" and "Equipment" Levels follow the definitions from (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011). Eventually, "Component" Level deals with all the units at the lowest integration level (labelled as EEE Components, mechanical Parts and materials (C&P) in (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011)). For sake of clarity, the list of BB Segments defined by ESA and shown in Figure 99 (i.e., Launcher, Satellites & Probes, Orbital Transportation & Re-entry System and Ground Segment) are herein referred as BB Segment *categories* which a specific Segment or design (e.g., Case Study 1) can belong to. Similar remarks apply to the other BB Levels, so that BB Stage, BB System, etc. categories can be defined from the ESA Product Tree, while the specific BB Stages, Systems, etc. applicable to a case study can be derived from Functional Analysis or from the PBS. Further details can be found in Section 4.5.1.2.

4.3.2.3 Activity/ Mission Concept (AC/MC)

Moreover, as far as the pillar Mission Concept (MC) is concerned, it is here labelled as AC/MC (Activity/Mission Concept) to stress the difference between low-TRL activities (AC) performed in laboratory environment or on-ground and high-TRL proto-flight and flight missions (MCs), including both demonstrative and operative missions. As suggested in (Cresto Aleina, 2018), a preliminary list of ACs and MCs can be derived from TRL definitions provided by ESA in (ECSS (European Cooperation for Space Standardization), 2017). This list is generic and applicable to any aerospace-related initiative and it has to be customized to better fit the case study. Considering that the application of TRIS proposed in this Dissertation is mainly focused on Case Study 1 (Section 4.5.1), great attention is paid to further specify the list of ACs and MCs to increase maturity of such vehicle (Section 4.5.1.1). Therefore, the preliminary list of MCs and ACs based on TRL definitions can be specialized looking at the real activities carried out in Europe and outside to enhance TRL of hypersonic technologies. Notably, considering the fundamental role of technology demonstrators in enabling hypersonic technologies, by merging the TRL definitions provided in (ECSS (European Cooperation for Space Standardization), 2017) and the hypersonic flight demonstrations suggested by (Bowcutt, 2003), the following three main demo missions can be suggested for a Mach 8 vehicle like Case Study 1:

- Flight Demo 1a: 6-10 Small Scale Vehicle(s) (1/10 of full-scale cruiser), recoverable (not reusable) allowing to characterize hypersonic environment at different flight conditions in the Mach range 3 to 8;
- Flight Demo 1b: 3 Mid Scale reusable vehicles (1/3 scale engine) able to perform 6-9 flight tests in the Mach range 3 to 8;
- Flight Demo 2: 2 Near Full Scale reusable vehicles allowing to test the whole spectrum hypersonic conditions encountered during the final mission (Mach 0 to 8).

Looking at TRL definitions (ECSS (European Cooperation for Space Standardization), 2017), Flight Demo 1a and 1b can be associated to an overall TRL transit from TRL 6 to 7, while Flight demo 2 can allow to move from TRL 7 to 8. As a result, main attributes of ACs and MCs are Start (or Enabling) TRL and End (or Target) TRL achieved through the mission. The latter allow to identify the TRL Transit accomplished through the AC/MC. Complex MCs should also be described in terms of the main mission phases constituting the mission (e.g., Take-off, Subsonic Climb, Supersonic Climb, Hypersonic Climb, Orbital Phase, Re-entry, etc.) to distinguish demo missions from operative ones. To further define MC complexity, the target environment should be also specified (e.g., LEO, Beyond LEO, Moon, Mars).

4.3.2.4 Operational Capability (OC)

The definition of OCs considered in this Dissertation is the same already adopted in SoA TRIS (Section 4.1.2.1) In this context, the list of OCs derived in (Cresto Aleina, 2018) is deemed applicable to RLVs as well. Its derivation is based on the results from Functional Analysis, which provided the following high-level functions:

1. Take-off functions
2. Cruise functions
3. Landing functions
4. Servicing functions
5. Support functions

From these functions, an OC can be derived as the combination of several mission features and a specific performance type (which are equivalent to a requirement) as expressed by Eq.(151).

$$\text{Operational Capability} = \cup(\textbf{Mission Features}) + \textbf{1 Performance Type} \; (\cong \textit{Requirement}) \tag{149}$$

For example, considering Take-off functions, the lists of Mission Features and Performance Types in Figure 101 can be considered.

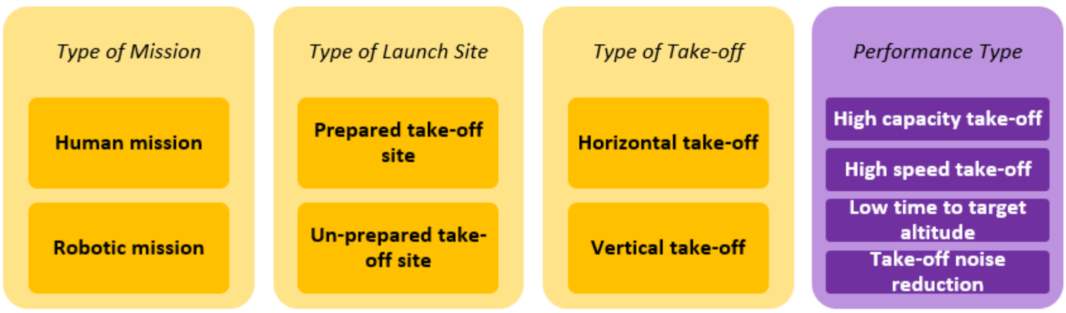


Figure 101: Performance Types and Mission Features related to Take-off functions from (Cresto Aleina, 2018)

The final list of OCs can be derived by properly combining, for each high-level function, the specific performance types (in purple) and related mission features (in yellow). As an example, the following OC related to Take-Off function is obtained:

High-capacity take-off applied to a human mission with prepared site and horizontal take-off

Please, notice that the list of OCs considered in Dissertation are reported in Section 4.5.1.2.

4.3.2.5 Programme and Projects

This additional pillar is included in the enhanced TRIS to further characterize elements and to track the Programmes/Projects in which they are developed. For sake of clarity, a Programme can collect several Projects in which specific ACs/MCs are performed to enhance the TRL of a set of Techs. For example, the STRATOFLY Project was part of the H2020 Programme, which included several other Projects. As described in Section 4.1.2.1, the possibility to associate elements to specific Programmes/Projects is at the basis of the definition of a structured database collecting previous efforts in hypersonic technology development. A Programme can be characterized in terms of available budget, status (on-going/cancelled/completed), starting/ending date and funding scheme (e.g. Basic Technology Research Programme (TRP), General Support Technology Programme (GSTP), etc. (ESA, 2015)). Complementary, relevant attributes for a Project are status, available, budget, type (i.e., Ground Demo project, Flight Demo Project, or Ground Demo Project) and details on Project Phases achievement (according to ESA subdivision in Figure 88).

4.3.3 Prioritization Studies

The third step of updated TRIS methodology consists in Prioritization Studies, in line with the original TRIS activity flow (Viola et al., 2020). However, as anticipated in Section 4.1.3, the logic behind this step is completely revised to better represent stakeholders' requests into the technologies ranking process. Similar remarks apply to Activities (ACs) and Mission Concepts (MCs) ranking, for which a revised routine based on classical trade-off analysis is proposed in Section 4.3.3.2.

4.3.3.1 Technologies' Prioritization

As far as Technologies' Prioritization is concerned, it is worth specifying that it can be intended as a process to 1) rank alternative technologies aiming at performing the same function (like in the IXV example (Viola et al., 2020)) or 2) rank technologies required for the target application (not alternative) in order to give a priority for future budget allocations (in case of limited resources available). The latter case is specifically addressed within Case Study 1 (Section 4.5.1.5).

In this context, the formalization of Stakeholders' Analysis as independent step in the TRIS workflow allows to set up in a structured way all the inputs required during Prioritization Studies. Indeed, as expressed by Eq.(148), stakeholder impact in the analysis can be clearly stated through K_{SG_i} weights, while importance of criteria asked by the generic stakeholder is elicited thanks to $K_{C_{ij}}$ weights. Basing on the key limitations of Prioritization Studies implemented in State-of-the-Art (SoA) TRIS (Section 4.1.3), a new technology prioritization routine is proposed. The approach is based on a trade-off analysis able to account for the specific requests of each stakeholder basing on his/her impact. For sake of clarity, further details about the classical trade-off methodology are provided later on in Section 5.3.2. In order to perform trade-off analysis, it is important to collect in a structured way all useful input data deriving from Step 1 and Step 2 (Table 68).

Table 68: Generical summary of input data for Prioritization Studies from Stakeholders' Analysis

		Parameters in A/D Order			
		Parameter 1 in A/D Order	Parameter 2 in A/D Order	...	Parameter J in A/D Order
SH_1	K_{SG_1}	$K_{C_{11}}$	$K_{C_{21}}$	...	$K_{C_{J1}}$
SH_2	K_{SG_2}	$K_{C_{12}}$	$K_{C_{22}}$	...	$K_{C_{J2}}$
...	...	...	...	...	...
SH_I	K_{SG_I}	$K_{C_{1I}}$	$K_{C_{2I}}$	...	$K_{C_{JI}}$
		W_1	W_2	...	W_J
		W			

Specifically, the overall list of J parameters entailed during Stakeholders' Analysis along with related prioritization order (A stands for Ascending, while D for Descending) is reported in Table 68. In addition, the list of I stakeholders involved in the analysis is provided along with the weight value (K_{SG_i}) associated to the i[th] stakeholder (SH) in the list. Please, note that, basing on the definitions provided in Section 4.3.1, $\sum_{i=1}^{I} K_{SG_i}$ must be 1. In addition, Table 68 gathers the

$K_{C_{ij}}$ values associated to the j[th] parameter asked by the i[th] SH (again, the sum of $K_{C_{ij}}$ for the same SH must be 1). By collecting K_{SG_i} in the row vector K_{SG} and $K_{C_{ij}}$ in the $[I \times J]$ matrix K_C, the W_J values in the row vector W can be obtained through the matrix product in Eq.(152).

$$W = K_{SG} \times K_C \tag{150}$$

Where W contains the total weight of each criterion taking into account both stakeholders' impact as well as specific criteria ranking preferences expressed by each stakeholder.

Moreover, by means of Elements' Definition (Step 2), the list of T technologies along with all the technology parameters asked as criteria by stakeholders can be collected or properly retrieved from a database. For the purposes of Prioritization Studies, technology data can be organized as in Table 69. Notably, the parameters' values for each Tech have to be properly normalized between 0 and 1 according to the prioritization order assigned to each parameter. For example, supposing that Parameter 1 is current TRL asked Ascending Order, TRL values for each Tech are ordered giving priority to lower TRLs. In this case, normalization is performed basing on the lowest available TRL value, which must be associated to the highest normalized value so that associated Tech has higher priority in the ranking. As a result, basing on the nomenclature herein exploited, the generic normalized value of the j[th] parameter referred to the n[th] Tech is t_{jn}, which is part of the $[J \times T]$ matrix t shown in green in Table 69.

Table 69: Generical summary of input data for Prioritization Studies from Elements' Definition

Criteria		Normalized Criteria Values for Techs			
Parameters in A/D Order	W	Tech 1	Tech 2	...	Tech T
Parameter 1 in A/D Order	W_1	t_{11}	t_{12}	...	t_{13}
Parameter 2 in A/D Order	W_2	t_{21}	t_{22}	...	t_{23}
...	...	...	...	...	...
Parameter J in A/D Order	W_J	t_{J1}	t_{J2}	...	t_{JT}
		R_1	R_2	...	R_T
		Ranked Values			

At this point, thanks to the matrix product in Eq.(151), it is possible to weight the normalized t_{jn} values according to stakeholders' requests and impact (summarized in W). Please, notice that this relationship is the core of the trade-off analysis herein presented. The result is the row vector R of normalized values. Notably, by ordering this vector in ascending order (i.e., from lower up to higher values), the final ranked list of Techs can be obtained.

$$R = W \times t \tag{151}$$

To evaluate the effect of inputs modification on the final ranked list, a sensitivity analysis on results can be carried out. Using the same lists of stakeholders and criteria defined in the first iteration, it is possible to:

1. Modify stakeholder position in the Strategy Grid;
2. Modify criteria ranking for each stakeholder.

In this way, it is possible to obtain a new ranked list of technologies to be compared with the first iteration list.

4.3.3.2 Activities (ACs) and Mission Concepts (MCs) Prioritization

As described in Section 4.1.2.2, roadmapping elements are strictly connected one another. This is also tackled in Section 7.3, discussing the new HyDat architecture. On this basis, the relationship between ACs/MCs and Techs has been thoroughly analysed in order to fully comprehend the potential benefits in performing ACs/MCs prioritization and, most importantly, to explore its connection with technologies' prioritization described in the previous Section. As far as the MCs Prioritization routine proposed in SoA TRIS is concerned, it entailed the prioritization of the entire list of MCs linked to Techs by progressively applying well-defined criteria to MCs at the same ranking position (Section 4.1.2.3). In that case, the matching of MCs and Techs occurred during the Planning Definition (Figure 86), taking into account Techs ranking, the TRL Transit to be pursued for each Tech, and the derived ranked list of MCs.

Starting from the former MCs prioritization routine and making benefit of the study of ACs/MCs and Techs relationships performed in this work (Section 7.3), it is possible to propose an enhanced version of the ACs/MCs prioritization process able to support and improve the subsequent Planning Definition phase. Notably, as discussed in Section 4.3.2.3, an AC/MC is mainly characterized in terms of the TRL Transit enabled. However, from a Tech perspective, several ACs and MCs can be required to attain a specific TRL Transit and alternative paths (i.e., different combinations of ACs/MCs) can be pursued to achieve the same Target TRL. Basing on these considerations, from Elements' Definition phase it is possible to derive several sub-lists of linked ACs and MCs, one per each Tech and per each TRL Transit as in the example of Table 70.

Table 70: Generical overview of sub-lists of ACs/MCs linked to Techs and referred to specific TRL Transits.

	TRL 1 to TRL 2	TRL 2 to TRL 3	...	TRL 8 to TRL 9
Tech 1	L_{11}	L_{12}	...	L_{18}
Tech 2	L_{21}	L_{22}	...	L_{28}
...	...	...	...	...
Tech T	L_{T1}	L_{T2}	...	L_{T8}

Considering the generic sub-list L_{tk} linked to the tth Tech and referred to the kth TRL Transit, it can be generally intended as a combination of ACs/MCs strictly required to pursue the TRL Transit and of alternative missions as in Eq.(152). The list of alternative missions is a set of ACs/MCs with similar characteristics and purposes: among them only one can be considered as required for the fulfilment of the specified TRL Transit and has to be added to the list of required ACs/MCs.

$$L_{tk} = (Required\ ACs/MCs) \cup (Alternative\ ACs/MCs) \tag{152}$$

In account of this, first of all, ACs/MCs in a certain L_{tk} have to be further characterized as "required" or "alternative" thanks to TRIS user expertise. Then, it is important to identify strategies to select the most promising alternative AC or MC to be added to the list of required missions. At this purpose, a trade-off procedure similar to that already described for Techs Prioritization analysis is suggested. Main inputs required are generically summarized in Table 71.

Table 71: Generical overview of inputs for MCs Prioritization

Criteria		Normalized Criteria Values for Alternative ACs and MCs linked to tth tech and related to kth TRL Transit			
Parameters in A/D Order	W	AC/MC 1	AC/MC 2	...	AC/MC X
Parameter 1 in A/D Order	W_1	a_{11}	a_{12}	...	a_{13}
Parameter 2 in A/D Order	W_2	a_{21}	a_{22}	...	a_{23}
...	...	...	...	...	...
Parameter H in A/D Order	W_H	a_{H1}	a_{H2}	...	a_{HX}
		R_1	R_2	...	R_X
		Ranked Values			

Specifically, a set of H parameters, such as AC/MC cost, number of technologies linked, number of BBs linked, etc. is associated to a prioritization order (A/D) to derive criteria in line with those already proposed by SoA TRIS in Section 4.1.2.4. Then, a weight is assigned to each criterion and stored in the row vector W. Please, notice that stakeholders' impact is not considered for criteria weight definition but high-level programmatic requirements are represented into MCs Prioritization criteria (Section 4.1.2.4). In addition, the list of alternative ACs/MCs under analysis is characterized basing on the parameters asked as criteria. Considering X alternative ACs/MCs, normalized parameters values for each AC/MC (depending on the prioritization order selected for each parameter) are collected in the $[H \times X]$ matrix a. The matrix product of W and a provides, as in Eq.(151), the weighted parameters values (R vector) which, considered in ascending order, gives the final list of alternative ACs/MCs ordered according to the selected criteria. As mentioned, the first alternative AC/MC in the ranking should be added to the list of required missions. The same procedure should be repeated for each Tech, defining a list of required ACs/MCs needed to pursue each TRL Transit. Moreover, as for Techs Prioritization, sensitivity analysis can be carried out, examples, by changing the weight assigned to each criterion or their prioritization order.

4.3.4 Planning

In the original algorithm proposed in State-of-the-Art SoA TRIS (Section 4.1.2.3), the ranked lists of technologies and missions were combined mainly checking the Enabling TRL of Mission Concepts (MCs) and Activities (ACs) and their position in the ranking. The main drawback of this approach lies in the fact that technologies were associated to MCs one by one neglecting the possibility to increase the TRL of a set of technologies with a single AC or MC. Since the integration of technologies is a crucial aspect of hypersonic systems, the possibility of reproducing it during the Planning Definition phase is central to suggest economically viable as well as technologically sustainable development paths. Therefore, a new Planning Definition routine is proposed in this Dissertation. The approach can tackle the complex issue of integrated technologies demonstration making benefit of the results from Techs and ACs/MCs Prioritization. The flowchart of the new Planning Definition approach is graphically depicted in Figure 102.

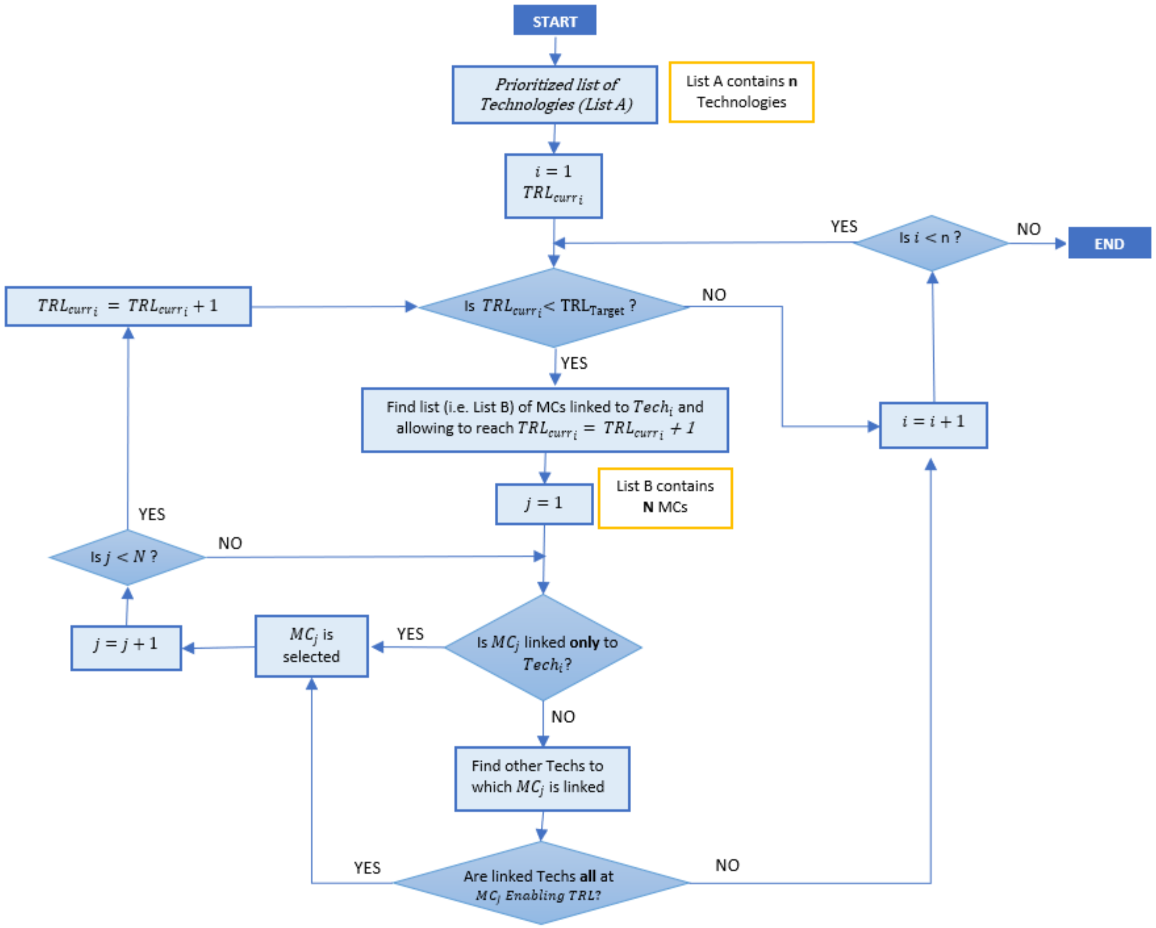


Figure 102: New Planning algorithm (Viola et al., 2022)

The new routine takes into account the preferences expressed by stakeholders in terms of technologies' prioritization as well as the effective possibility to perform each AC/MC depending on technology maturation attained. Notably, the ranked list of n technologies (referred as "List A" in Figure 102) that stems out from Prioritization studies is considered at the beginning of the process. Starting from the first technology (i.e., $Tech_i = 1$) in List A, its TRL at the beginning of roadmapping activities (also referred as current TRL, i.e., TRL_{curr_i}) is evaluated and compared to a Target TRL (i.e., TRL_{Target}). For sake of clarity, Target TRL is the TRL that each technology shall reach at the end of technology development in the timeframe spanned by the roadmap. If technology development is effectively required (i.e., $TRL_{curr_i} < TRL_{Target}$), the list of N required ACs/MCs (referred as "List B") allowing to increase TRL_{curr_i} is considered. Please, note that, thanks to this approach, generic TRL increments are considered (not necessarily unitary steps, as in SoA TRIS). Moreover, it is generically assumed that the TRL increment can be accomplished through several ACs/MCs (in contrast to SoA TRIS, where a single mission was suggested per each step). In particular, the list of N ACs/MCs contains all missions required to increment TRL_{curr_i} since alternative MCs, if available, have already been analysed through MCs Prioritization. At this point, two alternative options can be pursued:

1. MC_j in List B is linked only to $Tech_i = 1$: MC_j can be selected for the final MCs Planning and it is possible to consider the next MC in List B to include all MCs required to fulfil increase TRL;
2. MC_j in List B is linked to $Tech_i = 1$ and to other technologies at lower priority: MC_j can be included in the final MCs Planning only if all linked technologies already reached the Enabling TRL of MC_j. In this case, the next MC in List B may be considered. Otherwise, MC_j cannot be envisaged yet because the maturity level of all linked technologies is not sufficient to enable that MC. Therefore, the loop into List B is exited (i.e., a TRL transit cannot be performed at the moment for that Tech) and the analysis moves to the subsequent technology in the ranking in order to enable all pending MCs.

Once all technologies in the ranked list are considered, an ordered list of ACs/MCs to pursue technology development is suggested. This list takes into account the effective possibility to integrate different technologies in a unique demonstrator only once required maturity for all technologies is reached. Please, note that the ordered list of MCs here derived could also represent a fundamental tool in the phase of budget allocation. In particular, in case limited resources are available for technology development, the Planning Definition routine suggests the MCs that should have higher priority in order to accomplish stakeholders' expectations.

To complete the Planning Definition, the ordered list of MCs just derived has to be distributed on a timeline. In this context, the time distribution of TRL Transits previously proposed by SoA TRIS (Figure 87), conceived for Space Exploration systems, is not suitable for the case study tackled in this Dissertation. Therefore, a new time breakdown specifically tailored for future RLVs is proposed starting from the overall timeframe for hypersonic technology development proposed by FESTIP programme (Section 1.2.2).

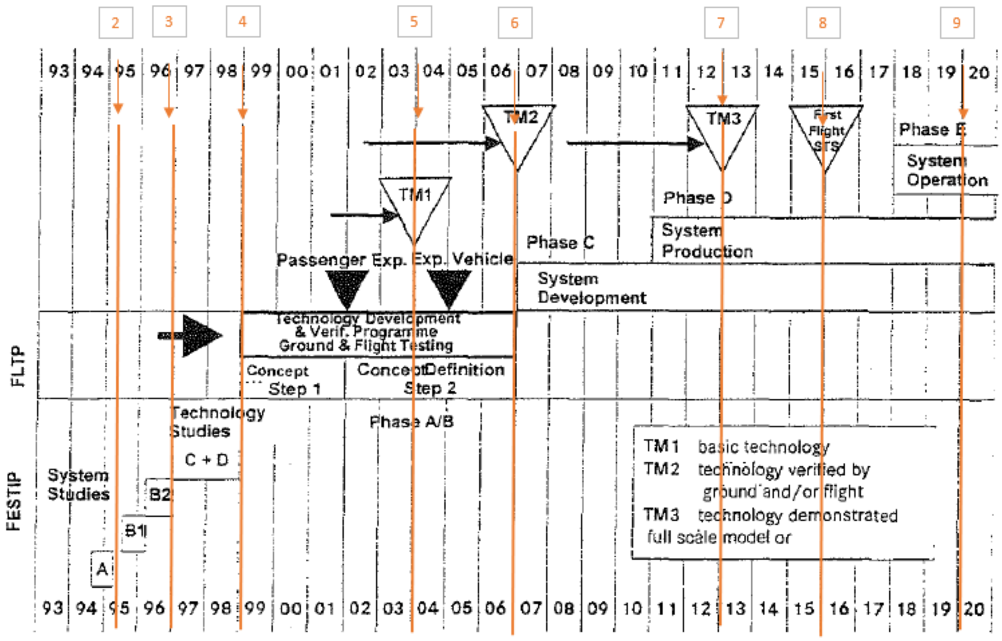


Figure 103: FESTIP envisaged timeline with TRL Milestones added (Kuczera & Johnson, 1999)

Notably, despite the original timeline was not fulfilled mainly for budgetary constraints, FESTIP-proposed timeline in Figure 103 gives an idea of the projected duration of each project phase in relation to the others. On this basis, following the TRL definitions provided in (ECSS (European Cooperation for Space Standardization), 2017), TRL milestones can be added to the original FESTIP timeline as shown in Figure 103. Eventually, the Time at Completion (TaC) distribution on TRL transits in Figure 104 can be obtained including actual time data from Sänger project (Sacher, 2010) referred to lower TRL levels (i.e. from 0 to 2).

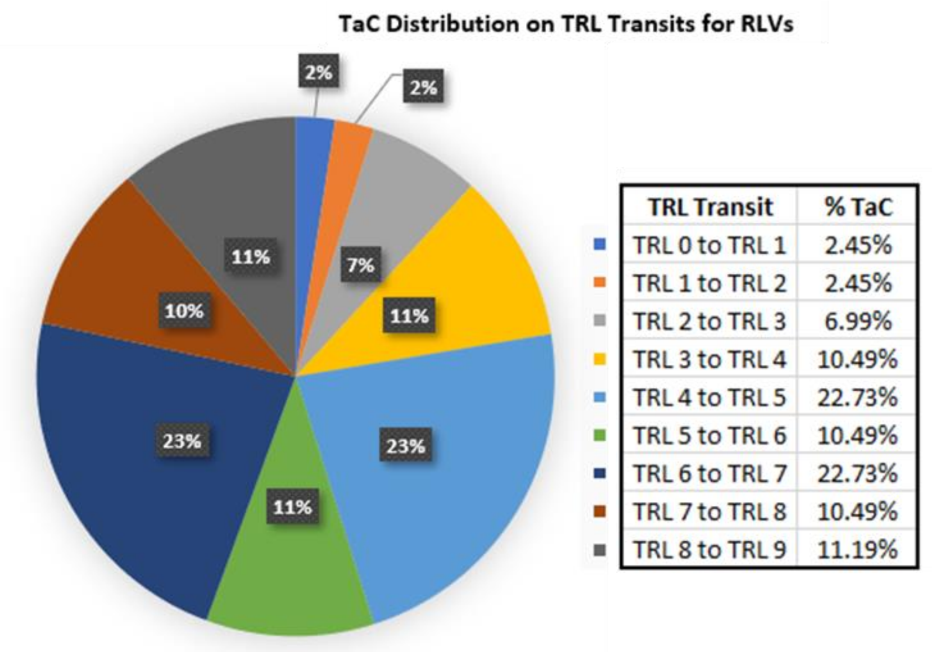


Figure 104: Newly derived TaC distribution on TRL transits for RLVs

In order to exploit the time breakdown just obtained to define a preliminary development timeline for each technology, it is necessary to define the roadmap timeframe. Notably, a starting date coinciding with the current date in which technology roadmapping activities must be defined along with a target ending date for the overall technology development in which Target TRL is achieved. By setting these two milestones, the exploitation of the time breakdown in Figure 106 allows to define preliminary dates for the achievement of TRL milestones up to Target TRL. This preliminary timeline has to be then refined considering the actual list of MCs to be performed to cover each TRL transit. In particular, in case an AC/MC is linked to more than a technology, the starting date of that ACs/MC has to be posed after all the related technologies have reached the minimum TRL requested by the MC itself to start. This activity leads to the definition of a final timeline or planning for the maturation of each technology and a timeline for ACs/MCs accomplishment in order to pursue technology development. As anticipated, the timelines stemming from Planning Definition suggest a possible incremental path for technology maturation not only able to cope with the preferences expressed by stakeholders in terms of technologies' ranking but also looking at the best way to integrate technologies, thus optimizing the exploitation of available budget resources.

4.3.5 Results Evaluation

The Results Evaluation step it the synthesis of the overall roadmapping activities carried out in the previous steps. Already foreseen in State-of-the-Art (SoA) TRIS version, it is basically maintained as it is in the enhanced TRIS. As described in Section 4.1.2.5, the goal of this phase is to analyse the obtained technology roadmap and to support the analysis of different out-of-nominal scenarios, assuming that the main outputs of TRIS methodology (i.e., technologies and MCs development timelines) reflect an optimal or nominal TRL increase path. During this final step, risk analysis is also performed in order to associate each technically viable roadmap to a level of risk, depending on the foreseeable difficulties in reaching the TRL target and using the AD^2 index (Bilbro, 2008; Viola et al., 2020) Specifically, once the nominal schedule is available from Planning Definition phase, it is possible to assess the impact of possible delays or over-costs onto the roadmap. As described in c delays or over-costs usually derive from issues related to three main areas, i.e., technical (design-related), political and economic issues. For technical and political issued it is possible to determine the impact on the roadmap both in terms of costs increase and time delay. Indeed, by estimating AD^2, it is possible to derive over-costs related to technical issues as suggested in (Cresto Aleina, 2018). Complementary, knowing the stakeholders, it is possible to preliminary estimate the frequency of political delays. For example, as reported in (Cresto Aleina, Fusaro, Viola, Rimani, et al., 2017) a change in the ESA organizational structure occurs every 5 years (e.g., new directors' elections), a change in intent and strategy every 2 years (e.g., a new ministerial council) and a change in the policy and rules every 7 years (e.g., a change in the standards that designers have to follow). As a result, the amount of delay that can be proposed is, respectively, of 9 years, 3 years and 1 year. Basing on experts' opinion, an over-cost of 175 man-year per each year of delay (corresponding to 32 MECU/year, i.e., 32Mln€) can be assumed.

4.4 Software implementation

The previous Sections discussed the improvements introduced into SoA TRIS to tackle the issues pointed out in Section 4.1.3, thus proposing an enhanced version of the Roadmapping Methodology. Similarly to HyCost Methodology (Section 3.3), the enhanced TRIS has been implemented within the open-source

Python Qt environment by means of a user-friendly Graphical User Interface (GUI). The resulting tool (called TRIS, like the methodology) is intended as a quick and flexible mean to perform roadmapping analyses for a broad spectrum of SoSs in the aerospace domain. Like HyCost Tool, TRIS Tool is based on a tab-oriented architecture (see Section 3.3) and each tab implements a specific step on the methodology according to the flowchart in Figure 97. Figure 105, Figure 106 and Figure 107 provide an overview of the key features of the TRIS tool, showing the main tabs to be filled by the user. Starting from Figure 105, it can be noticed that tabs are progressively shown during tool exploitation, thus guiding the user along the steps of TRIS. The process starts with the definition of high-level programmatic requirements (strictly connected to the Planning phase), i.e., envisaged timeframe of technology development and target TRL. At this stage, a possible out-of-nominal scenario (in relation to the Results Evaluation step) can be defined by entering values for delta costs (user input) and envisaged years of delay with respect to the optimal schedule. Subsequently, a dedicated tab allows to perform Stakeholders' Analysis (Figure 105), defining all the stakeholders involved in the roadmapping process and related criteria. Stakeholders are properly visualized onto the Strategy Grid according to the role assigned by the user. At the end of Stakeholders' Analysis, it is possible to move to Elements' Definition (Figure 106). In this context, proper Python routines allow to link to the HyDat back-end (Section 7.3) and retrieve data. After data retrieval, thanks to the GUI it is possible to visualize the available list of technologies and select those to be considered within the analysis. The GUI also allows to easily visualize the lists of other pillars linked to the selected list of technologies. These TRIS features, achieved thanks to the adoption of a GUI, certainly supports the overall roadmapping process, providing the user with a clear overview of all available data. The tool also implements the trade-off methodology for technologies' prioritization described in Section 4.3.3, showing the final ranked list of technologies within the GUI (Figure 107). Thanks to the GUI is possible modify stakeholders' roles and criteria ranking and perform sensitivity analysis on results. Considering the importance of evaluating different scenarios in the framework of technology Roadmapping, the possibility to "play" with the inputs is certainly another key feature of the GUI. Similar remarks apply to MCs and ACs prioritization routine (Section 4.3.3.2) implemented within the tool (Figure 106). Also in this case, it is possible to specify through the GUI alternative ACs and MCs for a specific TRL Transit and technology. Moreover, in case of multiple missions, available trade-off analysis and subsequent sensitivity analysis can be performed. This procedure, allowing to define the sub-lists of required missions, can be easily repeated for any technology and TRL Transit. Eventually, the final Planning tab allows to automatically generate two dedicated Gantt charts for technologies and ACs/MCs (Figure 107). Notably, the proposed planning for technology development and the suggested timeframe for MCs/ACs accomplishment are obtained by implementing the Planning flowchart in Figure 102 along with the new TaC breakdown (Figure 104). In addition, exploiting the inputs related to the out-of-nominal scenario (Figure105), the Cost at Completion (CaC) increase due to the introduction of delta costs and delays in technology development is assessed.

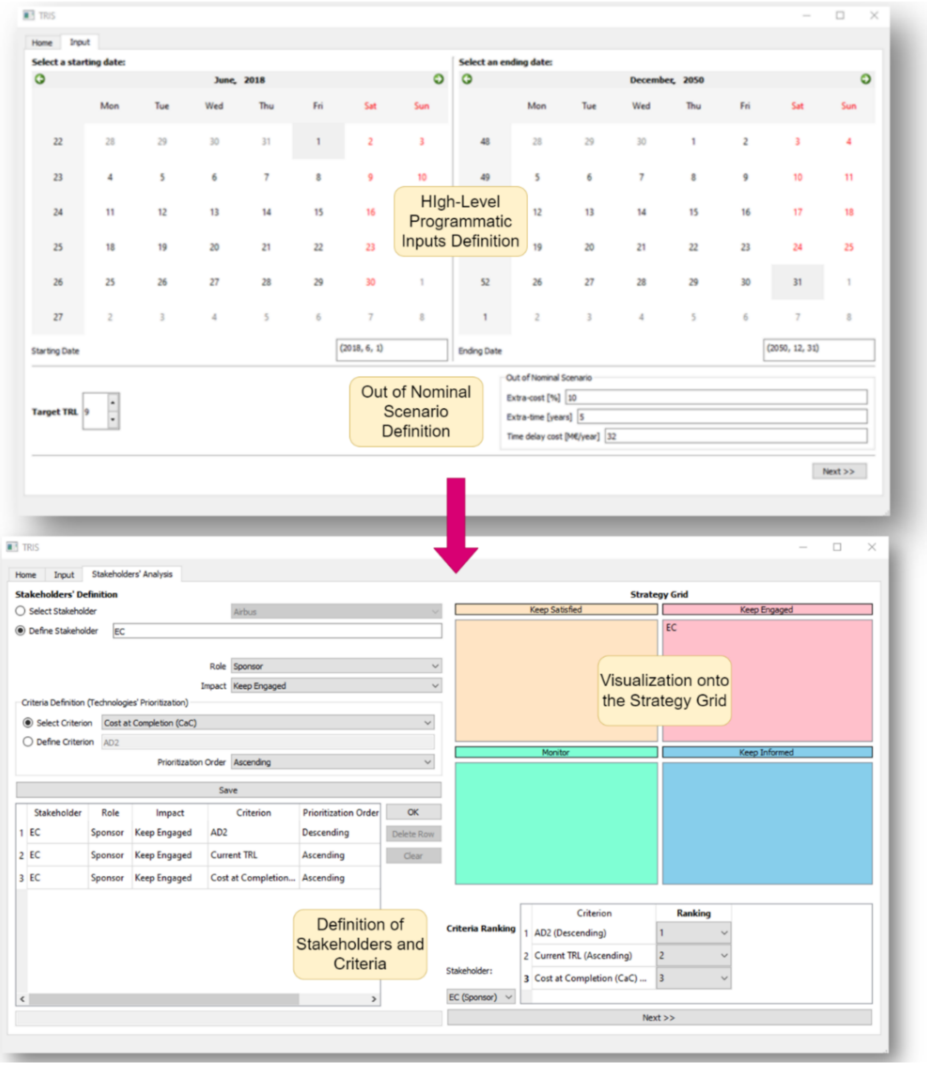


Figure 105: TRIS Tool (1)

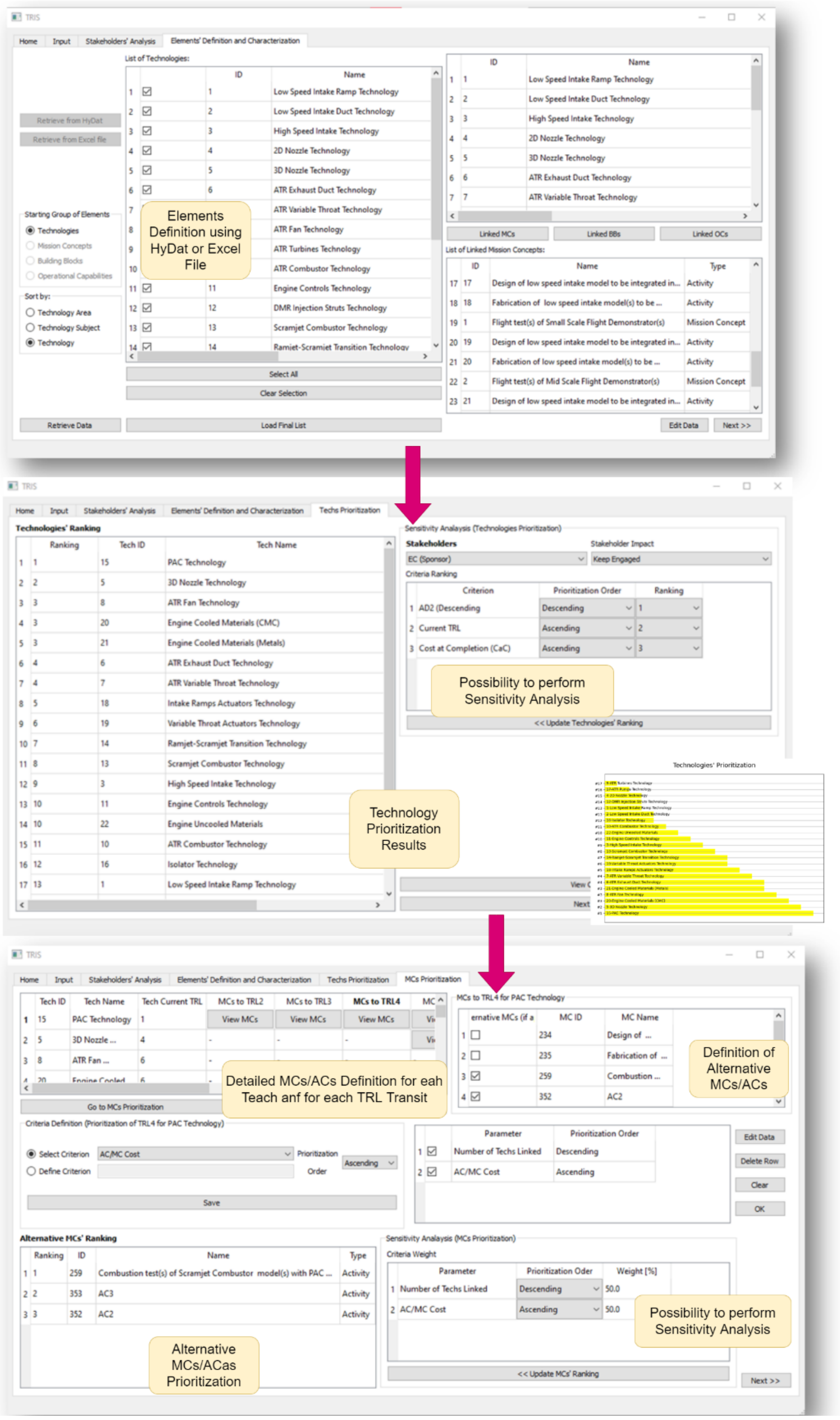


Figure 106: TRIS Tool (2)

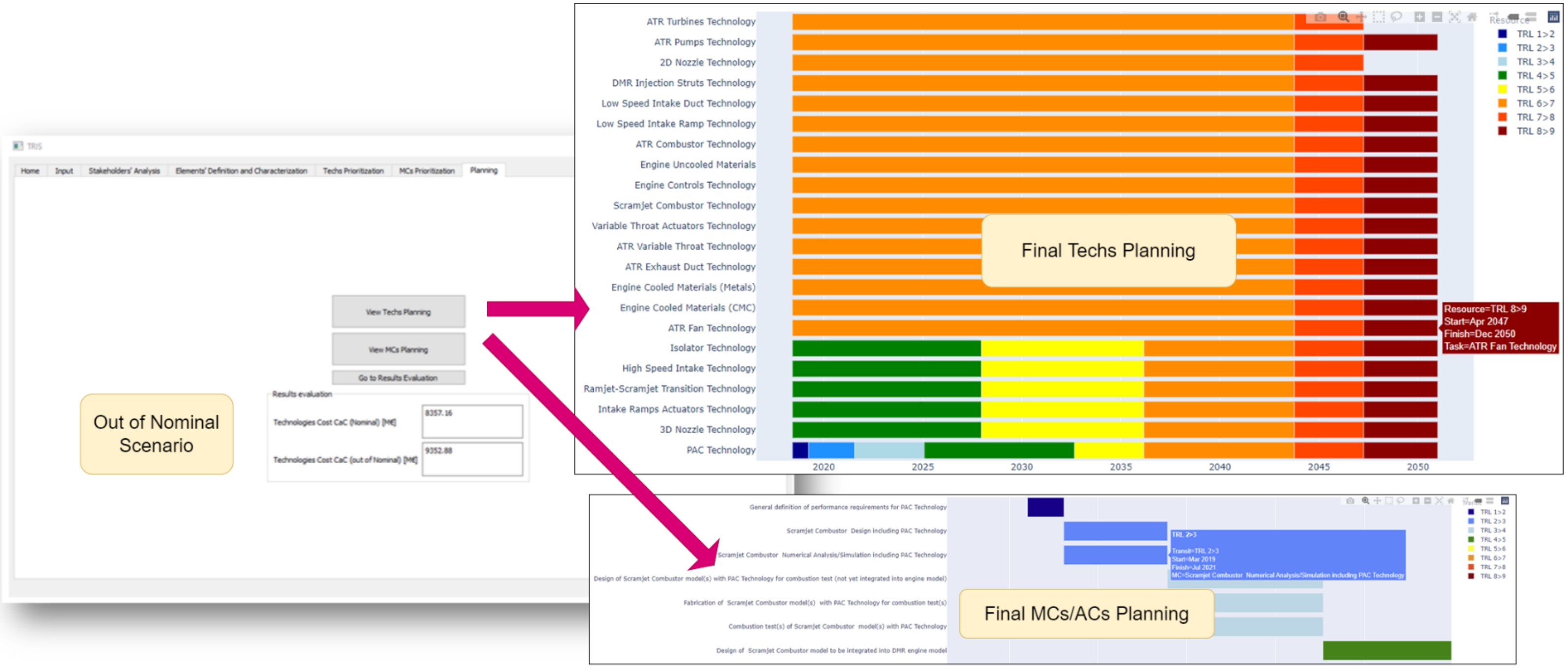


Figure 107: TRIS Tool (3)

4.5 Application to the Case Studies

4.5.1 Case Study 1

The thorough description of enhanced TRIS methodology provided in Section 4.3 and, even more, the software implementation of TRIS in Section 4.4 highlighted that a great amount of input data is required to perform Technology Roadmapping for a complex SoS. Indeed, despite the inherent flexibility of the approach in supporting roadmapping exercises for different case studies, dedicated analyses have to be performed for the specific application in order to derive suitable lists of elements and to characterize them (e.g., links with other pillars, TRL, CaC, etc.), making benefit of available expertise and/or dedicated databases. As a result, Step 2 (Figure 97) is far the most demanding phase of the upgraded methodology. This is particularly true in case of unavailability of a structured database from which elements' data can be retrieved, thus dramatically increase the effort required to propose a Technology Roadmap and the complexity of the overall process. Such challenges are encountered in performing Technology Roadmapping for the highly innovative First Stage of the STRATOFLY TSTO Vehicle. Indeed, the lack of a database containing lists of technologies for each applicable Technology Domain (TD) as well as of Mission Concepts (MCs) imposes the definition of elements and elements' links from scratch. In addition, fundamental inputs for roadmapping activities are missing, such as the assessment of the TRL status of each technology. On this basis, taking into account the crucial role of powerplant in motivating the search for highly performant and integrated technologies since the STRATOFLY-precursor projects such as LAPCAT I/II (see Section 1.2.), the following Sections deal with the step-by-step application of TRIS methodology to STRATOFLY MR3-modified with special focus on key enabling technologies related to powerplant. Please, notice that, from a technological perspective, the STRATOFLY MR3-modified and the STRATOFLY MR3 Cruiser (original) have the same features (Section 2.1.1). In account of this, the Technology Roadmapping exercise herein described generically refers to the STRATOFLY MR3. In addition, recalling the purpose of the H2020 STRATOFLY to assess the potential of a high-speed transport vehicle to reach TRL 6 by 2035 (Viola et al., 2021), the ultimate goal of the analysis herein presented is to verify whether the selected propulsive technologies may effectively reach that TRL target in the specified timeframe. Complementary, as far as the Second Stage of the STRATOFLY TSTO is concerned, remembering that its design is based on an expendable rocket vehicle derived from an already operational design (i.e., ARIANE 5 upper stage, as described in Section 2.2.1.4), the derivation of a Technology Roadmap is deemed not strictly required for the purposes of this Dissertation, so that the TRIS application is focused only on the First Stage.

4.5.1.1 Step 1: Stakeholders' Analysis

As required by the enhanced TRIS methodology, a Stakeholders' Analysis is performed at the beginning of the roadmapping process with the aim to define the main actors participating in vehicle development. At this stage, as stated in Section 4.3.1, it is also important to specify the main programmatic requirements related to the technology development, i.e., the timeframe spanned by the roadmap (notably, roadmap starting and ending dates) and Target TRL achieved at the ending date. For Case Study 1, the starting date is set at the beginning of the H2020 STRATOFLY Project (i.e., mid 2018). In addition, in order to assess the potential to reach TRL 6 by 2035, it is judged appropriate to evaluate the overall technology development process up to TRL 9 (Target TRL). In this context, 2050 is set as ending date in line with the outcome of previous roadmapping analyses for hypersonic transportation systems performed during the HIKARI project (Blanvillain & Gallic, 2015). In that framework, a preliminary technology development schedule was proposed for the major TDs but no details about specific technologies involved were provided. As such, the technology roadmapping exercise proposed in this Dissertation, able to provide details up to technology level, can constitute an improvement of the preliminary analysis performed during HIKARI.

Going back to the main purpose of TRIS first Step, i.e., Stakeholders' Analysis, considering the STARTOFLY MR3 as a European project, the European Commission (EC) would undoubtedly have the most impacting role in the development of this concept, in view of its political and economic interests in the initiative. As a result, EC is the unique stakeholder considered in the present study (i.e., $K_{SG} = 1$ in Eq.(148)). In addition, the analysis of EC needs allows to identify a set of interesting criteria to be then used during Prioritization Studies (Step 3). Notably, in line with EC research policies, high-risk/high-gain technology development initiatives are usually supported (e.g., in the H2020 framework). Furthermore, the emphasis onto breakthrough technologies implies a focus on low-TRL. Eventually, to fulfil budget constraints, EC might recommend an optimization of budget resources pursuing maximum results with minimum expenditures. These specific needs can be translated into the following criteria (with related weighting factors according to Eq.(148)):

1. AD^2 in Descending Order: remembering that AD^2 expresses the risk encountered in technology development (Bilbro, 2008), the list of technologies is ranked starting from those associated to higher risk in order to define, in a conservative way, the most critical technology development path;

2. Starting TRL in Ascending Order: considering Starting TRL as the TRL already reached by each technology at the roadmap starting date, the list of technologies is ranked starting from those at lower TRL in order to level out the TRL of all technologies and enable the introduction of proper flight demonstrators;

3. CaC in Ascending Order: the list of technologies is ranked starting from those with lower CaC in order to increase TRL of as much technologies as possible with the available budget. In line with the definitions in Section 4.2.2.2, technologies' CaC is herein intended as the CaC required to reach TRL 8.

4.5.1.2 Step 2: Elements' Definition

During Step 2 (Section 4.3.2), the lists of elements to be considered in the roadmapping process are defined. To tackle the substantial lack of readily available lists of elements from a database, the following Sections describe the strategies adopted to derive lists of elements for the present application exploiting the guidelines provided in Section 4.3.2. In addition, basing on the new HyDat back-end structure described in Section 7.3, the implementation of the newly derived lists of elements within HyDat is shown. Please, notice that all HyDat Tables herein mentioned are thoroughly discussed in Section 7.3.

Technologies. As discussed in Section 4.5.1.2, the results of conceptual design activities expressed in terms of PBS can represent a fundamental starting point to derive the list of technologies to be considered during the roadmapping exercise. Notably, a PBS for the STRATOFLY MR3 is provided by (Ferretto, 2020) (Figure 108(a)). Considering that the STRATOFLY MR3-modified configuration is the same as the STRATOFLY MR3 and the main difference lies in the quantity of fuel carried (Section 2.2.1), the available PBS is considered as baseline for this study.

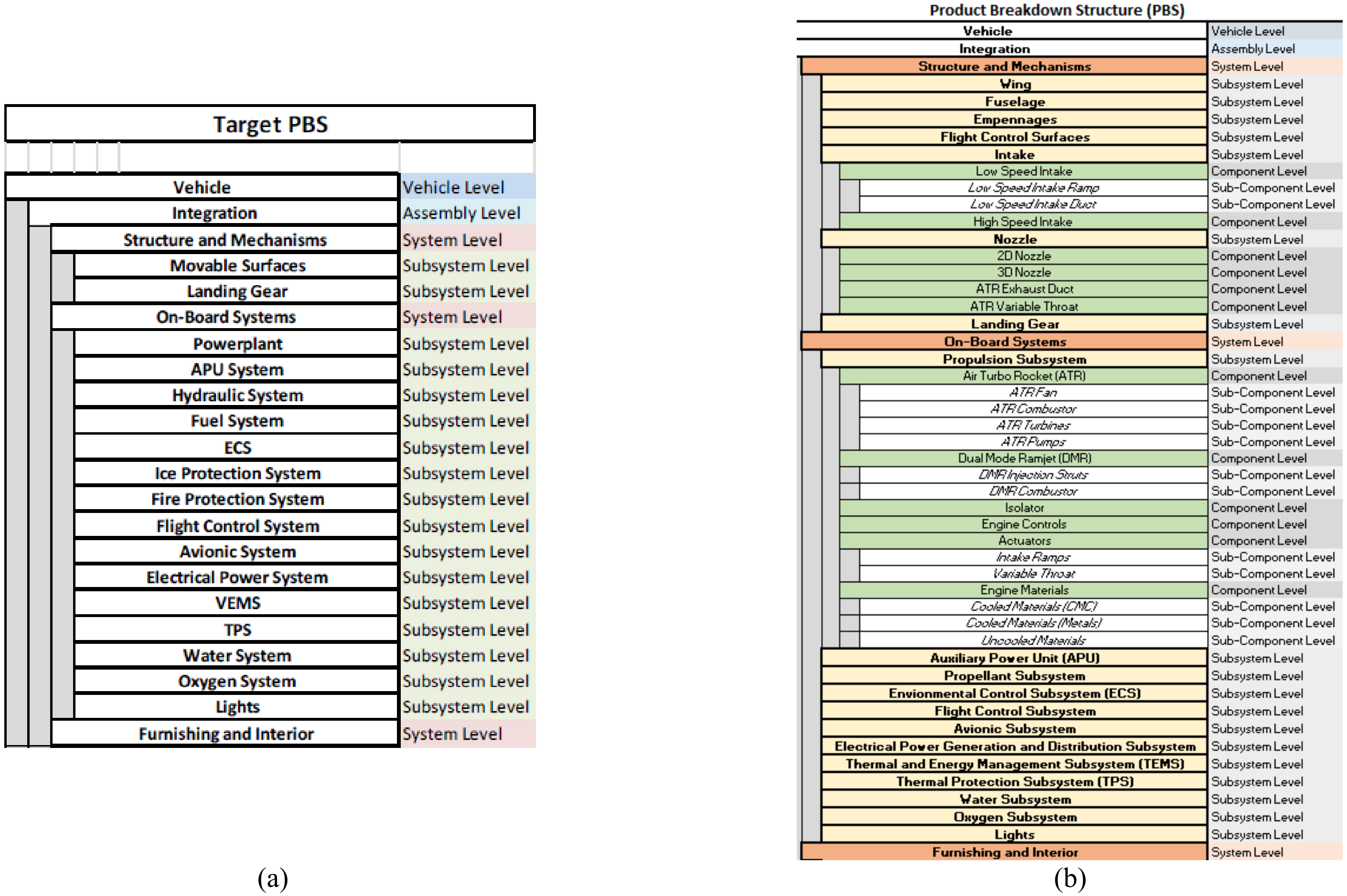


Figure 108: (a) STRATOFLY MR3 PBS from (Ferretto, 2020); (b) Modified STRATOFLY MR3 PBS derived in this work

Thanks to the possibility to access detailed results of conceptual design activities carried out by Politecnico di Torino in the framework H2020 STRATOFLY project (Viola et al., 2021) and also making benefit of the interaction interact with experts involved, the more detailed PBS presented in Figure 108(b) is considered in this work. As mentioned in Section 4.5.1, this study focuses onto powerplant-related technologies, so that the PBS in Figure 108(b) provides an insight up to Component or Sub-Component Level for the PBS items directly related to powerplant. These PBS items belong to Propulsion Subsystem, as well as to Intake and Nozzle (part of Structures and Mechanisms). Considering the items at the lowest PBS Level in Figure 108(b) (i.e., Components or Sub-Components) and merging experts' feedbacks, the list of technologies considered for Case Study 1 is summarized in Table 72.

.

Table 72: List of technologies considered for the roadmapping exercise (Case Study 1)

		Parameters related to Criteria		
Tech ID	**Tech Name**	**AD[2]**	**Starting TRL**	**CaC [M€ FY2021]**
1	Low Speed Intake Ramp Technology	4	6	415.27
2	Low Speed Intake Duct Technology	4	6	415.27
3	High Speed Intake Technology	5	4	415.27
4	2D Nozzle Technology	1	7	119.16
5	3D Nozzle Technology	5	4	119.16
6	ATR Exhaust Duct Technology	5	6	119.16
7	ATR Variable Throat Technology	5	6	119.16
8	ATR Fan Technology	7	6	722.33
9	ATR Turbines Technology	2	7	481.55
10	ATR Combustor Technology	5	6	722.33
11	Engine Controls Technology	5	6	481.55
12	DMR Injection Struts Technology	3	6	481.55
13	Scramjet Combustor Technology	6	6	481.55
14	Ramjet-Scramjet Transition Technology	6	4	722.33
15	Plasma Assisted Combustion (PAC) Technology	6	1	144.47
16	Isolator Technology	4	4	722.33
17	ATR Pumps Technology	2	6	481.55
18	Intake Ramps Actuators Technology	6	4	337.09
19	Variable Throat Actuators Technology	6	6	337.09
20	Engine Cooled Materials (CMC)	7	6	722.33
21	Engine Cooled Materials (Metals)	7	6	722.33
22	Engine Uncooled Materials	5	6	481.55

In order to align to the nomenclature reported in ESA Technology Tree (ESA, 2020a), technologies derived from PBS items related to Propulsion Subsystem are assigned to Propulsion TD (herein referred as $TD_{Propulsion}$), while those related to Structures TD ($TD_{Structures}$). This is also summarized in Eq.(153).

$$Technologies\ List = Technologies\ _{TD_{Propulsion}} \cup Technologies\ _{TD_{Structures}} \quad (153)$$

Where $Technologies\ List$ is the list of technologies in Table 72, while $Technologies\ _{TD_{Propulsion}}$ and $Technologies\ _{TD_{Structures}}$ are, respectively, technologies belonging to $TD_{Propulsion}$ and $TD_{Structures}$ in that list.

At this point, to proceed towards the derivation of the Technology Roadmap, technology data needed for Prioritization Studies has to be collected or derived. Considering the criteria asked by EC stakeholder in Section 4.5.1.1, Starting TRL, Cost at Completion (CaC) and AD^2 values for each technology are required. The latter are collected in Table 72 as well. In particular, the AD^2 parameter can be assessed looking at the definition reported in (Bilbro, 2008) and with the support of the experts' judgement. Similarly, Starting TRL derives from a thorough literature study and interactions with experts. Notably, the TRL values in Table 72 represent the 2018 European Scenario. Of course, other scenarios can be simulated, such as the US one, thus demonstrating the inherent flexibility of TRIS methodology. Furthermore, as far as the technologies CaC is concerned, due to the lack of actual cost data for powerplant-related technologies, the values reported in Table 42 are exploited (i.e., STRATOFLY MR3-modified RDTE, ATR RDTE and DMR RDTE for governmental scenario). At this purpose, the value of $Vehicle\ CaC_{(TRL8)}$ (or $RDTE$ 1) for Case Study 1 (First Stage) is derived from Eq.(142) using the same strategy adopted in Section 4.2.2.1 for the overall TSTO. As a result, $RDTE$ 1 for the First Stage is equal to 27,850.70 M€. In addition, basing on the methodology presented in Section 4.2.2.2, a costs allocation onto PBS items is needed to derive TDs contribution onto RDTE costs, i.e.,K_{TDj} in Eq.(147). At this purpose, in the present analysis, the RDTE costs allocation onto PBS items for STRATOFLY MR3 available from (Ferretto, 2020) and reported in Figure 109 is taken as reference for K_{TDj} values, with special focus on *Structure*, *ATR engines*, and *DMR engines* contributions.

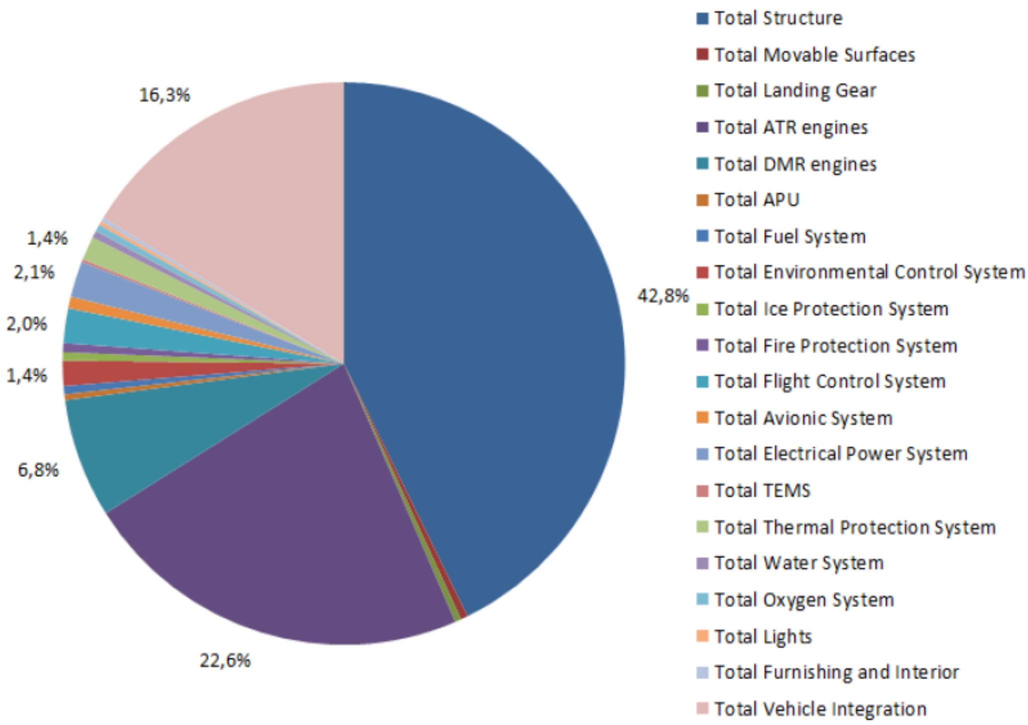


Figure 109: Development cost allocation onto PBS elements for STRATOFLY MR3 vehicle (Ferretto, 2020)

For sake of clarity, K_{TDj} values in Figure 109 are not a fraction of $Vehicle\ CaC_{(TRL8)}$ (as required in Eq.(147)) but of Vehicle RDTE. Nevertheless, taking into account the subdivision proposed in Figure 91, $Vehicle\ CaC_{(TRL8)}$ is, as a first approximation, equal to Vehicle RDTE, K_{TDj} is considered referred to $Vehicle\ CaC_{(TRL8)}$ as well. The following Sections describe in detail how to determine the CaC of $Technologies\ _{TD_{Structures}}$ and $Technologies\ _{TD_{Propulsion}}$ using information from Figure 109.

$\boldsymbol{Technologies\ _{TD_{Structures}}}$ **CaC**. As far as *Structures* contribution is concerned (Figure 109), it represents the RDTE cost fraction of all technologies belonging $TD_{Structures}$ (with $K_{TD_{Structures}} = 42.8\%$). On this basis, Eq.(146) can be rewritten as in Eq.(154), considering only $Technologies\ _{TD_{Structures}}$ defined in Eq.(153).

$$Technology\ CaC_{i_{TD_{Structures}}} = K_{Tech\ i_{TD_{Structures*}}} \cdot K_{TD_{Structures*}} \cdot Vehicle\ CaC_{(TRL8)} \tag{154}$$

However, only the cost fraction associated to powerplant-related structural elements (precisely, Intake and Nozzle) is of interest for the present analysis. This means that only the portion of $K_{TD_{Structures}}$ related to these elements (herein referred as $K_{TDStructures^*}$) has to be considered in the application of Eq.(154). In account of this, the latter can be re-arranged into Eq.(157) and Eq.(156) to highlight nozzle and intake technologies.

$$Technology\ CaC_{i_{TD_{Structures}(Nozzle)}} = K_{Tech\ i_{TD_{Structures}(Nozzle)}} \cdot K_{TD_{Structures^*}} \cdot Vehicle\ CaC_{(TRL8)} \tag{155}$$

$$Technology\ CaC_{i_{TD_{Structures}(Intake)}} = K_{Tech\ i_{TD_{Structures^*}(Intake)}} \cdot K_{TD_{Structures^*}} \cdot Vehicle\ CaC_{(TRL8)} \tag{156}$$

In order to derive $K_{TD_{Structures^*}}$, a detailed cost analysis to assess the impact of specific components such as nozzle and intake onto Vehicle RDTE costs has been carried out using Price True Planning commercial software. From results, $K_{TD_{Structures^*}}$ is equal to 0.43, with 3.98% of $K_{TD_{Structures^*}}$ allocated to nozzle and 10.40% to intake. For the nozzle, three technologies are listed in Table 72. Therefore, by equally splitting nozzle RDTE cost contribution among them, $K_{Tech\ i_{TD_{Structures^*}(Nozzle)}}$ in Eq.(157) is equal to 0.01327 (i.e., 3.98%/3). In addition, for each of the four technologies related to the intake, $K_{Tech\ i_{TD_{Structures^*}(Intake)}}$ is equal to 0.026. Therefore, by applying Eq.(155) and Eq.(156) using these values, the CaC for nozzle and intake-related technologies in Table 72 (from ID1 to ID7) is obtained.

$\boldsymbol{Technologies_{\ TD_{Propulsion}}}$ **CaC.** As far as TD Propulsion is concerned, *DMR engines* and *ATR engines* in Figure 109 represent overall Propulsion Subsystem contribution to RDTE cost ($K_{TD_{Propulsion}} = 29.4\%$). This also includes elements applicable to both ATR and DMR such as Isolator, Engine Controls, Actuators and Engine Materials components (Figure 108(b)). As a result, Eq.(146) can be specialized as in Eq.(157) considering $Technologies_{\ TD_{Propulsion}}$.

$$Technology\ CaC_{i_{TD_{Propulsion}}} = K_{Tech\ i_{TD_{Propulsion}}} \cdot K_{TD_{Propulsion}} \cdot Vehicle\ CaC_{(TRL8)} \tag{157}$$

In this case, it is not possible to obtain cost data allocated on a detailed PBS up to Component Level as performed for $Technologies_{TD_{Structures}}$ CaC assessment. Therefore, to determine $K_{Tech\,i_{TD_{Propulsion}}}$ in Eq.(157), a preliminary estimation of required RDTE effort is performed by assigning to each technology in TD Propulsion a label (high, moderate, moderate-high, low-moderate, low, very low) as provided in Table 73. The label qualitatively estimates the expected level of RDTE effort for each technology basing on the comments collected from propulsion experts involved in H2020 STRATOFLY project. Each level is then associated to a numerical value (or "weight") which is translated into $K_{Tech\,i_{TD_{Propulsion}}}$. As mentioned, the estimated CaC up to TRL8 for $Technologies_{TD_{Propulsion}}$ (from ID8 to ID22) is collected in Table 72.

Table 73: $K_{Tech\ i_{TD_{Propulsion}}}$ estimation for $Technologies_{\ TD_{Propulsion}}$

Reference PBS Element	Powerplant Technology	Estimated RDTE Effort Level	Level Weight	$K_{Tech\ i_{Powerp}}$ [%]
ATR	ATR Fan Technology	MODERATE	1.5	9%
	ATR Turbines Technology	LOW-MODERATE	1	6%
	ATR Combustor Technology	MODERATE	1.5	9%
	ATR Pumps Technology	LOW-MODERATE	1	6%
DMR	DMR Injection Struts Technology	LOW-MODERATE	1	6%
	Scramjet Combustor Technology	LOW-MODERATE	1	6%
	Ramjet-Scramjet Transition Technology	MODERATE	1.5	9%
	PAC Technology	VERY LOW	0.3	2%
Isolator	Isolator Technology	MODERATE	1.5	9%
Engine Controls	Engine Controls Technology	LOW-MODERATE	1	6%
Actuators	Intake Ramps Actuators Technology	LOW	0.7	4%
	Variable Throat Actuators Technology	LOW	0.7	4%
Engine Materials	Engine Cooled Materials (CMC)	MODERATE	1.5	9%
	Engine Cooled Materials (Metals)	MODERATE	1.5	9%
	Engine Uncooled Materials	LOW-MODERATE	1	6%

HyDat Filling (Technologies). To conclude the description of activities carried out in this Dissertation in relation to technologies definition and characterization for Case Study 1, it is worth mentioning that the results collected in Table 72 have been stored into HyDat (Section 7.3) in order to begin the process of database filling. Notably, as shown in Table 74 and in Table 75, *technologies* and *trl_plan* table described in Section 7.3 have been properly filled with available information. Notably, basing on Section 7.3, *technologies* Table allows to store technology data including the ID of linked TG. However, in the phase of technologies' list derivation previously described in this Section only the link between technologies and TDs has been explored. Therefore, additional considerations are required to correctly associate technologies to the complete ESA technology Tree hierarchy. Notably, according to (ESA, 2020a), $TD_{Propulsion}$ and $TD_{Structures}$ are linked, respectively, to TD19 and TD20. Looking at the TSs associated to TD19, the most suitable TS connected to technologies with ID from 8 to 22 seems *Chemical Propulsion Technologies* and the TG mostly in line with this subset of technologies is *Technologies for Structural Integration*. Complementary, the TS for the remaining technologies belonging to TD20 is *Chemical Propulsion Technologies* and the TG is *Air-Breathing and Hybrid Propulsion Subsystems*. It is specified that the ESA technology Tree does not directly associate an ID to TSs and TGs (but only to TDs) so that a progressive ID is assigned in this work to properly store them in HyDat. Notably, as shown in Table 74, the TGs *Air-Breathing and Hybrid Propulsion Subsystems* and *Technologies for Structural Integration* are connected, respectively, to the IDs 216 and 245. Please, notice that the ESA Technology Tree is mainly conceived to classify space-related technologies, hence the association with more aeronautical technologies like those envisaged for the STRATOFLY MR3 is not straightforward and might be not fully fitting. For this exercise the already available ESA categorization is adopted for simplicity, however the new HyDat architecture described in Section 7.3 allows to easily define new TGs in the future to make the Technology Tree more representative also for the aeronautical domain.

Table 74: HyDat *technologies* Table filling with available technology data

Tech_ID	Tech_name	Tech_description	CaC	CaC_Currency	CaC_RefYear	Tech_group_ID
1	Low Speed Intake Ramp Technology	NULL	415.27	M€	2021	245
2	Low Speed Intake Duct Technology	NULL	415.27	M€	2021	245
3	High Speed Intake Technology	NULL	415.27	M€	2021	245
4	2D Nozzle Technology	NULL	119.16	M€	2021	245
5	3D Nozzle Technology	NULL	119.16	M€	2021	245
6	ATR Exhaust Duct Technology	NULL	119.161	M€	2021	245
7	ATR Variable Throat Technology	NULL	119.16	M€	2021	245
8	ATR Fan Technology	NULL	722.33	M€	2021	216
9	ATR Turbines Technology	NULL	481.55	M€	2021	216
10	ATR Combustor Technology	NULL	722.33	M€	2021	216
11	Engine Controls Technology	NULL	481.55	M€	2021	216
12	DMR Injection Struts Technology	NULL	481.55	M€	2021	216
13	Scramjet Combustor Technology	NULL	481.55	M€	2021	216
14	Ramjet-Scramjet Transition Technol...	NULL	722.33	M€	2021	216
15	PAC Technology	NULL	144.47	M€	2021	216
16	Isolator Technology	NULL	722.33	M€	2021	216
17	ATR Pumps Technology	NULL	481.55	M€	2021	216
18	Intake Ramps Actuators Technology	NULL	337.09	M€	2021	216
19	Variable Throat Actuators Technology	NULL	337.09	M€	2021	216
20	Engine Cooled Materials (CMC)	NULL	722.33	M€	2021	216
21	Engine Cooled Materials (Metals)	NULL	722.33	M€	2021	216
22	Engine Uncooled Materials	NULL	481.55	M€	2021	216

Table 75: HyDat *trl_plan* Table filling with available technology data

trl_plan_ID	trl_plan_date	trl	Tech_ID
1	2018-06-01	6	1
2	2018-06-01	6	2
3	2018-06-01	4	3
4	2018-06-01	7	4
5	2018-06-01	4	5
6	2018-06-01	6	6
7	2018-06-01	6	7
8	2018-06-01	6	8
9	2018-06-01	7	9
10	2018-06-01	6	10
11	2018-06-01	6	11
12	2018-06-01	6	12
13	2018-06-01	6	13
14	2018-06-01	4	14
15	2018-06-01	1	15
16	2018-06-01	4	16
17	2018-06-01	6	17
18	2018-06-01	4	18
19	2018-06-01	6	19
20	2018-06-01	6	20
21	2018-06-01	6	21
22	2018-06-01	6	22

ACs and MCs (with HyDat filling). Once all data related to technologies is available (i.e., Starting TRL, AD^2 and CaC), it is possible to define the second category of elements meaningful for roadmapping, i.e., ACs and MCs. In order to derive a complete list of ACs/MCs spanning all TRL levels for each technology, as suggested in Section 4.3.2.3, the definition of TRL levels provided in (ECSS (European Cooperation for Space Standardization), 2017) is used as guideline. Furthermore, to improve this list specifically for the list of technologies in Table 72, several literature sources are considered, such as those related to ATREX (Sato et al., 2007; Sawai et al., 2003) and S-Engine in Japan (Kobayashi et al., 2004; Kojima et al., 2015). Moreover, the final list is enriched with information useful to propose flight demonstration missions at higher TRL from (Bowcutt, 2003) (Section 4.3.2.3). As a result, Section 7.4 collects the complete list of ACs/MCs derived in this work and required to begin technology development (improperly associated to TRL0 for simplicity) up to TRL 9 for all technologies of interest. For each AC/MC, the Enabling and Target TRL are reported as well as linked technologies. Depending on the Starting TRL of each technology, only a subset of the full ACs/MCs list is effectively required for the Planning (Section 4.3.4). However, the full list can be included in HyDat to populate the database with ACs and MCs applicable to airbreathing RLVs. As an example, Table 76 and

Table 77 show, respectively, the list of ACs and MCs derived for Low-Speed Intake Technology (ID1).

For sake of clarity, the list in Section 7.4 contains only required ACs/MCs to pursue the specified TRL Transit (alternative ACs/MCs have already been evaluated and discarded). In addition, in case several ACs/MCs are connected to the same Targett TRL, they have to be all successfully performed in order to effectively succeed in that TRL transit. Please, notice that ACs and MCs cost data is not stored since it is not available at the moment. Similarly, additional MC information such as target Environment and Mission Profile is not included since it is not of interest for the current exercise. Starting the list in Section 7.4, the bridging Tables *technologyactivity_bridge* and *technologymission_bridge* mentioned in Section 7.3 can be easily filled

Table 76: HyDat *activities* Table filling with available AC data

Activity_ID	Activity_Name	Activity_Description	TRL_start	TRL_end	Activity_Cost	Activity_Cost_Currency	Activity_Cost_RefYear	Activity_Funded
1	Expression of basic principles for intended use o...	NULL	0	1	NULL	NULL	NULL	NULL
2	Identification of potential applications of Low Sp...	NULL	0	1	NULL	NULL	NULL	NULL
3	Design of Low Speed Intake Ramp, providing un...	NULL	1	2	NULL	NULL	NULL	NULL
4	Formulation of potential application of Low Spee...	NULL	1	2	NULL	NULL	NULL	NULL
5	General definition of performance requirements ...	NULL	1	2	NULL	NULL	NULL	NULL
6	Low Speed Intake Design	NULL	2	3	NULL	NULL	NULL	NULL
7	Low Speed Intake Numerical Analysis/Simulation	NULL	2	3	NULL	NULL	NULL	NULL
8	Design of low speed intake model for windtunn...	NULL	3	4	NULL	NULL	NULL	NULL
9	Fabrication of low speed intake model(s) for wi...	NULL	3	4	NULL	NULL	NULL	NULL
10	Windtunnel test(s) of low speed intake model(s)	NULL	3	4	NULL	NULL	NULL	NULL
11	Design of low speed intake model to be integrat...	NULL	4	5	NULL	NULL	NULL	NULL
12	Fabrication of low speed intake model(s) to be i...	NULL	4	5	NULL	NULL	NULL	NULL
13	Propulsion Plant Windtunnel test(s) to verify crit...	NULL	4	5	NULL	NULL	NULL	NULL
14	Design of low speed intake model to be integrat...	NULL	5	6	NULL	NULL	NULL	NULL
15	Fabrication of low speed intake model(s) to be i...	NULL	5	6	NULL	NULL	NULL	NULL
16	Sea-level firing test(s) of propulsion plant model(s)	NULL	5	6	NULL	NULL	NULL	NULL
17	Design of low speed intake model to be integrat...	NULL	6	7	NULL	NULL	NULL	NULL
18	Fabrication of low speed intake model(s) to be i...	NULL	6	7	NULL	NULL	NULL	NULL
19	Design of low speed intake model to be integrat...	NULL	7	8	NULL	NULL	NULL	NULL
20	Fabrication of low speed intake model(s) to be i...	NULL	7	8	NULL	NULL	NULL	NULL
21	Design of low speed intake model to be integrat...	NULL	8	9	NULL	NULL	NULL	NULL
22	Fabrication of low speed intake model(s) to be i...	NULL	8	9	NULL	NULL	NULL	NULL

Table 77: HyDat *missionconcepts* Table filling with available MC data

MC_ID	MC_Name	MC_Description	MC_Target_Environment	MC_TRL_start	MC_TRL_end	MC_Cost	MC_Cost_Currency	MC_Cost_RefYear	MC_MissionProfile	MC_Funded
1	Flight test(s) of Small Scale Flight Demonstrator(s)	NULL		6	7	NULL	NULL	NULL	NULL	NULL
2	Flight test(s) of Mid Scale Flight Demonstrator(s)	NULL		6	7	NULL	NULL	NULL	NULL	NULL
3	Flight test(s) of Near Full Scale Flight Demonstr...	NULL		7	8	NULL	NULL	NULL	NULL	NULL
4	STRATOFLY MR3 Mission(s)	NULL		8	9	NULL	NULL	NULL	NULL	NULL

BBs (with HyDat filling). With reference to the BB hierarchy proposed in Section 4.3.2.2, it is possible to derive lists of BBs at the different Levels for the present application exploiting information from the detailed PBS provided in Figure 108(a). At this purpose, the correspondence between each Level in the reference BB hierarchy and the Levels in the PBS has to be specified. Notably, STRATOFLY TSTO is the specific BB Segment considered and it belongs to both Launcher and Orbital Transportation & Re-entry System categories. In addition, STRATOFLY MR3 can be labelled as a linked BB Stage in the BB hierarchy. It is associated to the BB Stage Category *Airbreathing First Stage Vehicle* and it corresponds to Vehicle Level in the PBS. Concerning the lists of linked BB Systems, Equipment and Components, it is worth referring to Figure 100, which reports the information of interest for this analysis from the ESA Product Tree. In this context, recalling that this roadmapping study specifically deals with the First Stage of STRATOFLY TSTO, only the Launcher portion of the ESA Product Tree is reported in Figure 110. For this Segment, Propulsion and Structures Systems are clearly of great importance for this work taking into account the previous discussion on technologies. In addition to that, basing on the nomenclature provided in Figure 110, Materials is considered as System due to the PBS items related to engine materials.

Products:
Equipment
Building Blocks (BB)
EEE Components, mechanical Parts and materials (C&P)

	Segment		Systems		Products: Equipment/Building Blocks/EEE Components, mechanical Parts and materials		Description
I	Launchers	D	Materials	1	Metallic		
				2	Non-metallic		
				3	Composite Materials	a	Reinforcement Material: Glass Fibres
						b	Reinforcement Material: Carbon Fibres
						c	Reinforcement Material: Aramid Fibres
						d	Reinforcement Material: Silicon Carbide, both Fibre and Particulate (SiC)
						e	Reinforcement Material: Alumina, both Fibre and Particulate (Al_2O_3)
						f	Reinforcement Material: New polymeric fibres
						g	Reinforcement Material: Others
						h	Matrix Structure: Epoxy
						i	Matrix Structure: Cyanate Ester
						j	Matrix Structure: Ceramic (SiC)
						k	Matrix Structure: Metal (Al, Ti, C)
						l	Matrix Structure: Others
		G	Propulsion	1	Liquid propulsion systems		
				1.1	Liquid propulsion systems - BB	a	Propellant Tanks *See Structures*
						b	Pressure Tanks *See Structures*
						c	Feeding system devices (feed lines, filters, valves, ...)
				2	Storable liquid engines		
				3	Cryogenic liquid engines		
				4	Hydrocarbon liquid engines		
				2/3/4.1	Liquid propulsion engines - BB	a	Combustion chambers
						b	Flow control and distribution devices (Pipes, Valves, Actuators, Filters, ...)
						c	Gas generators (gas generetor cycle engine)
						d	Nozzles
						e	Pre-burners (stage combustion cycle engine)
						f	Turbo-pumps
						g	Other
				5	Solid propulsion motors		
				5.1	Solid propulsion motors - BB	a	Motor Cases (metallic, composite)
						b	Thermal Protection
						c	Propellant Grain
						d	Igniters
						e	Nozzles
						f	Other
				6	Reaction and Attitude Control Systems		
				6.1	Reaction and Attitude Control Systems - BB	a	Thrusters
						b	Flow control and distribution devices
						c	Tanks *See Structures*
						d	Other
				7	Propulsion System SW	a	SW tools for propulsion system and engine design, analysis, simulation, etc.
		I	Structures	1	Stage structures	a	Intestages, skirts, thrust frame, ...
				2	Tanks		
				3	Propellant tanks		
				4	Pressure tanks		
				5	Fairing		
				6	Payload adapters		
				7	Other		
				1/2/3/4/5/6/7.1	Structures - BB	a	Structural joints, dampers, interfaces support, interface rings, ...
						b	Plates panels and bearing walls
						c	Other
				8	Structural Engineering SW	a	SW for Structures design, analysis, simulation, etc.

Figure 110: Portion of ESA Product Tree of interest for this study (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011)

As a result, by merging the information from the ESA Product Tree and the available PBS breakdown, it is possible to define a set of BB Systems categories to be included into HyDat at *bb_system_category* Table (Section 7.3). As shown in Table 78, the three BB System categories obtained from the ESA Product Tree are reported along with those typically installed onto aircraft-like hypersonic systems like the STRATOFLY MR3. As it can be noticed, the list in Table 78 mainly covers items originally at Subsystem Level in the PBS (e.g., Propulsion, APU, Propellant, etc.) except for Structures and Mechanisms (at System Level) and Materials (mentioned at Component Level in strict connection to the engine).

Table 78: HyDat *bb_system_category* Table filling

BB_System_Category_id	BB_System_Category_name
1	Structures
2	Propulsion System
3	Auxiliary Power Unit (APU)
4	Propellant System
5	Environmental Control System (ECS)
6	Flight Control System (FCS)
7	Avionic System
8	Electical Power System (EPS)
9	Thermal and Energy Management System (TEMS)
10	Water System
11	Oxygen System
12	Lights
13	Materials

The generic list of BB System categories can now be used to classify the specific BB Systems onboard the STRATOFLY MR3. As a result, *bb_system* Table in HyDat can be filled as in Table 79. The latter also reports the reference BB System category for each BB System thanks to the field *BB_System_Category_ID* (Section 7.3).

Table 79: HyDat *bb_system* Table filling

BB_System_ID	BB_System_name	BB_System_description	BB_System_Category_id
1	STRATOFLY MR3 Structures		1
2	STRATOFLY MR3 Propulsion System		2
3	STRATOFLY MR3 APU		3
4	STRATOFLY MR3 Propellant System		4
5	STRATOFLY MR3 ECS		5
6	STRATOFLY MR3 FCS		6
7	STRATOFLY MR3 Avionic System		7
8	STRATOFLY MR3 EPS		8
9	STRATOFLY MR3 TEMS		9
10	STRATOFLY MR3 Water System		10
11	STRATOFLY MR3 Oxygen System		11
12	STRATOFLY MR3 Lights		12
13	STRATOFLY MR3 Materials		13

Moving to Equipment Level, it is highlighted in red in the ESA Product Tree of Figure 110. Looking at the Equipment linked to Propulsion System, *Cryogenic*

Liquid Engine is the most suitable for the current application. In addition, basing on the information provided in (Ferretto, 2020), *Stage Structures* and *Tanks* categories seem appropriate to describe vehicle structure as well as integral tanks. The result is *bb_equipment_category* Table (Table 80), in which Equipment related to Materials System (not specifically included in ESA Product Tree at Equipment Level) have been added to fill the hierarchy and avoid gaps. In this case, the correspondence with the original PBS Levels is not possible since an Equipment Level was not envisaged. As already performed with Systems, Equipment categories in Table 81 are used to derive the detailed set of Equipment installed on the STRATOFLY MR3.

Table 80: HyDat *bb_equipment_category* Table filling

BB_Equipment_Category_id	BB_Equipment_Category_name
1	Stage Structures
2	Tanks
3	Cryogenic Liquid Engine
4	Metallic Materials
5	Non-Metallic Materials
6	Composite Materials

Table 81: HyDat *bb_equipment* Table filling

BB_Equipment_ID	BB_Equipment_name	BB_Equipment_description	BB_Equipment_Category_id
1	STRATOFLY MR3 Empennages		1
2	STRATOFLY MR3 Flight Control Surfaces		1
3	STRATOFLY MR3 Landing Gear		1
4	STRATOFLY MR3 Thrust Frame		1
5	STRATOFLY MR3 Wing Integral Tanks		2
6	STRATOFLY MR3 Fuselage Integral Tanks		2
7	STRATOFLY MR3 ATR Engine		3
8	STRATOFLY MR3 DMR Engine		3
9	STRATOFLY MR3 Metallic Materials		4
10	STRATOFLY MR3 Non-Metallic Materials		5
11	STRATOFLY MR3 Composite Materials		6

As far as Component Level is concerned, as mentioned in Section 4.3.2.2, the nomenclature adopted in the BB hierarchy is not fully in line with the ESA Product Tree. This is due to the need to avoid the term Building Block to define a sublevel. In account of this, the definition of Component within this Dissertation entails both the products highlighted in green in Figure 110 (referred as Building Blocks in the ESA Product Tree) as well as those in yellow (i.e., EEE Components, mechanical parts and materials). By comparing these products with the available PBS items, the following BB Component categories can be easily included in *bb_component_category* Table (Table 82): Nozzle, Combustion Chamber, Turbopump and Materials-related Components. The remaining categories in Table 82 can be defined exploiting the PBS items at Subsystem Level (i.e., Intake and Nozzle) and at Component and Sub-Component Level. For sake of clarity, the PBS items at Sub-Component Level can also be used to derive the detailed list of Components applicable to the STRATOFLY MR3 and top be included into *bb_component* Table (Table 83).

Table 82: HyDat *bb_component_category* Table filling

BB_Component_Category_id	BB_Component_Category_name
1	Intake
2	Nozzle
3	Exhaust Duct
4	Variable Throat
5	Fan
6	Combustion Chamber
7	Turbine
8	Turbopump
9	Injection Strut
10	Isolator
11	Engine Controls
12	Actuator
13	CMC Materials
14	Metals
15	Non-Metals

At this point, to fully represent the BB hierarchy, it is required to define the links between BBs at different levels. At this purpose, exploiting the newly-derived lists of BB Systems, Equipment and Components and taking into account the hierarchy defined by the PBS, it is possible to express relationships between BBs as provided in Table 83 and in Figure 111. As a result, the HyDat Tables discussed in Section 7.3, able to store the links between BBs (i.e., *bb_stage_in_segment, bb_system_in_stage, bb_equipment_in_system* and *bb_component_in_equipment),* can be easily filled

Table 83: HyDat *bb_component_category* Table filling

BB_Component_ID	BB_Component_name	BB_Component_description	BB_Component_Category_id
1	STRATOFLY MR3 Low Speed Intake Ramp		1
2	STRATOFLY MR3 Low Speed Intake Duct		1
3	STRATOFLY MR3 2D Nozzle		2
4	STRATOFLY MR3 3D Nozzle		2
5	STRATOFLY MR3 ATR Engine Exhaust Duct		3
6	STRATOFLY MR3 ATR Engine Variable Throat		4
7	STRATOFLY MR3 ATR Engine Fan		5
8	STRATOFLY MR3 ATR Engine Combustor		6
9	STRATOFLY MR3 ATR Engine Turbines		7
10	STRATOFLY MR3 ATR Engine Pumps		8
11	STRATOFLY MR3 DMR Engine Injection Struts		9
12	STRATOFLY MR3 DMR Engine Combustor		6
13	STRATOFLY MR3 DMR Engine Isolator		10
14	STRATOFLY MR3 Engine Controls		11
15	STRATOFLY MR3 Intake Ramps Actuators		12
16	STRATOFLY MR3 Variable Throat Actuators		12
17	STRATOFLY MR3 Engine Cooled Materials (CMC)		13
18	STRATOFLY MR3 Engine Cooled Materials (Metals)		14
19	STRATOFLY MR3 Engine Uncooled Materials		15

.

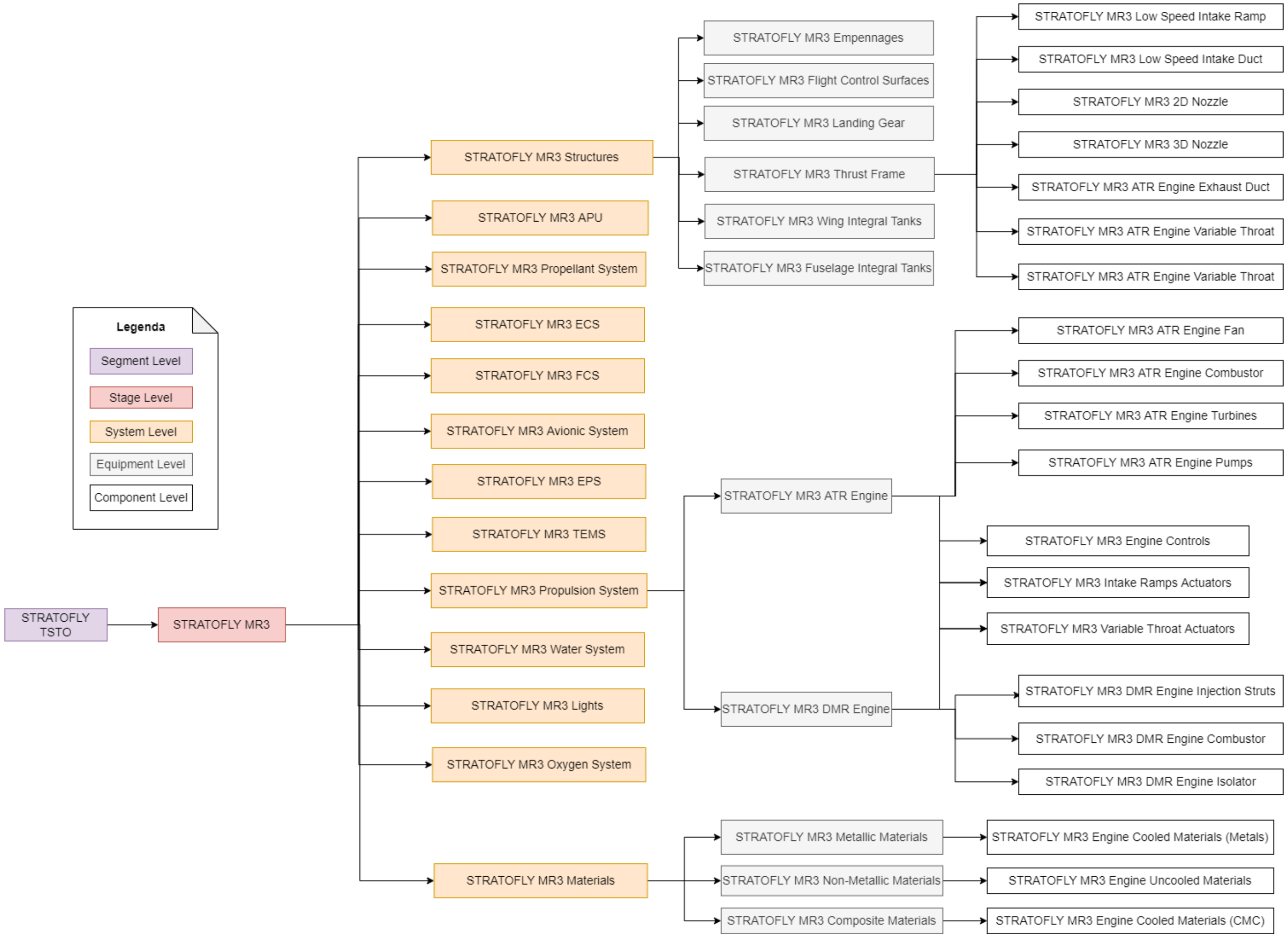


Figure 111: BBs Hierarchy for STRATOFLY MR3

OCs. As mentioned in Section 4.3.2.4, the list of OCs considered in this Dissertation is extracted from (Cresto Aleina, 2018). However, in the framework of the roadmapping analysis here performed, only a subset of that list is effectively applicable. The latter, properly loaded within the *operationalcapabilities* Table in HyDat (Section 7.3) is summarized in Table 84. In this context, considering that in HyDat OCs are directly linked to BB Stages (see Section 7.3 for further details), each element is connected to the BB Stage *STRATOFLY MR3* and the link can be stored within the *oc_in_bb_stage* Table.

Table 84: HyDat *operationalcapabilities* Table filling

OC_ID	OC_name
1	High capacity take-off applied to a human mission with prepared site and horizontal take-off
2	Take-off noise reduction applied to a human mission with prepared site and horizontal take-off
3	High capacity transfer applied to a human mission
4	High speed transfer applied to a human mission
5	Cruise lower consumption applied to a human mission
6	High capacity landing applied to a human mission with airfield landing and horizontal landing
7	Low time to reuse applied to a human mission with airfield landing and horizontal landing
8	Landing noise reduction applied to a human mission with airfield landing and horizontal landing

4.5.1.2 Step 3: Prioritization Studies

As far as technologies' prioritization is concerned, the trade-off analysis described in Section 4.3.3.1 is applied. In this phase, the list of technologies is ranked according to criteria previously defined by stakeholders and exploiting technology data from Table 72. As required by the trade-off methodology, Table 85 collects technology data normalized on maximum (MAX) or minimum (MIN) value according to the prioritization order assigned by EC stakeholder to each criterion (respectively, descending or ascending). As mentioned, $K_{SG} = 1$ due to the presence of a unique stakeholder, while a specific weight is associated to each criterion basing on the importance assigned by EC stakeholder as provided in Section 4.5.1.1. Notably, $K_{C_{AD2}} = 0.50, K_{C_{TRL}} = 0.33$ and $K_{C_{CaC}} = 0.17$, according to the nomenclature in Eq.(148). Using the inputs in Table 85, the ranked list of technologies reported in Table 86 is obtained.

From results, it can be noticed that PAC Technology should be considered as the highest priority technology, being associated to high risk and low Starting TRL and Cost at Completion (CaC). As far ACs/MCs are concerned, as already mentioned in Section 4.5.1.2. The list provided in Section 7.4, specifically derived for this application, already contains only required ACs/MCs. As such, ACs/MCs ranking is not necessary.

Table 85: Normalized technology data required for trade-off analysis

Technology Name	1) AD^2 (Descending) MAX	2) Starting TRL (Ascending) MIN	3) CaC (Ascending) MIN
Low Speed Intake Ramp Technology	0.57	0.17	0.29
Low Speed Intake Duct Technology	0.57	0.17	0.29
High Speed Intake Technology	0.71	0.25	0.29
2D Nozzle Technology	0.14	0.14	1.00
3D Nozzle Technology	0.71	0.25	1.00
ATR Exhaust Duct Technology	0.71	0.17	1.00
ATR Variable Throat Technology	0.71	0.17	1.00
ATR Fan Technology	1.00	0.17	0.16
ATR Turbines Technology	0.29	0.14	0.24
ATR Combustor Technology	0.71	0.17	0.16
Engine Controls Technology	0.71	0.17	0.24
DMR Injection Struts Technology	0.43	0.17	0.24
Scramjet Combustor Technology	0.86	0.17	0.24
Ramjet-Scramjet Transition Technology	0.86	0.25	0.16
PAC Technology	0.86	1.00	0.81
Isolator Technology	0.57	0.25	0.16
ATR Pumps Technology	0.29	0.17	0.24
Intake Ramps Actuators Technology	0.86	0.25	0.35
Variable Throat Actuators Technology	0.86	0.17	0.35
Engine Cooled Materials (CMC)	1.00	0.17	0.16
Engine Cooled Materials (Metals)	1.00	0.17	0.16
Engine Uncooled Materials	0.71	0.17	0.24

Table 86: Ranked list of technologies for Case Study 1

Position	Tech ID	Tech Name
1	15	PAC Technology
2	5	3D Nozzle Technology
3	8	ATR Fan Technology
3	20	Engine Cooled Materials (CMC)
3	21	Engine Cooled Materials (Metals)
4	6	ATR Exhaust Duct Technology
4	7	ATR Variable Throat Technology
5	18	Intake Ramps Actuators Technology
6	19	Variable Throat Actuators Technology
7	14	Ramjet-Scramjet Transition Technology
8	13	Scramjet Combustor Technology
9	3	High Speed Intake Technology
10	11	Engine Controls Technology
10	22	Engine Uncooled Materials
11	10	ATR Combustor Technology
12	16	Isolator Technology
13	1	Low Speed Intake Ramp Technology
13	2	Low Speed Intake Duct Technology
14	12	DMR Injection Struts Technology
15	4	2D Nozzle Technology
16	17	ATR Pumps Technology
17	9	ATR Turbines Technology

4.5.1.4 Step 4: Planning Definition

By exploiting the Planning Definition flowchart in Figure 102, the ordered list of ACs/MCs in Section 7.5 is derived. As described in Section 4.3.4, required ACs and MCs are ordered in a logical way by considering not only the preferences expressed by stakeholders (i.e., Techs ranking) but also optimizing ACs/MCs accomplishment through the integration of all applicable technologies in single mission. To complete the analysis, the ordered list of ACs/MCs has to be properly distributed on a timeline in order to verify that the initial goal (i.e., TRL 6 by 2035) can be achieved in the subsequent phase of Results Evaluation. At this purpose, remembering the link between ACs/MCs and Techs, the TaC distribution reported in Figure 104 is exploited to estimate the duration of TRL transits and to derive a preliminary development timeline for each technology. For example, considering that "Low Speed Intake Ramp Technology" was at TRL 6 in 2018 and, as projected, it should be at TRL 9 in 2050, according to Figure 104, 44% of total TaC is accomplished in 11901 days (for sake of clarity, between 01/06/2018 and 31/12/2050). From this information, TaC can be easily assessed and, as a result, the days required to perform each TRL transit are estimated by re-applying the time breakdown in Figure 104. In this way, basing on the estimated duration of each TRL transit, it is possible to preliminary determine, for each technology, the date in which each TRL milestone could be achieved. This preliminary technologies' timeline can be then refined by taking into account the set of ACs/MCs to be performed during each TRL transit and their applicability to several technologies. In particular, it is assumed that ACs/MCs linked to many technologies can start only once all related technologies have reached the required Enabling TRL. For example, assume that a generic MC1 is enabled at TRL4 and that it is linked to Tech 1, Tech 2 and Tech 3. Thanks to the preliminary timeline derived, the estimated dates in which Tech 1, Tech 2 and Tech 3 may reach TRL 4 are available (respectively, Date 1, Date 2 and Date 3). If Date 1 < Date 2 < Date 3, MC1 can effectively start at Date 3, when all technologies have reached the required TRL milestone. By applying this logic to the whole ranked list of ACs and MCs (Section 7.5) is derived. Please, note that basing on the algorithm in Figure 102 the ranked list of ACs and MCs already accounts for stakeholders' preferences. In addition, the Gantt charts with the proposed planning for missions (Figure 112) and missions (Figure 113) can be obtained. The latter constitutes the final Technology Roadmap for STRATOFLY propulsive technologies proposed in this study.

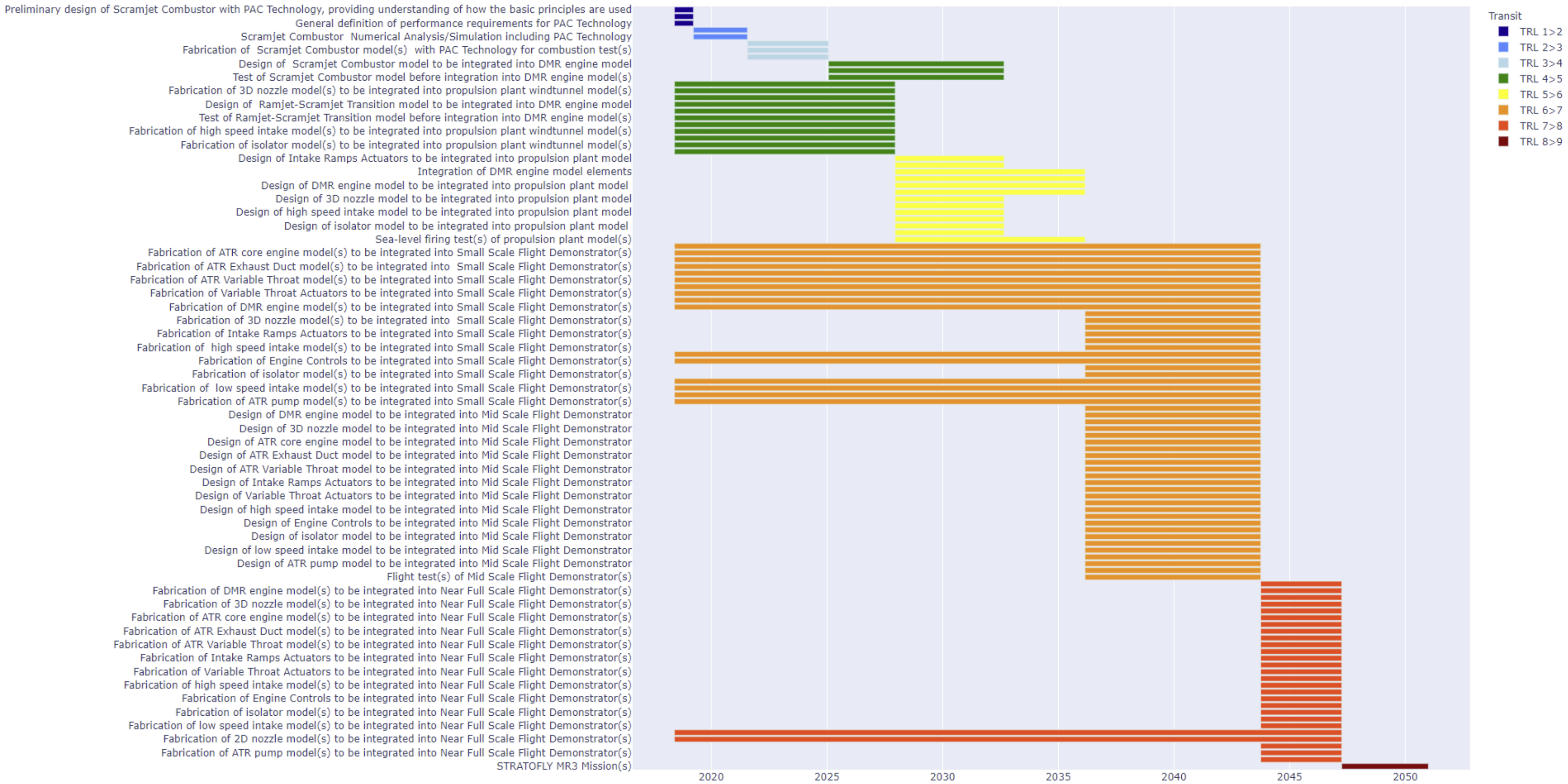


Figure 112: Proposed MCs' Planning for Case Study 1

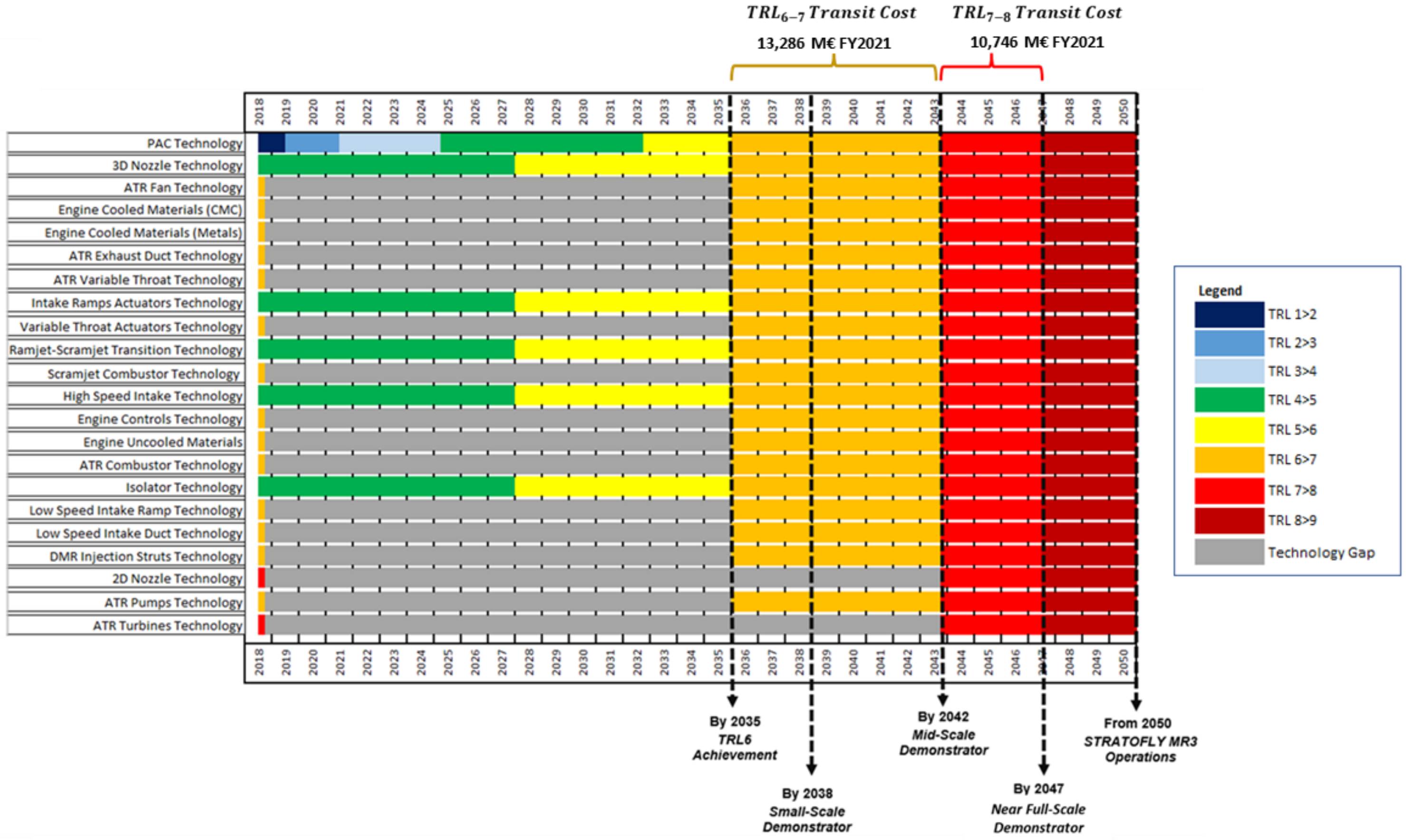


Figure 113: Proposed Techs Planning for Case Study 1 (STRATOFLY MR3 Technology Roadmap)

4.5.1.5 Step 5: Results Evaluation

By analysing the Technology Roadmap depicted in Figure 113, it emerges that all technologies may reach TRL 6 by 2035 if no out-of-nominal events occur and, most importantly, if available budget will be sufficient to cover the Cost at Completion of all technologies. In addition, the following milestones are envisaged:

- Small-Scale Demonstrator by 2038;
- Mid-Scale Demonstrator by 2042;
- Near Full-Scale Demonstrator by 2047;
- Beginning of STRATOFLY MR3 Operations from 2050.

Figure 113 also depicts the costs of flight demonstrators associated to the TRL Transits 6-7 and 7-8. For sake of clarity, the so-called “Technology Gap” in Figure 113 highlights, for some of the technologies under consideration, the need to freeze the technology development at a specific TRL in order to enable, with the development of the remaining technologies, the ACs/MCs required to proceed towards the next milestone. It is also worth emphasizing that the Technology Roadmap in Figure 113 is basically in line with HIKARI results reported in (Blanvillain & Gallic, 2015) according to which flight demonstration of an integrated system would occur around 2045.

4.5.2 Case Study 2 (Planning update)

As introduced in Section 4.5, the roadmapping activities reported in this Dissertation mainly focus onto the STRATOFLT MR3 thanks to the huge data availabiliy deriving from the involvement of Politecnico di Torino within the H2020 STRATOFLY Project. In that context, the support of experts participating in the Project was fundamental to derive great part of the inputs required for technolgoy Roadmapping. Indeed, as described in Section 4.5.1, the collaboration with experts was a fundamental aid in performing technology assessment and technology characterization (mainly in terms of TRL). This culminated in the definition of the list of technologies and related characteristis provided in Table 72. For Case Study 2, a similar huge amount of information was not available, specifically for what concerns the specific technologies on-board the vehicle. In account of this, as anticipated, a complete Technology Roadmappng exercise is not reported in this Dissertation for SpaceX Starship TSTO. However, thanks to the new TaC breakdown reported in Figure 104, it is possible to preliminary verify the Planning envisaged by SpaceX in relation to Starship and Heavy

Booster development (Musk, 2017b). Moreover, since the available Planning was proposed in 2017, it can be updated with the key achievement obtained through to the extensive testing campaign on-going at SpaceX. At this purpuse, Figure 114 provides a slighly modified version of the development Planning originally proposed by SpaceX (Musk, 2017b). Notably, it shows two key milestones: the start of the SN6 Starhopper testing in mid-2019 and the First Orbital Flight of SN20 and BN4 projected by the end of 2022 (this is not accomplished while writing this Dissertation). For sake of clarity, the SN6 is a scaled version of the Starship (First Stage) aimed at performing suborbital flight testing. Moreover, SN20 and BN4 are, respectively, more accurate prototypes of the Starship and the Super Heavy currently under ground testing. Using this information and taking into account the TRL definitions provided in Section 4.1.1, it can be preliminary stated that the accomplishment SN6 flight testing is linked to the achievement of TRL 5 for the overall system (i.e. test of subscale model in relevant environment). In addition, the projected orbital testing for SN20 and BN4 can lead to TRL6 (i.e. full scale demonstration in relevant environment). From a preliminary analysis of original SpaceX Planning (Figure 114), it can be noticed that the actual testing is delayed with respect to projections. In partiular, the orbital testing has (at least) two years of delay. Therefore, basing on the two available TRL milestones, the TaC breakdown in Figure 104 can be exploited to propose an updated development timeline for Space X Starship TSTO basing on current achievemnts. Results of this analysis as shown in Figure 114, where the TRL milestones up to TRL 9 are highlighted. From these results, it can be noticed that full operational capability (i.e. TRL 9) might be effectively attained in 2038. As such, the TaC routine provided by TRIS can be a powerful tool in verifying already proposed technoclogy development timelines, providing a warning about possible overoptimistic projections.

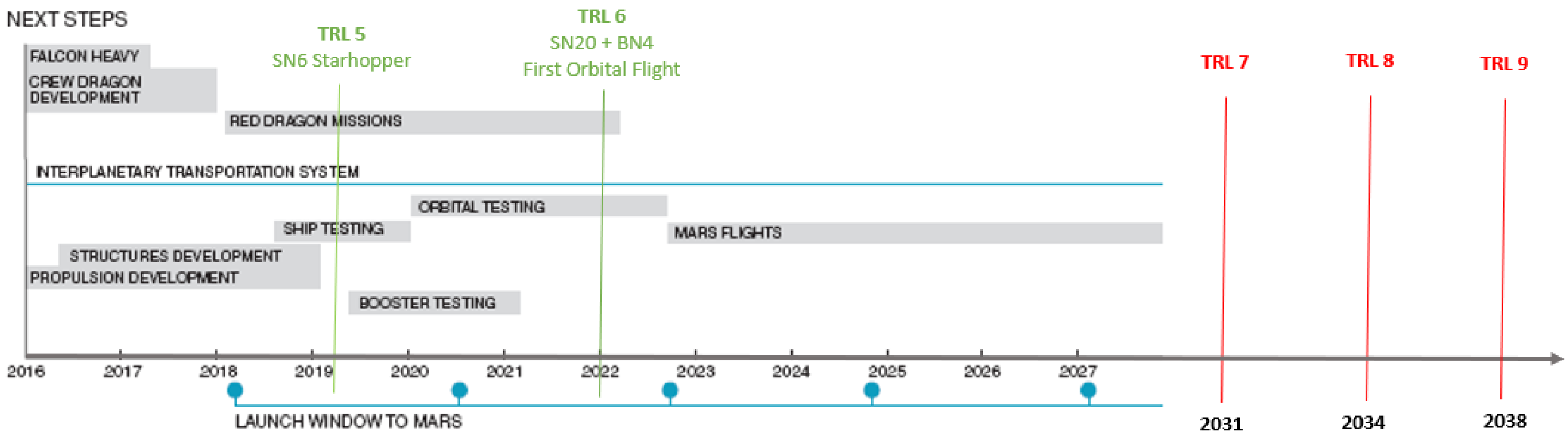


Figure 114: Comparison with SpaceX Planning (Musk, 2017b) using TRIS TaC Breakdown

4.6 Chapter 4 Abbreviations

AC	Activity
AD^2	Advancement Degree of Difficulty
ALT	Approach and Landing Test
BB	Building Block
CaC	Cost at Completion
CMC	Ceramic Matrix Composite
ConOps	Concept of Operations
DDTE	Design, Development, Test and Evaluation
DOC	Direct Operating Cost
EC	European Commission
ECSS	European Cooperation for Space Standardization
ESA	European Space Agency
FESTIP	Future European Space Transportation Investigations Programme
FMOF	First Orbital Manned Flight
FoM	Figure of Merit
GSTP	General Support Technology Programme
GUI	Graphical User Interface
H2020	Horizon 2020
HTHL	Horizontal Take-Off Horizontal Landing
HyDat	Hypersonic Database
IOC	Indirect Operating Cost
IST	Innovation Support Technology
IXV	Intermediate eXperimental Vehicle
LAPCAT	Long-Term Advanced Propulsion Concepts and Technologies
LCC	Life-Cycle Cost
LEO	Low Earth Orbit
MC	Mission Concept
MECU	Million European Currency Unit
MS	Microsoft
NASA	National Aeronautics and Space Administration
OC	Operational Capability
PAC	Plasma Assisted Combustion
PBS	Product Breakdown Structure
PEST	Political, Economic, Socio-cultural and Technological
QR	Qualification Review
RDTE	Research, Development, Test and Evaluation
RLV	Reusable Launch Vehicle
RSC	Refurbishment and Spares Cost
SH	Stakeholder
SoA	State-of-the-Art

SoS	Systems of Systems
SRR	System Readiness Review
STRATOFLY	Stratospheric Flying Opportunities for High-Speed Propulsion Concepts
TA	Technology Area
TaC	Time at Completion
TD	Technology Domain
Tech	Technology
TFU	Theoretical First Unit
TG	Technology Group
TPS	Thermal Protection System
TREx	Technology Roadmaps for space Exploration
TRIS	Technology RoadmappIng Strategy
TRIZ	Teoriya Resheniya Izobreatatelskikh Zadatch
TRL	Technology Readiness Level
TRP	Technology Research Programme
TS	Technology Subdomain
TSTO	Two Stage to Orbit
US	United States

Chapter 5

Cost-Effectiveness

This Chapter aims at describing how results from Life Cycle Cost (LCC) assessment derived in Chapter 3 can be merged to the results of Effectiveness Analysis to provide a final Cost-Effectiveness (C-E) assessment for future Reusable Launch Vehicles (RLVs). In the brief introductory Section, key definitions useful for the remainder of the Chapter are summarized, while in Section 5.2 recalls the main concepts related to Effectiveness analysis with special emphasis onto the nomenclature introduced by NASA. Then, Section 5.3 gathers the main results of the thorough literature analysis performed in this work and aimed at determine the major State-of-the-Art (SoA) methods allowing to carry out Effectiveness Analysis and C-E assessment. Notably, Section 5.3.1 resumes an analytical approach for C-E studied in the past by several authors, while Section 5.3.2 focuses on how trade-off analysis has been used to perform Effectiveness Analysis. Moreover, Section 5.3.3 summarizes the key features of a parametric methodology able to provide a quantitative estimation of Effectiveness starting from design parameters. Subsequently, basing on the main outcomes of the literature review, an Effectiveness Model specifically tailored for RLVs is proposed. A detailed analysis of Effectiveness attributes is carried out, establishing the key characteristics to be included within the Effectiveness Model. This is performed by exploiting the results from high-level requirements definition from Chapter 2. Then, the capabilities of SoA approaches described in Section 5.3.2 and Section 5.3.3 are merged into a final Effectiveness Model, able to exploit design information to estimate the key attributes of Effectiveness as well as trade-off analysis to derive a comprehensive evaluation of Effectiveness by properly weighting the attributes. Then, the Effectiveness Model is applied to the Case Studies described in Section 2.2 and a final C-E assessment is performed using the results from previous LCC analysis and the Effectiveness Assessment. Eventually, results are evaluated and the most cost-effective option is suggested. At the end of the Chapter, a summary table reports all abbreviations used.

5.1 Introduction

Cost-Effectiveness is by far a decisive system attribute to evaluate while comparing alternative solutions during the design process. This is particularly true in the RLVs context, where the achievement of the most cost-effective design has been a key target (see Section 1.1). Before entering into the detail of Cost-Effectiveness (C-E) issues, it is important to recall main definitions related to this topic. In broad terms, C-E is "*the measure of a system in terms of mission fulfillment (system effectiveness) and total life-cycle cost*" (Blanchard & Fabrycky, 2015), whilst C-E analysis (intended as study) is "*the process of comparing alternative solutions to mission requirements in terms of value received (effectiveness) for the resources expended (costs)*" (ARINC Research Corporation, 1971). On this basis, since Chapter 3 extensively tackled the LCC component of C-E specifically for RLVs, no further discussion on this topic is herein provided. As far as effectiveness is concerned, it is addressed in a similar way in all major Systems Engineering Handbooks (DoD (Department of Defense), 2001; INCOSE, 2015; NASA, 2016a). However, considering the field of application of this Dissertation, the definitions provided by (NASA, 2016a), taken as reference, are summarized in Section 5.2.

5.2 System Effectiveness: Key Definitions

By definition, system (or product) effectiveness is *"a quantitative measure of the degree to which the system's purpose is achieved*" (NASA, 2016a). It is expressed by means of Measures of Effectiveness (MOEs) that are "*dependent upon the individual and integrated performance of the system components*" (NASA, 2016a). MOEs are "*the measures of success that are designed to correspond to accomplishment of the system objectives as defined by the stakeholder's expectations. They are stated from the stakeholder's point of view and represent criteria that are to be met in order for the stakeholder to consider the project successful*" (NASA, 2016a). Since MOEs are developed based on stakeholders' expectations, it is clear that they are strictly related to requirements generation

(Section 2.1.2). However, "*MOEs are typically not directly used as a technical requirement for the system but will be the basis for the concept of operations and requirements definition*". MOEs are expressed qualitatively and each MOE can be further specified in more quantitative and technical terms through a set of Measures of Performance (MOPs). In particular, "*MOPs are derived from MOEs* [and they] *are generated during requirements definition*", providing "*insight into the performance of the system*" (NASA, 2016a). A MOE can be connected to one or more MOPs. The main difference between MOEs and MOPs lies in the viewpoint from which they are formulated. Indeed, MOEs express customer/user viewpoint, while MOPs are more linked to the supplier's in that they measure "*the desired performance of a supplier's design solution*" (NASA, 2016a). MOPs can be in turn detailed using physical or functional system characteristics called Technical Performance Measures (TPMs), representing characteristics crucial for mission success. TPMs should be monitored all along the project to detect their progress and identify possible deficiencies that might constitute a risk towards the fulfilment of a critical system requirement. In-between MOEs and MOPs it is also possible to define the so-called Key Performance Parameters (KPPs), i.e., "*those performance capabilities and characteristics that are considered most essential for the operation of the system to satisfy the mission. […] KPPs are the minimum number of performance parameters established to characterize the major drivers of operational performance including supportability and interoperability*" (NASA, 2016a). To summarize, Figure 115 depicts the relationship between MOEs, KPPs, MOPs and TPMs starting from the definition of Needs, Goals, and Objectives (NGOs) as a result of mission statement elicitation (Section 2.1.2).

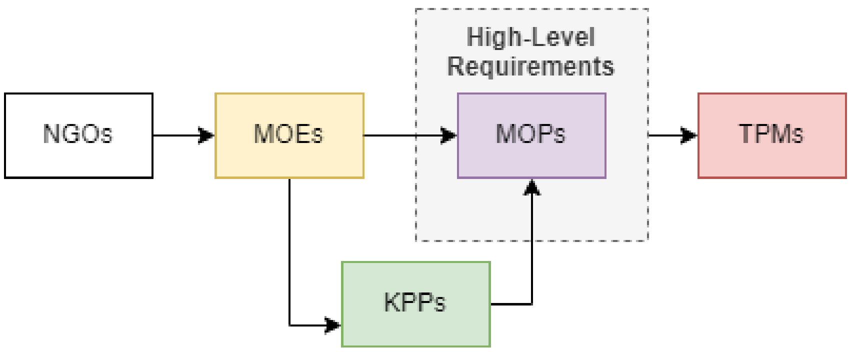


Figure 115: System Effectiveness Definition Process (adapted from (INCOSE, 2015; NASA, 2016a)

Notably, Figure 115 highlights the role of MOEs in the definition of high-level requirements and, as a consequence, of MOPs basing on the definitions provided by (NASA, 2016a) and just discussed. For sake of clarity, Figure 116 shows a practical example of MOE, KPP, MOP, TPM definition for a generic data system.

Example of MOE / KPP / MOP / TPM Flow

- MOE: The data system does not fail when processing mission critical functions
- KPP: Reliability
- MOP: Derived from the MOE—System provides uninterrupted computing for at least 100 hours
- TPM: Failure rate

Figure 116: Example of MOE, KPP, MOP, TPM definition for a generic data system (NASA, 2016a)

5.3 Literature Review

5.3.1 WSEIAC-related Methodologies (ARINC Research Corporation, 1971; Pecht, 2009; WSEIAC, 1966)

Early focus into Cost-Effectiveness (C-E) issues date back to the 1960s in the framework of large-scale military development and acquisition projects. In particular, it is worth mentioning the study performed by the Weapon System Effectiveness Industry Advisory Committee (WSEIAC) (WSEIAC, 1966), which provided a comprehensive approach to C-E analysis with special attention onto system effectiveness assessment. For sake of clarity, the effectiveness model proposed by WSEIAC has been further elicited thanks subsequent studies (ARINC Research Corporation, 1971; Pecht, 2009). Notably, WSEIAC expressed system effectiveness as function of three major system attributes:

1. Availability, a measure of system condition at the start of the mission;
2. Dependability, a measure of system condition while performing the mission given its condition at the start of the mission (availability);
3. Capability, a measure of mission results given the system condition during the mission (dependability).

In this context, (Pecht, 2009) also highlights the strict relation between availability and dependability, which can be split into three constituent elements, i.e. reliability, maintainability, and logistic supportability (RM&S) as depicted in Figure 117. The definition of these element of system effectiveness provided by (Pecht, 2009) was already provided in Section 1.1.

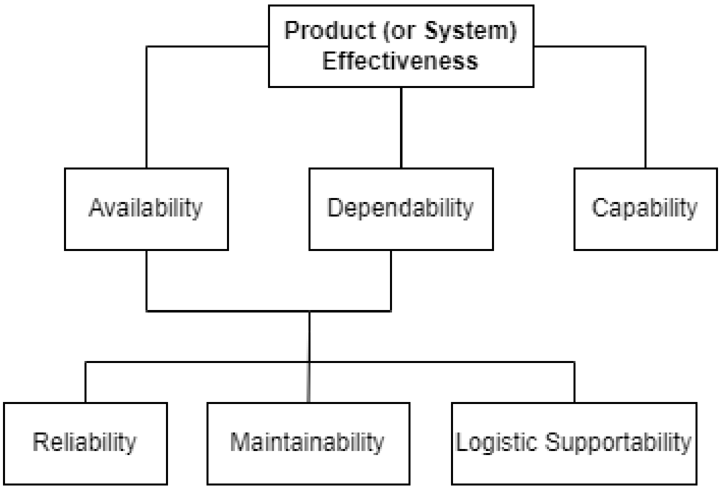


Figure 117: Major components of Product/System Effectiveness according to (Pecht, 2009)

Going back to WSEIAC study, the proposed analytical model is based on the definition of n system "states" required to accomplish the mission. For example, "*the condition in which all system hardware is functioning within design specifications is one state*" (WSEIAC, 1966). On this basis, system effectiveness (E) is expressed by the following matrix product:

$$E = \overline{A'}\,[D]\,\overline{C} \tag{158}$$

Where:

$\overline{A'} = [a_1, a_2, a_n]$ is the availability vector;

$D = \begin{bmatrix} d_{11} & d_{12} & \dots & d_{1n} \\ d_{21} & d_{22} & \dots & d_{2n} \\ d_{n1} & d_{n2} & \dots & d_{nn} \end{bmatrix}$ is the dependability matrix;

$\overline{C} = \begin{bmatrix} c_1 \\ c_2 \\ c_n \end{bmatrix}$ is the capability vector.

Please, notice that the specific expressions just provided for $\overline{A'}$, D, and $\overline{C}$ are reported in (ARINC Research Corporation, 1971). Considering the initial state i and the generic state j of the system during the mission:

- a_i is the probability that the system is in state i at the beginning of the mission;
- d_{ij} is the probability that the system will make the transition from state i to state j over a fixed time period,

- c_j is the capability of the system to perform the mission given the system is in state j and it can be a probability or a performance value associated to mission accomplishment.

Even from this preliminary description, it is clear that Eq.(158) constitutes a powerful approach to practically quantify system effectiveness starting from its main attributes (i.e., availability, dependability, and capability). However, a thorough analysis of the model reveals that it is not directly applicable to the present work since, at the current stage, a detailed analysis of system states during the mission profile is not available for the case studies introduced in Section 2.2 as well as required probability data (e.g., a_i and d_{ij} values). Nevertheless, the WSEIAC approach (as well as the linked references mentioned above) remains a benchmark in the definition of system effectiveness attributes. Indeed, following the NASA nomenclature reported in Section 5.2, the major components highlighted in Figure 117 can be intended as high-level MOEs to be generically considered in any C-E analysis and to be further detailed for the specific case study handled.
Furthermore, provided a suitable cost model to perform LCC analysis, WSEIAC suggests the exploitation of the following ratio model to obtain a final C-E assessment to be used to choose among alternatives (in this case, the design associated to the highest Cost-Effectiveness ($C\text{-}E$) should be selected (Hammond, 1999)):

$$C\text{-}E = \frac{System\ Effectiveness}{LCC} \tag{159}$$

According to (WSEIAC, 1966), "*this type of model has the advantage of providing a cost-effectiveness measure in natural terms* [and it] *is, therefore, very useful in comparing alternative solutions to the same problem*". However, the usefulness of the Cost-Effectiveness ratio is questioned in (ARINC Research Corporation, 1971), according to which it is "*not generally an adequate criterion for making a choice among competing systems*". Indeed, the C-E process should not end with a decision but with the presentation of C-E information in a format useful for the decision maker (ARINC Research Corporation, 1971). Therefore, the derivation of a unique index (i.e., the $C\text{-}E$) implies that a decision has already been made. A more generally accepted way of presenting results (ARINC Research Corporation, 1971; Pecht, 2009) is through a curve using cost as the abscissa and effectiveness as the ordinate. At this purpose, Figure 118 shows that several alternative designs are explored for two hypothetical equipment A and B.

Notably, a variation in design parameters implies both a variation in overall system effectiveness and in total cost. In these examples, it is interesting to notice that effectiveness is reported as a percentage as a result of the application on Eq.(158) (based on probability value between 0 and 1). Moreover, the portion of the Cost-Effectiveness curve with lower slope is indicated as the most desirable since it implies a large gain in effectiveness with a small increase in cost.

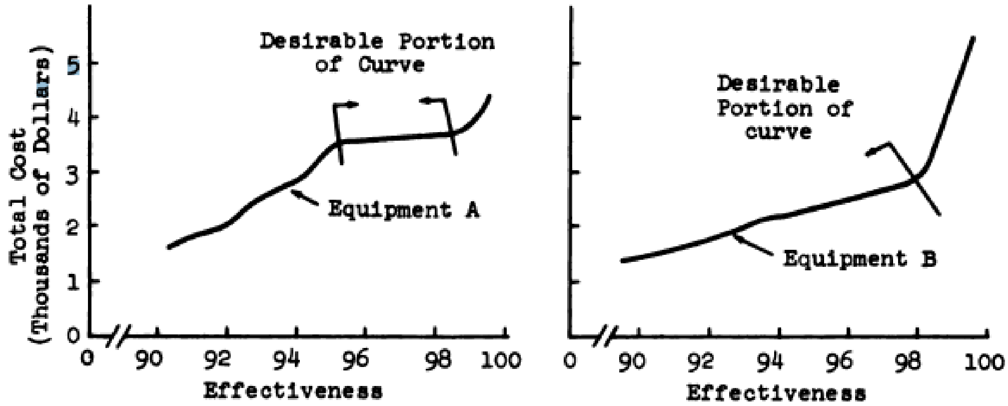


Figure 118: Examples of Cost-Effectiveness Curves from (ARINC Research Corporation, 1971)

To summarize, the exploitation of Eq.(158) by WSEIAC for system effectiveness assessment is not applicable in this work due to the huge amount of data required for the calculation of the matrix product. However, WSEIAC and WSEIAC-related approaches provide useful guidelines for high-level MOEs definition as well as some interesting indication on how final Cost-Effectiveness results shall be interpreted.

5.3.2 Cost-Effectiveness analysis based on Trade-Off (Hammond, 1999; Mroczek, 2014)

It is well established that "*the trade-off analysis methodology provides a structured, analytical framework for evaluating a set of alternative concepts or designs*" (Hammond, 1999). Its importance in decision analysis has already been discussed in Section 4.1.2.3 and 4.3.3, where it has been exploited in the framework of Technology RoadmappIng Strategy (TRIS) Prioritization Studies to rank lists of technologies and Mission Concepts and Activities (MCs/ACs). In this context, its usefulness in performing effectiveness analysis is highlighted thanks to the a generic example of weighted trade-off analysis provided by (Hammond, 1999) (Table 87). Notably, two competing systems (i.e., Option 1 and Option 2) are evaluated considering specific factors or criteria of interest in the decision process. It is worth noticing that the proposed set of criteria include performance parameters (i.e., weight), cost as well as effectiveness-related attributes like maintainability (recalling the components of system effectiveness previously introduced with Figure 117). Following the typical steps of trade-off analysis (Hammond, 1999), each factor is associated to a weight to describe its importance within the decision process and to a normalized rating representing how well Option 1 and Option 3 "meet" each factor. Eventually, by multiplying weights and ratings for each option score values are obtained. Eventually, the sum of scores provides a total for each option thus allowing to select the preferred option (Option 2 in the provided example).

Table 87: Generic example of trade-off analysis from (Hammond, 1999)

	Option 1			Option 2	
Factor	Weight	Rating	Score	Rating	Score
Weight	0.8	0.3	0.24	0.6	0.48
Cost	0.9	0.6	0.54	0.8	0.72
Complexity	0.3	0.9	0.27	0.6	0.18
Safety	0.6	0.9	0.54	0.7	0.42
Maintainability	0.4	0.9	0.36	0.6	0.24
Manufacturability	0.4	0.7	0.28	0.7	0.28
		Total	2.23		2.32

Source: *System Engineering Handbook*, Vol. 1, MSFC-HDBK-1912, NASA Marshall Space Flight Center, May 1991.

It is worth underlying that the utility of the trade-off methodology for system effectiveness analysis just discussed was fully explored by (Mroczek, 2014) with the aim of assessing the Cost-Effectiveness (C-E) of nanosatellites. Despite the proposed application differs from the target of this Dissertation, the approach for effectiveness assessment based on decision analysis from (Mroczek, 2014) is general enough to be extended to RLVs. The process starts with the definition of objectives, from which MOEs are established. This is perfectly in line with the NASA definitions for system effectiveness provided in Section 5.2, according to which MOEs are obtained from NGOs. As an example, Figure 119 shows the objectives hierarchy referred to a naval space mission derived by (Mroczek, 2014).

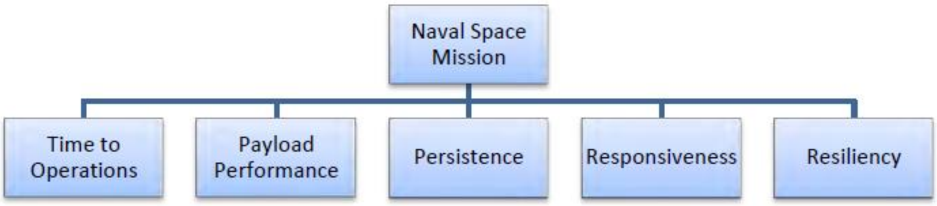


Figure 119: Example of Objectives Hierarchy for a Naval Space Mission used to derive MOEs (Source: (Mroczek, 2014))

As depicted in Table 88, the same high-level objectives, representing the effectiveness of the system under study, are also considered as MOEs and exploited within the trade-off analysis. Notably, Table 88 collects main information required for effectiveness analysis for an environmental monitoring scenario encompassing 2 alternative nano-satellites (i.e., Option 1 and Option 2 for the nomenclature reported in Table 87). As it can be noticed, the set of MOEs applicable to selected scenario is further divided into more quantifiable sub-objectives called Figures of Merit (FoMs) or MOPs in (Mroczek, 2014),

Table 88: Environmental Monitoring Scenario Effectiveness Model (Option 1) (adapted from (Mroczek, 2014))

Measure of Effectiveness	Measure of Performane	Threshold	Objective	Importance	Var. %	Var. bin	Raw Swing Weights	Normalized Swing Weights
Payload performance	Resolution	10	0.5	Med	53%	Med		
	Panchromatic Dynamic Range	8	16	Med	38%	Med		
	IR Dynamic Range	8	12	Low	0%	High		
Persistence	Percent of target area covered per day	5%	100%	High	39%	Med		
	Average Revisit Rate (hours)	72	8	High	75%	High		
	Number of passes (per day)	0.25	3	Med	60%	Med		
Resiliency	Capability with one lost satellite	50%	98%	Med	0%	High		
	Capability with one lost ground station	50%	98%	Med	0%	High		

Another interesting feature of the work from (Mroczek, 2014) is the exploitation of the Swing Weight Matrix technique for trade-off analysis. For sake of clarity, in the common trade-off methodology (Hammond, 1999) weights (i.e. the Weight column in Table 87) are only based on the importance assigned to each factor or criterion by the analyst. Conversely, in the Swing Weight Matrix approach proposed by (Parnell & Trainor, 2009) weights are determined "*by the importance and range of variation for the value measures*". Notably, "*a measure that is very* *important to the decision should be weighted higher than a measure that is less important. A measure that differentiates between alternatives, that is, a measure in which value measure ranges vary significantly, is weighted more than a measure that does not differentiate between alternatives*" (Parnell & Trainor, 2009). In the example from (Mroczek, 2014), such measures are the MOPs which, as shown in Table 88, are associated to:

1. an importance value, i.e., High (H), Medium (M) or Low (L);
2. a threshold value (i.e., minimum acceptable performance level);
3. an objective value (i.e., maximum acceptable performance level);
4. the percent variation between Option 1 and Option 2;
5. a variation value (H, M, or L);
6. Raw Swing Weights;
7. Normalized Swing Weights.

The importance value within the H M, and L scale (1.) is arbitrarily assigned by the analyst depending on the role of each MOP within the study, while the threshold and objective values (2. and 3.) depend on the target performance to be attained by the system. FoMs should be evaluated for both Option 1 and Option 2 and, basing on the nomenclature in Table 87, a set of non-normalized (or raw) ratings should be derived for each alternative (please, notice that this information is not reported in Table 88 for conciseness). Raw ratings are then scaled as percentages (i.e., normalized) by dividing them by the range between the threshold and the objective set for the specific FoM. Subsequently (4.), the percent variation between Option 1 and Option 2 is determined by measuring the difference between the normalized ratings for each FoM (please, notice that in case that more than two alternatives are tackled, the difference between the maximum and minimum normalized ratings should be considered). At this point, the percent variation calculated for each FoM is associated to a variation value in the H, M, or L scale (5.). According to (Mroczek, 2014), "*low was any value where the variation between the evaluated systems was less than or equal to 33%. Medium was defined as greater than 33% and less than or equal to 66% of the range. High was greater than 66% variation"*. For sake of clarity, the targeted output is the derivation of the columns "Importance" and "Variation" in Table 88, collecting the scales (H, M, or L) for both importance and variation attributed to each FoM. To merge information related to importance and variation and thus complete the multi-objective decision process, the core of the Swing Weight Matrix approach by (Parnell & Trainor, 2009) can now be defined, i.e. the Swing Weight Matrix (Figure 120).

		Importance of the value measure to the decision		
		Low	Med	High
Range of variation of the value measures	Low	1	25	75
	Med	12	50	90
	High	25	75	100

Figure 120: Raw Swing Weight Matrix assumed by (Mroczek, 2014)

The top of the matrix "*defines the value measure importance and the left side represents the range of value measure variation*" (Parnell & Trainor, 2009), reporting the scales previously defined (H, M, or L). For example, "*a measure that is very important to the decision and has a large variation in its scale would go in the upper left of the matrix*" (Parnell & Trainor, 2009). Each cell of the matrix contains a weight (called raw swing weight) which quantifies the underlying importance/variation combination. It is highlighted that the values for swing weights should be thoroughly defined depending on the specific case study tackled. In this sense, Figure 120 shows the values specifically assumed by (Mroczek, 2014). By means of the Swing Weight Matrix, the values for Importance and Variation in Table 88 can now be merged to derive the raw swing weights for each FoM. The latter should be then normalized by dividing the raw swing weight of each MOP by the sum of all raw swing weights. The result is a set of normalized swing weight on a percentage scale. Eventually, the effectiveness associated to each MOP can calculated by multiplying the scaled (or normalized) ratings by the normalized swing weight. As a result, the total effectiveness of each option, expressed on a percentage scale, is the sum of effectiveness for all MOPs. For sake of clarity, the trade-off methodology just described is summarized in the flowchart of Figure 121, where major steps are collected.

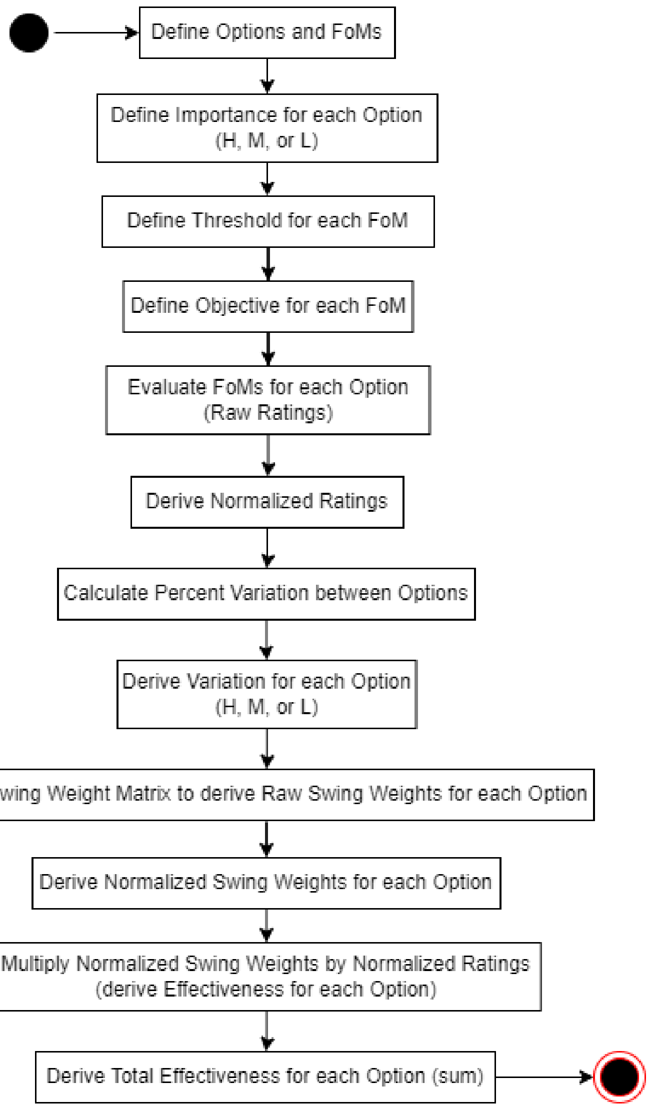


Figure 121: Trade-Off Approach based Raw Swing Weight Matrix (Mroczek, 2014)

To conclude the discussion on (Mroczek, 2014), it is also worth reporting how the final Cost-Effectiveness assessment is graphically provided. Notably, after assessing LCC for nano-satellites with dedicated approaches, C-E results for the specific nano-sat designs considered are displayed as in Figure 122. It is highlighted that a final C-E ratio is not calculated by (Mroczek, 2014). At this purpose, (Hammond, 1999) argues that this ratio could be an intuitive way to collect all information related to effectiveness and costs in a unique number, but to make it "*useful and meaningful,* [it] *must be uniquely determined and independent of the system cost*". As such, the exploitation of a C-E ratio might be admitted only in case cost is excluded from the parameters used to define effectiveness like in the study by (Mroczek, 2014).

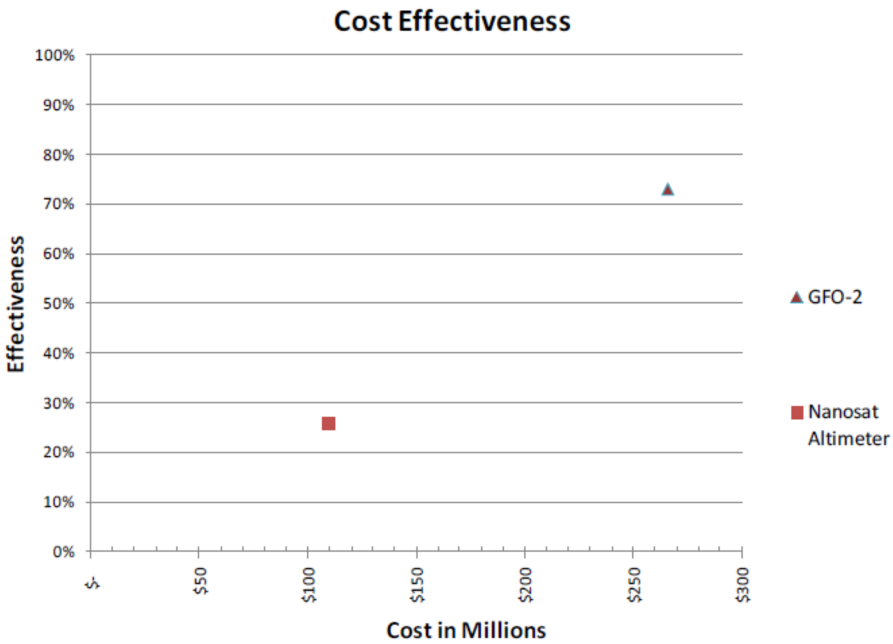


Figure 122: Environmental Monitoring Scenario Cost Effectiveness Results (Mroczek, 2014)

5.3.3 NASA RMAT (Ebeling, 1993a)

In the framework of the tools in support of effectiveness analysis, the NASA Reliability and Maintainability Analysis Tool (RMAT) (Ebeling, 2003) is certainly worth citing. As reported by (Nix, 2005), RMAT was a Visual Basic parametric model based on Shuttle and military aircraft data to assess the reliability and maintainability (R&M) of a reusable system starting from its physical characteristics. Despite the original Visual Basic tool and underlying models were not available for the present work, a former NASA report from the same author of RMAT (Ebeling, 1993a) provides details about the models implemented. Notably, (Ebeling, 1993a) describes a methodology for "*deriving reliability and maintainability parameters of conceptual space vehicles and for applying these parameters in establishing manpower and spares requirements*". The approach (herein referred as RMAT for simplicity) lies on the assumption that R&M estimates for new space systems can be "*based upon comparability with existing systems*" (Ebeling, 1993a). Key R&M parameters and other meaningful output from RMAT are collected in Figure 123.

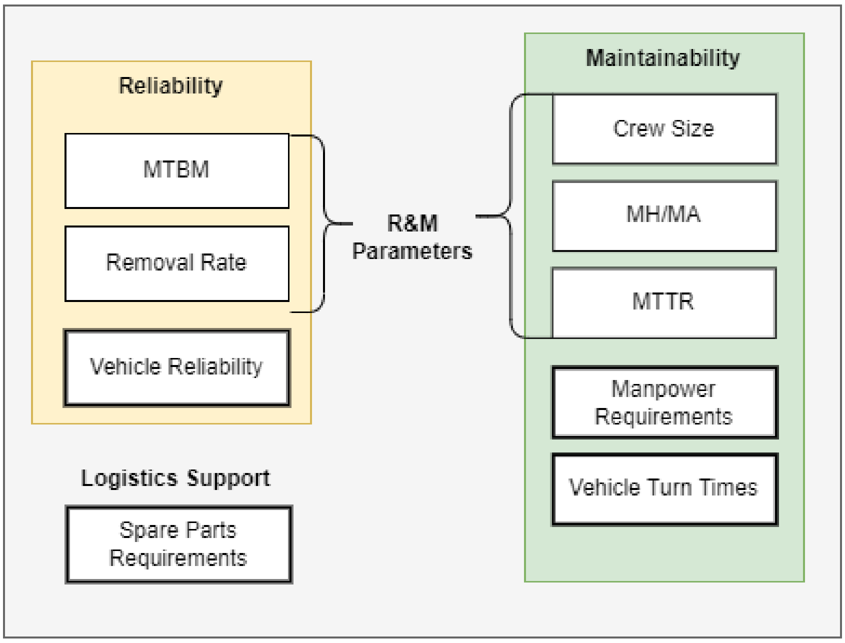


Figure 123: RMAT Summary

As depicted in Figure 123, RMAT allows to estimate the following primary R&M parameters using parametric equations function of main vehicle design characteristics (e.g., vehicle dry mass, wingspan, etc.):

- Mean Time Between Maintenance (MTBM), defined as "*the length of time in flying hours between maintenance actions on a particular subsystem or component*" (Ebeling, 1993);
- Removal Rate (RR), the "*percent of maintenance actions which results in a removal and replacement of a component from the aircraft*" (Ebeling, 1993) after each flight;
- Crew Size, the number of maintenance personnel required for maintenance activities after each flight;
- Maintenance manhours per maintenance action (MH/MA), the "*primary measure of maintainability*" according to (Ebeling, 1993);
- Mean Time to Repair (MTTR), measuring the amount of time required to perform maintenance activities and strictly connected to MH/MA

Starting from these parameters, as shown in Figure 123, RMAT derives a set of secondary outputs:

- Vehicle Reliability, also referred as mission reliability and representing the reliability of the vehicle in accomplishing the mission;
- Spares Requirements, i.e., the number of spares required after each flight to restore original vehicle conditions. In line with (Pecht, 2009), (Ebeling, 1993) describes this characteristic as strictly connected to logistic supportability;
- Vehicle Turn Times or vehicle turnaround time, i.e., the total time required to fully restore vehicle characteristics and return it into service.

Recalling the definitions from (Pecht, 2009; WSEIAC, 1966), the RMAT clearly tackles system effectiveness issues such as reliability, maintainability and logistic supportability. Notably, the approach seems particularly promising for the scope of this work since it allows to preliminary estimate meaningful R&M parameters starting from basic vehicle characteristics available from early design stages. Moreover, it provides real R&M data (e.g., MTBM and MTTR) for the Space Shuttle Orbiter, thus offering a useful benchmark for the evaluation new vehicles R&M characteristics derived from available parametric relationships. It is also highlighted that, despite the available RMAT version might seem outdated, suitable correction factors are suggested within the methodology to take into account the effect of future technological improvements onto R&M attributes. In this context, it is worth highlighting that the RMAT available from (Ebeling, 1993a) is quite complex and intricate and only a thorough analysis of the complete computer model attached within the same reference (coded in Quick BASIC Environment) has allowed a full understanding of all the R&M aspects tackled within the approach. For completeness, Section 7.6 summarizes the logic for Vehicle Reliability calculation suggested by (Ebeling, 1993a).

5.4 Effectiveness Model and Cost-Effectiveness Assessment

Despite the key role of system effectiveness in RLVs design (Section 1.21), the analysis of state-of-the-art highlighted the lack of a methodology to perform effectiveness analysis directly applicable to the scope of this work. However, the literature background discussed in Section 5.3 can be a useful benchmark for the derivation of a dedicated effectiveness model for RLVs to be exploited in this Dissertation. Notably, the trade-off analysis used by (Mroczek, 2014) for effectiveness assessment of nano-satellites (Section 5.3.2) is flexible enough to be adapted to the target application. Therefore, with the aim to apply the same approach to RLVs, it is required to 1) define high-level objectives; 2) derive MOEs from high-level objectives; 3) specify MOPs from MOEs and 4) use MOPs as FoMs for the trade-off analysis. However, to fully stick to NASA nomenclature (Section 5.2), MOPs shall be further broken down into lower-level TPMs which can be effectively exploited as FoMs for trade-off. It is worth highlighting that great part of these tasks were already performed in Section 2.1.2. Indeed, as discussed for Figure 15, high-level objectives (or NGOs according to Figure 115) were elicited by means of a mission statement and a preliminary list of mission requirements was obtained basing on a set of desired features for future RLV systems. Remembering that MOEs can be the basis of high-level requirements establishment (Figure 15), such “desired features” can now be intended as MOEs. In addition, looking at the examples of MOE, KPP, MOP, and TPM in Figure 116 in which reliability is labelled as KPP, it can be inferred that the major attributes of system effectiveness discussed by (Pecht, 2009) (i.e. reliability, maintainability, etc.) are KPPs for the present study. Then, a set of MOPs for RLVs is derived from the requirements. This is accomplished also taking into account the secondary outputs obtained from RMAT (Section 5.3.3), strictly connected to the identified KPPs. The resulting list of MOPs and its relationship with requirements is depicted in Figure 124, which is an extended version of Figure 15. As it can be noticed, MOPs are stated in more generical terms than in (Mroczek, 2014). This is due to the fact that the nomenclature adopted for MOPs is in line with that proposed by (NASA, 2016a) (please, refer to the MOP in Figure 116 as well as to additional examples available from (NASA, 2016a)). On this basis, MOPs are expressed in such a way to preliminary quantify the expected performance which will be further detailed in terms of TPMs. In particular, in Figure 124 the performance already achieved by current launchers and Space Shuttle are used to define minimum targets for future RLVs basing on the concept that they are intended to provide performance at least equal to that already attained by previous or current vehicles.

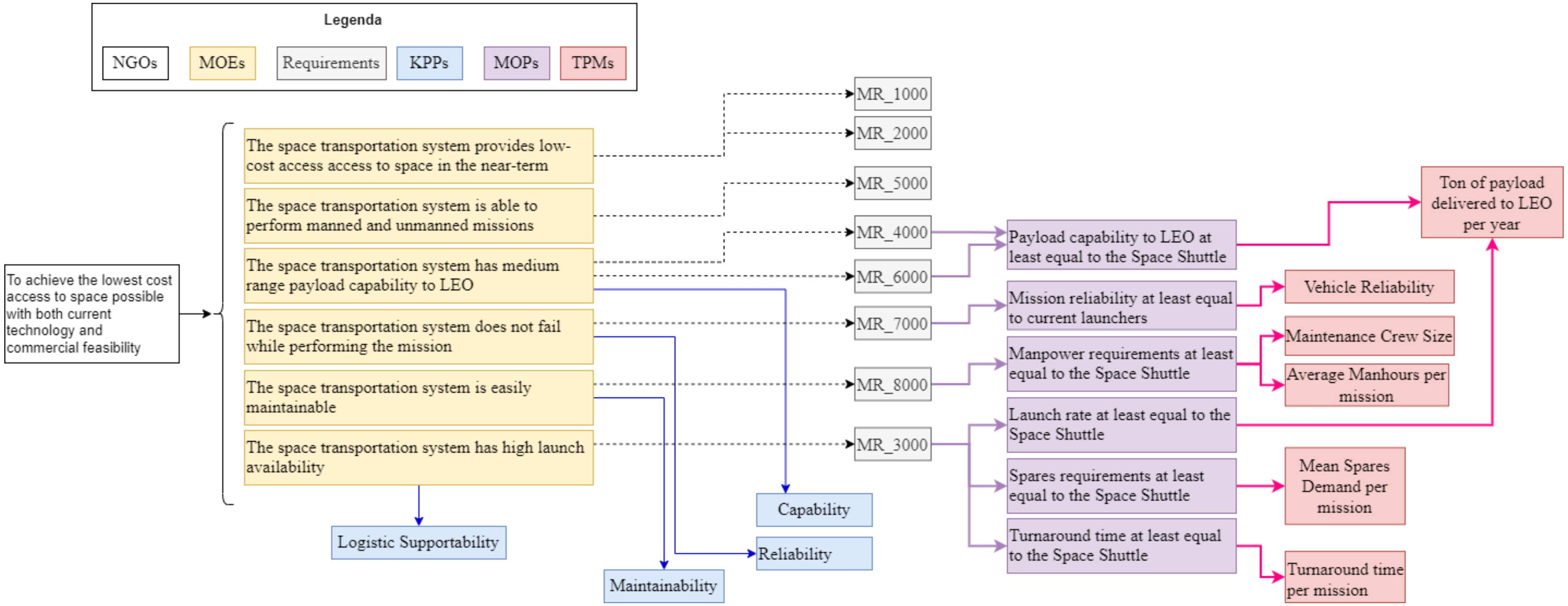


Figure 124: TPMs Derivation for RLVs starting from Mission Statement definition

Table 89: Template for Effectiveness Analysis

				Raw Ratings		Normalized Ratings							
TPM (FoM)	**Importance**	**Threshold**	**Objective**	**Option 1**	**Option 2**	**Option 1**	**Option 2**	**% Variation**	**Variation**	**Raw Swing Weights**	**Normalized Swing Weights**	**Effectiveness (Option 1)**	**Effectiveness (Option 2)**
Ton of Payload delivered to LEO per year													
Vehicle Reliability													
Maintenance Crew Size													
Average Manhours per Mission													
Mean Spares Demand per Mission													
Turnaround Time per Mission													

Total Effectiveness for each Option

Starting from MOPs and considering the primary R&M parameter stemming from RMAT (Figure 123), the list of TPMs shown in Figure 124 is suggested. Also in this case, the reference nomenclature used is that in Figure 115. For sake of clarity, the MOPs and related TPMs referred to payload capability derive from (Boone & Miller, 2016). At this point, it is possible to proceed with trade-off analysis following the Swing Weight Matrix methodology discussed in (Mroczek, 2014) and summarized in the flowchart of Figure 121. At this purpose, it is possible to organize trade-off information using the template in Table 89, which is derived basing on the example from (Mroczek, 2014) previously discussed. Notably, the TPMs just introduced in Figure 124 are used as FoMs. Moreover, considering two generic RLV options to be evaluated in terms of effectiveness by means of trade-off analysis, Table 89 also shows the data needed for each alternative (i.e., raw and normalized ratings) as well as the final output in terms of percent effectiveness achieved in relation to each TPM and of total percent effectiveness for each option. Please, notice that as far as raw ratings are concerned, they can be evaluated for each TPM using the relationships provided by (Ebeling, 1993a) and summarized in Section 7.6.

Once an estimation of system effectiveness is achieved for each option, it is possible to proceed towards the final Cost-Effectiveness assessment. This is accomplished by merging the results of effectiveness analysis just performed with the outcomes from LCC assessment. Notably, the LCC obtained from Eq.(135) is exploited.

Final results in terms of effectiveness and LCC can be graphically plotted for each competing design option similarly to (Mroczek, 2014) (Figure 122). Moreover, it is worth highlighting that the list of MOPs (and related TPMs) included in the proposed effectiveness model (Figure 124) is independent of cost (i.e., no MOPs/TPMs directly entail cost issues). As such, in line with (Hammond, 1999) the derivation of a final Cost-Effectiveness (C-E) ratio (Eq.(159)) is deemed applicable to the present study (Section 5.3.2). Therefore, the final figure for Cost-Effectiveness stemming from the C-E ratio can be intended as percent gain in effectiveness for each $ (or €) spent, i.e., % Effectiveness/$ (or % Effectiveness/€). Please, notice that, since LCC costs are usually expressed in B$ or B€ (Section 3.4), the exploitation of the figure % Effectiveness/B$ (or % Effectiveness/B€) is deemed more appropriate.

5.5 Application to the Case Studies

The Effectiveness Model described in Section 5.4 is here applied to the Case Studies introduced in Section 2.2 in order to eventually obtain a Cost-Effectiveness assessment and select the most cost-effective option among alternatives. Notably, the flowchart in Figure 121 is followed. Results are stored within the template for Effectiveness Analysis provided in Table 89, properly modified to deal with the Case Studies. As far as Figures of Merit (FoMs) definition is concerned, the TPMs in Table 89 are adopted, while the Options under analysis are Case Study 1 and Case Study 2. Then, Importance is arbitrarily assigned to each Options taking into account the envisaged relative importance of each FoM based on Author's judgement and experience (Table 90). Subsequently a Threshold and an Objective are associated to each FoM. Notably, the former stems from the evaluation of state-of-the-art launch systems, using as reference the performance achieved by the Space Shuttle and current launchers, while Objectives are assigned considering the minimum value theoretically achievable by each FoM (Table 90). Furthermore, an estimation of TMP values for both Case Studies is performed using the relationships available from RMAT (Ebeling, 1993a). TPMs are estimated at stage level and then extended at vehicle level. For sake of clarity, values for Vehicle Reliability (at stage level) are multiplied to obtain the final Vehicle reliability (at vehicle level), while the other TPMs contributions at stage level are summed up to obtained the value at vehicle level. Please, notice that Turnaround Time at Vehicle Level is obtained by adding stages contributions and by including an assumed value for pad and integration time (Ebeling, 1993a). The latter is assumed equal to 24 hours for SpaceX Starship TSTO (in line with current Falcon 9 operations), while an optimistic value of 1 hour is considered for STRATOFLY TSTO taking into the projected aircraft-like features. Calculated final raw ratings and percent variation between Options are also collected in Table 90. Detailed raw ratings are also shown in Table 91. From percent variations, a level of Variation is associated to each FoM. At this point, using the obtained values for Variation and Importance, the Swing Weight Matrix in Figure 120 is exploited to obtain Raw Swing Weights. The latter, after normalization, are multiplied to Normalized Ratings to calculated the % Effectiveness achieved by each Option in relation to each FoM. Eventually, a Total Effectiveness value is determined by summing up all contributions.

Table 90: Effectiveness Analysis for the Case Studies

TPM (FoM)	Importance	Threshold	Objective	Raw Ratings		Normalized Ratings		% Variation	Variation	Raw Swing Weights	Normalized Swing Weights	Effectiveness STRATOFLY TSTO	Effectiveness SpaceX STARSHIP TSTO
				STRATOFLY TSTO	SpaceX Starship TSTO	STRATOFLY TSTO	SpaceX Starship TSTO						
Ton of Payload delivered to LEO per year	H	129.25	6100	1050	2800	0.1542	0.4473	0.2931	H	100	0.2410	0.0372	0.1078
Vehicle Reliability	H	0.67	0.9995	0.8196	0.8326	0.4539	0.4935	0.0396	L	75	0.1807	0.0820	0.0892
Maintenance Crew Size	L	134	1	25	55	0.8195	0.5940	0.2256	H	25	0.0602	0.0494	0.0358
Average Manhours per Mission	H	40000	0	132.68	307.64	0.9967	0.9923	0.0044	H	100	0.2410	0.2402	0.2391
Mean Spares Demand per Mission	L	100	0	0.64	3.76	0.9936	0.9624	0.0312	H	25	0.0602	0.0599	0.0580
Turnaround Time per Mission	H	1296	0	14.19	98.76	0.9891	0.9238	0.0653	M	90	0.2169	0.2145	0.2003
												68.31%	73.02%
												Total Effectiveness for each Option	

Table 91: Details of Raw Ratings Values

TPM (FoM)	Raw Ratings					
	STRATOFLY TSTO			SpaceX Starship TSTO		
	STRATOFLY MR3-modified	CARGUS	VEHICLE	Super Heavy	Starship	VEHICLE
Ton of Payload delivered to LEO per year	0	1050	1050	0	2800	2800
Vehicle Reliability	0.9208	0.8900	0.8196	0.9191	0.9059	0.8326
Maintenance Crew Size	25	Not Applicable	25	23	32	55
Average Manhours per Mission	132.68	Not Applicable	132.68	89.68	217.97	307.64
Mean Spares Demand per Mission	0.64	Not Applicable	0.64	1.30	2.46	3.76
Turnaround Time per Mission	13.19	Not Applicable	14.19	8.07	66.69	98.76

To complete the analysis, calculated values for Effectiveness (Table 90) and LCC for each option are graphically shown in Figure 125. Notably, LCC values referred to a commercial scenario are considered for both alternatives to allow fair comparison (see Table 52 for STRATOFLY and Table 65 for SpaceX Starship TSTO). Thanks to Figure 125, it can be noticed that Case Study 2 is associated to higher Effectiveness but also to higher LCC costs.

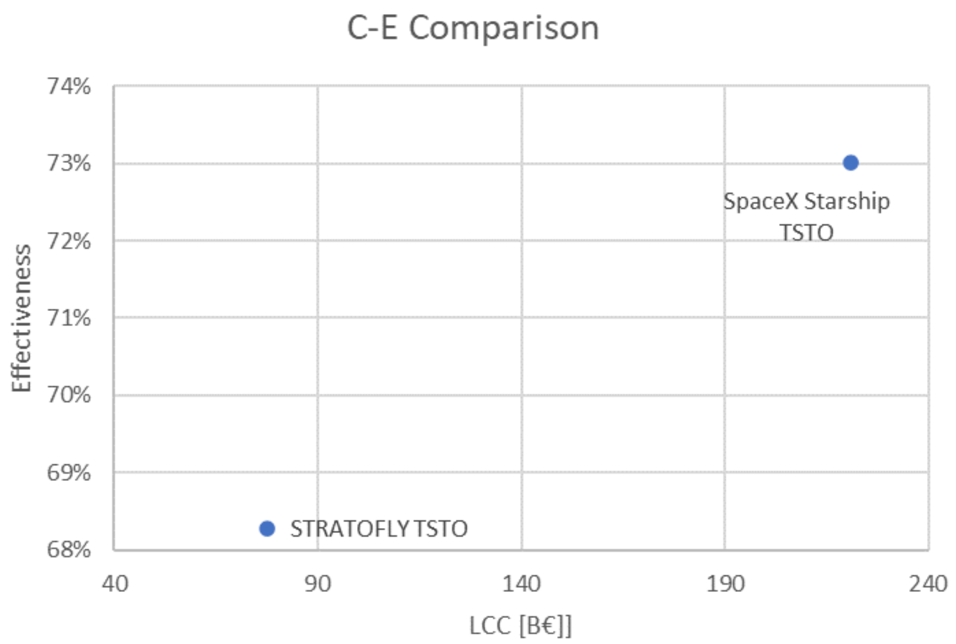


Figure 125: Cost-Effectiveness (C-E) Comparison: Case Study 1 vs. Case Study 2

With the aim to provide a deeper insight onto results, the graphical comparison in Figure 126 is proposed. From this chart it can be observed that, despite the Effectiveness of Case Study 2 is higher, the difference with respect to Case Study 1 is not huge (i.e., 73.02% vs. 68.31%), while the LCC of Case Study 2 is consistently higher than Case Study 1 (almost three times). As such, the slightly higher Effectiveness of SpaceX Starship TSTO is achieved by means of a huge LCC expenditure, while the lower (but still comparable to Case Study 2) Effectiveness of STRATOFLY TSTO derives from a consistently reduced economical effort. This is also confirmed by the Cost-Effectiveness ratios shown in Figure 125. Indeed, basing the definitions provided in Section 5.4, the % gain in Effectiveness associated to Case Study 1 is higher than Case Study 2. As a result, basing on the assumptions collected in Table 90 and Table 91, the STARTOFLY TSTO is more cost-effective than the SpaceX Starship TSTO.

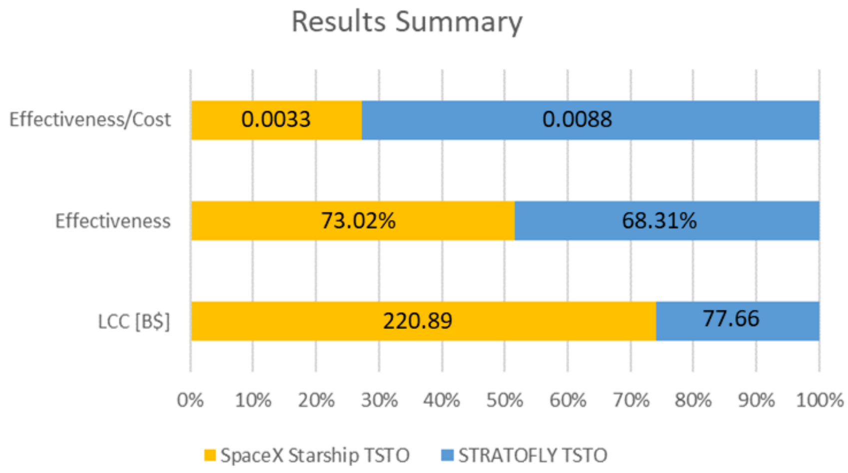


Figure 126: Results Summary for the Case Studies

5.6 Chapter 5 Abbreviations

C-E	Cost-Effectiveness
DoD	Department of Defense
FoM	Figure of Merit
KPP	Key Performance Parameters
LCC	Life-Cycle Cost
MCs/ACs	Mission Concepts and Activities
MH/MA	Maintenance manhours per maintenance action
MOE	Measure of Effectiveness
MOP	Measure of Performance
MTBM	Mean Time Between Maintenance
MTTR	Mean Time to Repair
NASA	National Aeronautics and Space Administration
NGOs	Needs, Goals, and Objectives
R&M	Reliability and Maintainability
RLV	Reusable Launch Vehicle
RM&S	Reliability, Maintainability, and logistic Supportability
RMAT	Reliability and Maintainability Analysis Tool
RR	Removal Rate
SoA	State-of-the-Art
STRATOFLY	Stratospheric Flying Opportunities for High-Speed Propulsion Concepts
TPM	Technical Performance Measure
TRIS	Technology RoadmappIng Strategy
TSTO	Two Stage to Orbit
WSEIAC	Weapon System Effectiveness Industry Advisory Committee

Chapter 6

Conclusions and Future Works

This Dissertation has proposed a comprehensive methodology aimed at supporting preliminary and conceptual design activities by determining the Cost-Effectiveness (C-E) and the technological sustainability of advanced RLV concepts. This has been accomplished through the development of three key Modules specifically tailored for future RLVs analysis, i.e., a Cost Model (Module 1), an Effectiveness Model (Module 2) and a Methodology for Technology Roadmapping (Module 3). Results from Module1 and Module 2 have been properly merged to suggest the most cost-effective solution among competing options. Moreover, the integration of Module 1 and Module 3 has also been extensively studied with the purpose to exploit the outcomes from cost estimation to determine the technological sustainability of future reusable concepts. Selected case studies have also been introduced to verify and test each Module, providing an overview of the major outputs of each Module.

At the beginning, a through literature review on previous efforts on RLVs development has been presented, highlighting the major technological challenges encountered in past activities. Notably, key role of airbreathing high-speed propulsion in enabling future RLVs has been highlighted. Benefitting of the historical overview, a discussion about the most promising design options has been performed. This allowed to select proper case studies to be used to test the proposed models. Then, a Cost Model has been proposed. The latter has been built on the heritage of state-of-the-art methodologies with the main purpose of tackling their main gaps and limitations in to providing Life Cycle Cost (LCC) assessment for RLVs. In this context, special attention has been devoted in developing a dedicated set of Cost Estimation Relationships (CERs) for the most promising RLV configurations previously identified, suggesting a structured mathematical approach to be followed for new CERs derivation. The proposed Cost Model has been tested with the selected Case Studies, comparing obtained results with previous estimations from independent sources. Moreover, in support of technological sustainability assessment, an enhanced version of a state-of-the-art methodology for Technology Roadmapping (called TRIS) has been presented. The improvements introduced to the reference methodology have been specifically aimed at smoothing the overall roadmapping process, enhancing the major routines, and at extending the application to RLVs. The enhanced TRIS version has been applied to noteworthy case study among those previously identified, providing a practical example of technological sustainability assessment. To support the roadmapping process, a thorough revision of an already existing database (HyDat) set up to store data required for Technology Roadmapping has been performed. In particular, an improved HyDat back-end has been proposed and an initial set of data has been included. Then, after introducing suitable approaches to perform C-E assessment, an Effectiveness Model specific for RLVs and based on trade-off has been proposed, providing guidelines towards C-E assessment and results evaluation. Ultimately, the C-E comparison of case studies has provided, suggesting the most cost-effective option.

The main result shown within this Dissertation is, by far, the development of a comprehensive framework for cost estimation, Technology Roadmapping and C-E assessment in support of preliminary and conceptual design activities. As far as the Cost Model is concerned, a wide set of new CERs has been derived, allowing to tackle all the major RLV configurations and differentiating them basing on their design characteristics (e.g., take-off and landing mode, propulsive strategy, etc.). In addition, the impact of specific design parameters onto development and production costs has been determined. In particular, the effect of Staging Mach has been explored for several cost items. Another noteworthy result of this work is the establishment of a link between cost estimation and technology roadmapping to estimate the Technology Development Cost. Notably, a general approach to estimate the resources required to accomplish technology development depending on vehicle maturity currently attained has been introduced. In addition, a strategy to assess the Cost at Completion (CaC) starting from development costs allocated onto a Product Breakdown Structure (PBS) has been proposed. In addition, thanks to the application of the enhanced TRIS methodology, a Technology Roadmap for STRATOFLY MR3 vehicle has been derived, assessing the overall technological sustainability of the vehicle. Notably, TRL 6 can be potentially achieved if all identified missions are accomplished and if required budget resources are allocated. In addition, complete technology maturity (TRL 9) can be achieved by 2050 if required technology demonstrations are performed. In particular, a Small-Scale Demonstrator should be established by 2038 and a Mid-Scale Demonstrator by 2042 to achieve the TRL Transit 6 to 7. Eventually, a Near Full Scale Demonstrator should be set up by 2047 to move to TRL 8. To accomplish these two Transits, respectively, 13.286 B€ and 10.746 B€ are needed. Eventually, thanks to the C-E assessment, the STRATOFLY TSTO has been selected as most-cost effective design solution with respect to the SpaceX Starship. This substantially proves the potential of aircraft-like airbreathing concepts to be cost-effective (other than technologically sustainable as determined by means of the Technology Roadmap) in the near future. Despite the proposed cost model provides results in line with other cost estimations, these outcomes shall be interpreted with caution and uncertainties in cost estimation shall be carefully considered. This is particularly true for highly innovative concepts like future RLVs, for which a solid statistical base in not available. Notably, uncertainties onto cost drivers (i.e., design variables) and cost parameters shall be taken into account. As such, as suggested within the Dissertation, detailed analysis shall be performed to define suitable confidence and prediction bounds. In this context, the new CERs a provided with the estimation of associated Standard Error (SE), which can be used for a preliminary evaluation of uncertainties.

As far as the Cost Model is concerned, future works may deal with the study of other case studies to test its applicability to different concepts. The issues related to uncertainty in cost estimation shall also be tackled more in detail in future analyses. For the Effectiveness Model, considering the great impact of user's judgement in the definition of Importance and Variation associated to Figures of Merit, sensitivity analysis can be performed in order to evaluate the input of different assumptions within the trade-off and the effect on Total Effectiveness estimation. As for the Cost Model, by performing Effectiveness analysis additional concepts, the C-E comparison provided at the end of this Dissertation can be enriched with additional data points, providing a deeper insight onto the C-E of future RLVs. Eventually, considering the Technology Roadmapping applied STRATOFLY TSTO, a more detailed Stakeholders'

Analysis can be carried out, evaluating the impact of several actors within the final Technology Roadmap.

Chapter 7

Annexes

This chapter collects the annexes referenced within the Dissertation Chapters.

7.1 Work-Year (WYr) Conversion Factors

Table 92 collects the exchange rates (or WYr Conversion Factors) to convert 1 WYr into US$ or € (or into European Currency Unit (ECU) before €) from (Koelle, 2013).Values vary through the years due to inflation. For sake of clarity, TC provides WYr Conversion Factors between 1961 to 2016, remaining values up to 2021 are estimated by interpolation.

Table 92: Work-Year (WYr) Conversion Factors

Year	US$	€ (ECU)		Year	US$	€ (ECU)
1961	27000	18900		1991	162500	145900
1962	28000	20000		1992	168200	151800
1963	29000	21000		1993	172900	156800
1964	30000	22000		1994	177200	160800
1965	31000	23200		1995	182000	167300
1966	32,300	24,400		1996	186900	172500
1967	33200	25700		1997	191600	177650
1968	34300	27400		1998	197300	181900
1969	36000	29100		1999	203000	186300
1970	38000	31000		2000	208700	190750
1971	40000	33050		2002	222600	201200
1972	44000	35900		2003	230400	207000
1973	50000	38700		2004	240600	212800
1974	55000	43600		2005	250200	219200
1975	59500	50000		2006	259200	226300
1976	66000	55100		2007	268800	234800
1977	72000	60500		2008	278200	243600
1978	79700	65150		2009	286600	252700
1979	86300	71800		2010	296000	261000
1980	92200	79600		2011	303400	268800
1981	98770	86700		2012	312000	275500
1982	105300	92400		2013	320000	285000
1983	113000	98300		2014	328700	292400
1984	120800	104300		2015	337100	301200
1985	127400	108900		2016	347200	310200
1986	132400	114350		**2017**	**359838**	**326627**
1987	137700	120000		**2018**	**370000**	**3398278**
1988	143500	126000		**2019**	**380137**	**354072**
1989	150000	133000		**2020**	**390190**	**369449**
1990	156200	139650		**2021**	**400090**	**386052**

7.2 Summary of New RDTE and TFU Production CERs (HyCost)

Table 93: New RDTE CERs

Cost Item	**CER**	**Eq.**
HTHL Rocket First Stage RDTE	$176.51W_{dry(w/o\ eng)}^{0.49}$	(74)
HTHL Airbreathing First Stage and Advanced Aircraft RDTE	$22857 + 0.24W_{dry(w/\ eng)}$	(78)
HTHL Airbreathing First Stage RDTE	$0.68 + 922.56W_{dry(w/\ eng)}^{0.12}Mach^{1.39}$	(84)
RDTE CER for Liquid Propellant Rocket 2° Stage with HL (1)	$21470 + 0.69W_{dry(w/out\ eng)}$	(85)
Rocket Second Stage with HL RDTE (2)	$32.82W_{dry(w/\ eng)}^{0.68}Mach^{0.064}$	(89)
VTHL or HTHL Rocket SSTO RDTE	$1.71W_{dry(w/out\ eng)}^{0.96}$	(93)
VTVL Rocket SSTO RDTE	$743.36W_{dry(w/out\ eng)}^{0.39}$	(97)
VTVL Liquid Propellant Rocket First Stage RDTE	$96.42W_{dry(w/out\ eng)}^{0.56}$	(100)
Scramjet Engine RDTE	$1.5982 \cdot M_{E_{dry}} + 10391$	(102)
Rocket/Ramjet CC Engine RDTE	$546.71M_{E_{dry}}^{0.48}$	(104)
Turboramjet/Rocket CC Engine RDTE	$364.47M_{E_{dry}}^{0.48}$	(105)
Air Ejector/Ramjet/Scramjet/Rocket CC Engine RDTE	$911.18M_{E_{dry}}^{0.48}$	(106)

Table 94: New TFU Production CERs

Cost Item	**CER**	**Eq.**
HTHL Liquid Propellant Rocket First Stage TFU Production	$2607.7{+}0.017W_{dry(w/o\ eng)}$	(110)
VTHL First Stage TFU Production	$420.56{+}0.02W_{dry(w/o\ eng)}$	(112)
HTHL Airbreathing First Stage TFU Production	$1.55W_{dry(w/\ eng)}^{0.54}Mach^{0.67}$	(121)
VTVL, VTHL and HTHL Rocket SSTO TFU Production	$0.0495W_{dry(w/out\ eng)}^{1.027}$	(125)
Liquid Propellant Rocket Second Stage with HL TFU Production	$0.212W_{dry(w/out\ eng)}^{0.978}$	(128)
VTVL Liquid Propellant Rocket First Stage TFU Production	$1.786W_{dry(w/out\ eng)}^{0.584}$	(131)

7.3 Database Architecture Formalization (HyDat Back-end)

The analysis of State-of-the-Art (SoA) TRIS in Section 4.1.2 highlighted the need to establish a structured database to collect elements' data to be used during the roadmapping process. In account of this, building on the heritage from previous activities on HyDat (Fusaro et al., 2017) and thanks to a thorough study of the ESA-confidential TREx database (Saccoccia, 2014), a brand-new database architecture able to optimize the data collection and exchange processes with TRIS is presented in this Section. Specifically referring to (Fusaro et al., 2017), Section 4.1.3 has emphasised several limitations of current HyDat platform mainly due to the MS-Excel-based structure adopted for the back-end. To solve these issues, the open-source MySQL platform is chosen in this Dissertation for the development the new HyDat back-end. As described in the following Sections, the proposed back-end is made up of "Tables" and each Table collects records (i.e., database entries, one per each Table row) characterized by common attributes (or fields, one per each Table column). Basing these definitions, the following Sections firstly introduce the content of the new HyDat back-end Tables. Subsequently, the relationships among Tables are thoroughly described.

7.3.1 Elements' Tables Definition

Starting from the definition of the main bricks of the database back-end, i.e., Tables, one or more Tables can be defined for each roadmapping element and Tables' attributes can be specified considering the parameters characterizing each element in the roadmapping process. For example, the *technologies* Table shown in Figure 127 gathers data related to technologies (Techs.) Notably, considering the parameters discussed in Section 4.3.2.1, each Tech can be characterized by the following attributes: ID, description, Cost at Completion (CaC) (specifying the reference year for CaC and the currency, respectively) and the ID of the linked Technology Group (TG) (*Tech_group_ID*). Please, notice that, in all Tables, ID refers to an identifier expressed as an integer value.

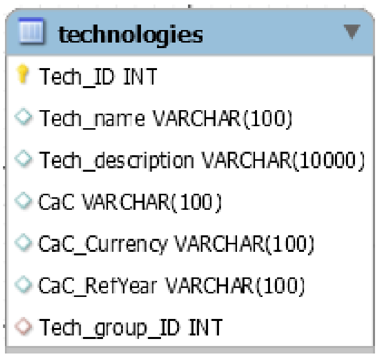


Figure 127: *technologies* Table

Similarly, the remaining Tables able to store all the required roadmapping data can be defined as shown in Figure 128, where Tables related to the same element are grouped.

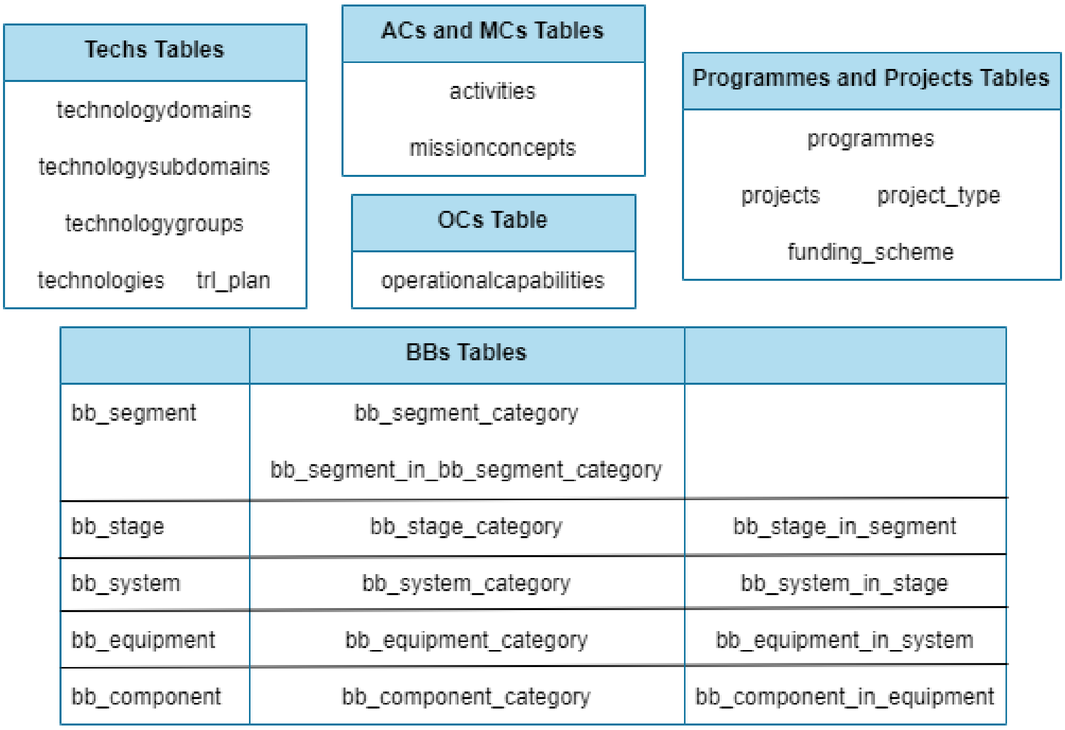


Figure 128: Overview of major HyDat Tables

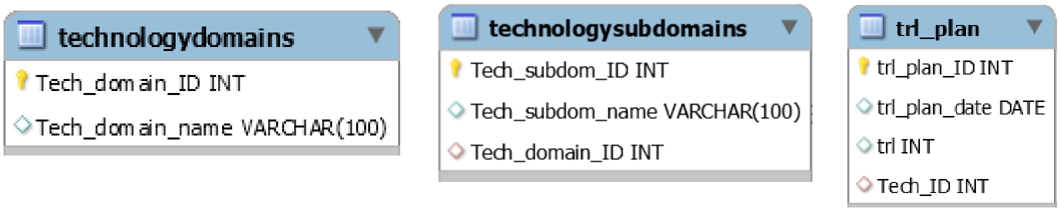


Figure 129: Techs Tables in HyDat

Specifically, all Tables related to Techs (with associated fields) are labelled as *Techs Tables* (Figure 129), including:

- *technologydomains*, with the list of Technology Domains (TDs) from ESA Technology Tree (ESA, 2020a) characterized by TD ID (*Tech_domain_ID*) and TD name (*Tech_domain_name*);
- *technologysubdomains*, containing the list of Technology Subjects (TSs) from ESA Technology Tree. As shown, each entry is defined in terms of TS ID (Tech_subdom_ID), TS name (*Tech_subdom_ID*) and ID of the TD linked to each TS (*Tech_domain_ID*). The latter allows to express the hierarchy between TDs and TSs envisaged by ESA Technology Tree through a *one-to-many* relationship between the Tables *technologydomains* and *technologysubdomains* (i.e., a TD can contain several TSs, but a TS can be associated to only one TD).
- *technologygroups*, with the list of Technology Groups (TGs) from ESA Technology Tree. Similarly to *technologysubdomains*, fields are TG ID (*Tech_group_ID*), TG name (*Tech_group_name*) and ID of the TS linked to each TG (*Tech_subdom_ID*), thus representing a *one-to-many* relationship between *technologygroups* and *technologysubdomains*;
- *technologies*, with *Tech_group_ID* expressing the *one-to-many* relationship between *technologies* and *technologygroups*;
- *trl_plan*, to host information related to TRL milestones achievement for each Tech. Each record, identified by an ID (*trl_plan_ID*), contains the date (*trl_plan_date*) in which a TRL milestone (*trl*) was reached for a certain technology (identified with its ID, i.e., *Tech_ID*). As a result, *trl_plan and technologies* are lined by a *one-to-many relationship* (i.e., a tech can be associated to several TRL milestones, but a specific TRL milestone with related date is referred only to a single Tech).

It is highlighted that, differently from *technologydomains*, *technologysubdomains* and *technologygroups*, the level of detail provided in ESA Technology Tree is not sufficient to fill the Tables *technologies* and *trl_plan*, which have to rely on more specific literature sources. However, the hierarchical levels (i.e., TDs, TSs, and

TGs) provided by ESA Technology Tree can be a useful guide for the categorization of a new technology entered into the database.

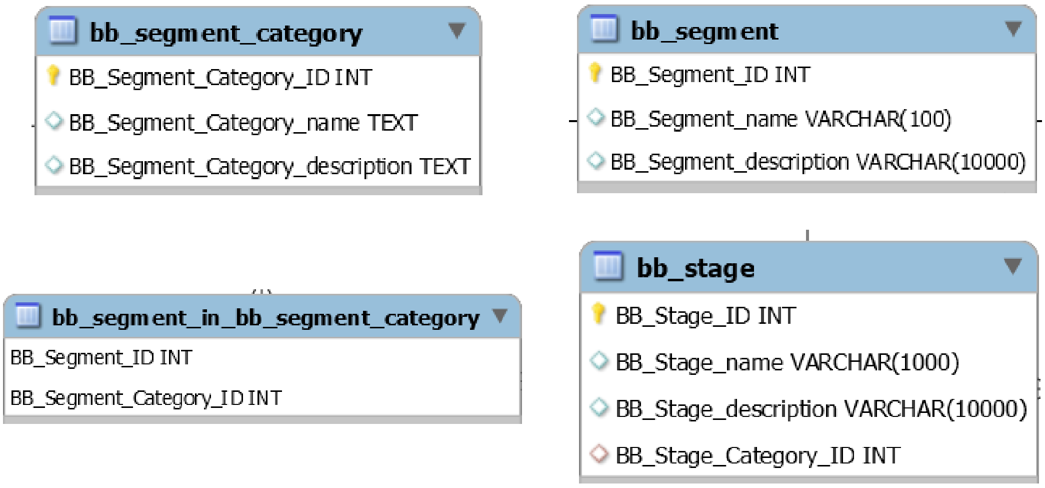


Figure 130: BBs Tables in HyDat

Moreover, *BBs Tables* in Figure 130 refer to the Building Blocks (BBs)-related Tables following the BBs hierarchy depicted in Figure 100. In detail:

- *bb_segment_category* stores the list of BB Segment categories available from ESA Product Tree (ESA-ESTEC (European Space Agency-European Space Research and Technology Centre), 2011) (Section 4.3.2.2). Each BB Segment category is defined through its ID (*BB_Segment_Category_ID*), name (*BB_Segment_Category_name*) and description (*BB_Segment_Category_description*);
- *bb_segment*, with a list of specific BB Segment designs or concepts (e.g., Case Study 1) available from literature, each characterized by a specific ID, name, and description
- *bb_segment_in_bb_segment_category,* a Table expressing the belonging of a specific BB Segment in *bb_segment* to a certain category in *bb_segment_category.* A similar Table is also referred as bridge Table for its capability to connect entries from different Tables. *bb_segment_in_bb_segment_category* stores the pairs of linked IDs (i.e., *BB_Segment_ID* and *BB_Segment_Category_ID*). For sake of clarity, a bridge Table allows to model a *many-to-many* relationship between Tables. In the specific case of *bb_segment_in_bb_segment_category,* it expresses the fact that a *BB_Segment_ID* can belong to many BB Segment categories and that a *BB_Segment_Category_ID* can be assigned to many BB Segments. This is in line with the fact that, as discussed in Section

4.3.2.2, a RLV can be intended both as a Launcher and as an Orbital Transportation & Re-entry System

- *bb_stage_category*, similar to *bb_segment_category*, but with the list of BB Stage categories (for sake of clarity, fields are *BB_Stage_Category_ID*, *BB_Stage_Category_name* and *BB_Stage_Category_description*). In this case, considering that the BB Stage Level has been added in this Dissertation to better represent RLV characteristics within the roadmapping process, a list of BB Stages is not available from ESA Product Tree. Please, notice that the preliminary list of BB Stages derived in this work is provided in Section 4.5.1.2.
- *bb_stage,* in line with *bb_segment*, gathers the characteristics of a specific BB Stage design. However, in this case the belonging to a specific BB Stage category stored in *bb_stage_category* is directly specified in *bb_stage* through *BB_Stage_category_ID.* This means that a *one-to-many relationship* is established (no bridge table is needed) to represent that a specific Stage can belong to only one BB Stage category.
- *bb_stage_in_segment*, a bridge table defining a *many-to-many* relationship between *bb_stage* and *bb_segment* through *BB_Stage_ID* and *BB_Segment_ID.* This reflects not only the fact that a certain BB Segment can be constituted by many Stages (i.e., multistage RLV) but also that a specific Stage design can be possibly reused, as it is, in several BB Segment configurations.
- *bb_system_category, bb_equipment_category* and *bb_component_category* have the same structure and meaning of *bb_stage_category* but they are referred, respectively, to systems, equipment, and components. Detailed lists for these BB levels can be found in Section 4.5.1.2;
- *bb_system*, *bb_equipment* and *bb_component* are analogous to *bb_stage* but they are referred, respectively, to systems, equipment and components.
- *bb_system_in_stage, bb_equipment_in_system* and *bb_component_in_equipment* are bridge tables similar to *bb_stage_in_segment* and express the relationship between the other BB levels.

Furthermore, the Tables shown in detail in Figure 131 specifically refer to the Activities and Mission Concepts (AC/MC) pillar. Notably, *activities* and *missionconcepts* are dedicated Tables to store, respectively, lists of ACs and MCs. Both contain information about the AC/MC in terms of ID, name, description, Enabling TRL (*TRL_start*), final TRL achieved (*TRL_end*), cost (with reference year for the cost datum as well as currency) and funding status (0 if not funded, 1 if funded). For MCs, taking into account that they can be complex missions performed in the Earth atmosphere and beyond, *missionconcepts* has two additional fields: *MC_Target_Environment*, to further characterize the MC in terms of target mission environment (i.e., Earth, LEO, Beyond LEO, Moon, or Mars) and *MC_MissionProfile*, with details about the mission profile performed during the MC.

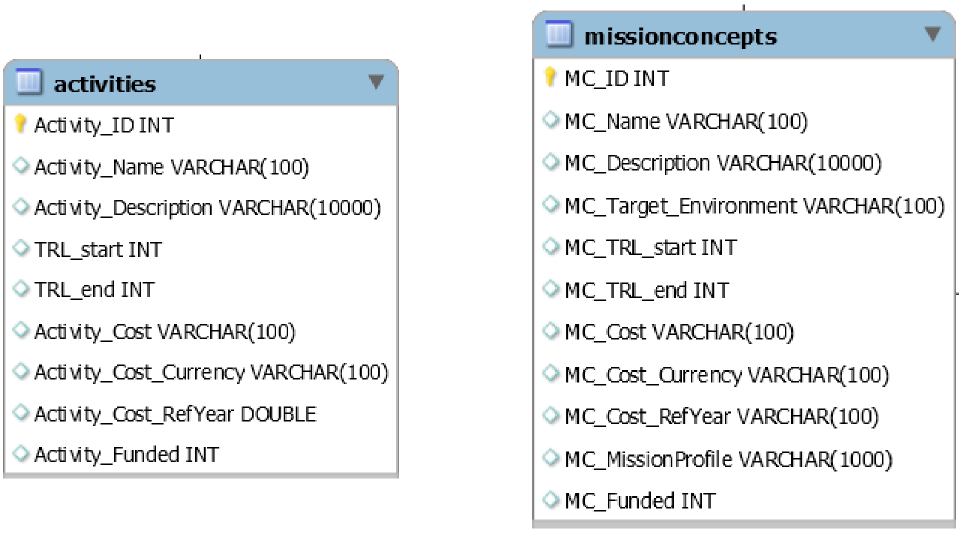


Figure 131: ACs and MCs Tables

For Operational Capabilities (OCs), each OC is stored within the *operationalcapabilities* Table under the field *OC_name* and associated to an ID (*OC_ID*). Eventually, Programmes and Projects Tables collect information related to the new pillar introduced within this Dissertation (Section 4.5.1.2). Figure 132 shows the attributes of *programmes* Table, which is linked to *funding_scheme* Table through a *one-to-many* relationship (i.e., a Programme can be linked to a single funding scheme). Please, note that *funding_scheme* collects the lists of all funding schemes with related attributes.

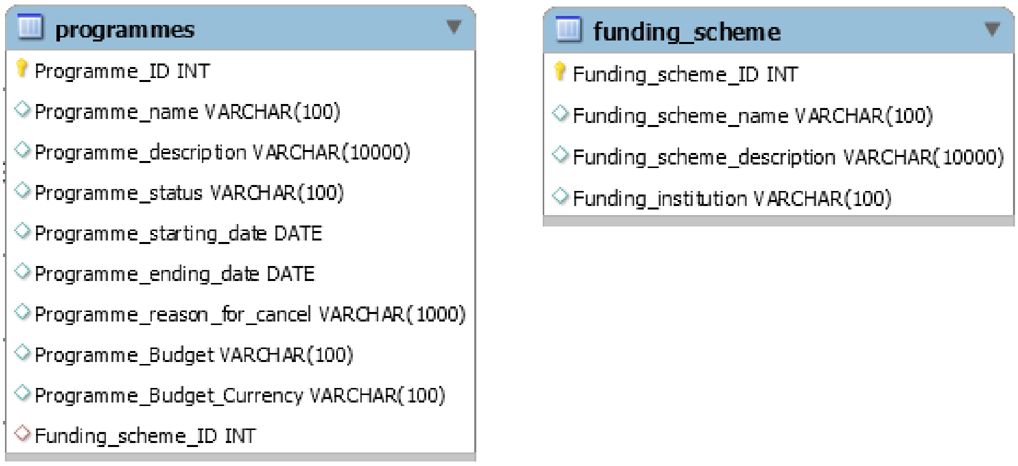
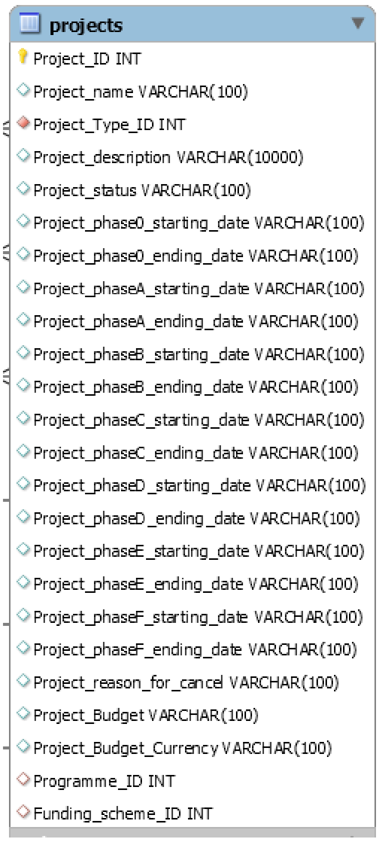
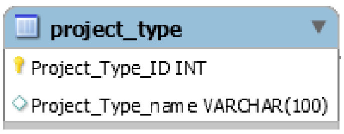


Figure 132: Programmes Tables





Project_Type_ID	Project_Type_name
1	Flight Project
2	Flight Demo Project
3	Ground Demo Project

Figure 133: Projects Tables

Complementary, as far as *projects* Table is concerned (Figure 133), the database is able to store details about the dates associated to Projects Phases basing to the ESA nomenclature in Figure 88 and about the project type. In addition, one-to-many relationships define the link between a Project and the reference Programme as well as the funding scheme related to the Project.

7.3.2 Relationships between Elements' Tables

After completing the definition of the main Elements' Tables, it is fundamental to establish the relationships between them, thus allowing to exploit the database to retrieve links between elements as required by the TRIS process (Section 4.3.2). In this context, it is clear that, in principle, the database back-end might represent all the possible elements' interconnections thanks to the definition of proper one-to-many and many-to-many relationships. However, this would dramatically increase the overall database intricacy, also complicating the filling process. Indeed, it is worth remembering that at the current stage HyDat is empty and it has to be manually filled with data. As such, the need to define all possible relationships between elements could result in an excessively time-consuming and prohibitive database filling procedure. In account of this, the HyDat back-end proposed in this Dissertation entails only the main relationships between elements. The logic of derivation of such relationships is based on the definition of a straightforward database filling process, able to tackle all the primary elements' interconnections (also referred as "direct links") to be reproduced within the back-end. The remaining links can be derived indirectly (i.e., "indirect links"). In this way the complexity of the overall HyDat architecture is drastically reduced, but a preliminary overview of all elements' links is still guaranteed. In this context, the process for HyDat filling previously proposed in (Fusaro et al., 2017) (Figure 82) can be a useful benchmark for the definition of the new procedure, providing a partial overview of elements' relationships to be implemented within the back-end. Notably, Figure 82 highlights that essential starting point for the filling process is the definition of a Project, which can be intended as a container of all the other elements. The Project is directly linked to the reference MC studied, so that the first link between elements is between Project and MC. The second link involves MC and Techs, considering that the reference MC is strictly related to the development of a specific set of technologies. Starting from these considerations, an improved version of the activity flow for database filling is proposed in Figure 134. The latter involves all the pillars of technology roadmapping described in Section 4.3.2 along with the links between them to be then reproduced within the back-end.

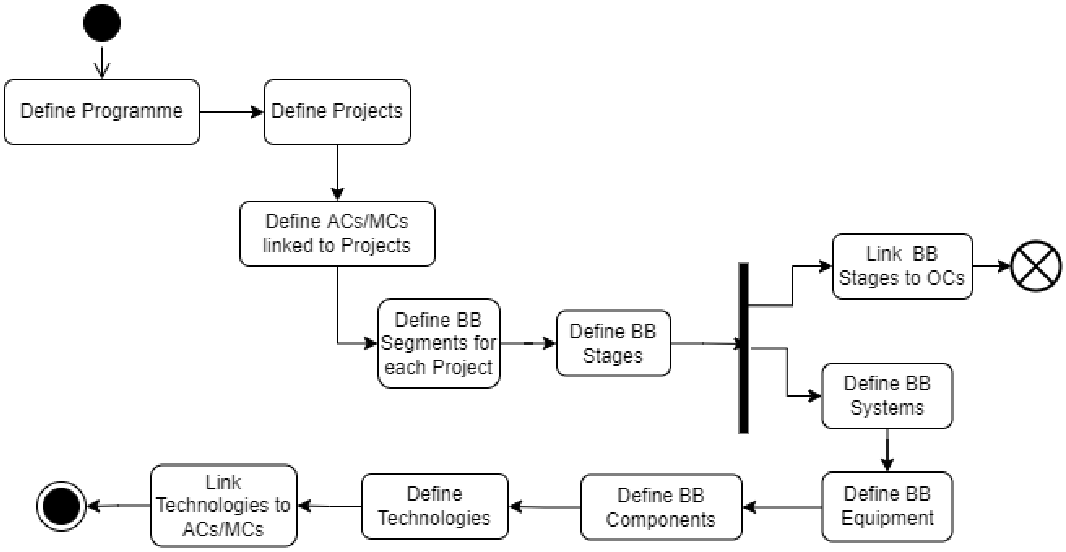


Figure 134: New HyDat back-end filling process

The overall process starts with the definition of a Programme and it proceeds by introducing linked Projects. Then, the list of ACs and MCs linked to each Project should be specified, along with the BB Segment(s) of interest in each Project. This means that Projects are directly linked not only to Programmes but also to ACs/MCs and BB Segments, while ACs/MCs are indirectly linked to BB Segments via the link to Projects. Then, by exploiting the BB hierarchy in Figure 100, the list of Stages linked to Segment(s) can be defined, thus deriving an indirect link between Stages and Projects via Segments(s). In addition, remembering the definition of OCs provided in Section 4.1.2.1, they can be intended as high-level functions expressed at Stage Level. As such, as shown in in Figure 135, a direct link between Stages and OCs can be established. Subsequently, the list of Systems installed on each Stage can be defined, thus obtaining indirect links with OCs, Segments and Programme/Projects. Similarly, the list of Equipment and, then, of Components, can be specified along with related indirect links with the previous elements. Eventually, the lower-level BBs, i.e., Components, can be used to obtain the list of Technologies. In this way, a direct link between BB Components and Technologies is set up along with indirect links with the other BB levels, OCs, and Programme/Projects. Eventually, considering the central role of Techs in the overall TRIS methodology, the direct link between the list of Techs with the list of ACs/MCs introduced at the beginning of the process should be elicited. In this way, all pillars are directly linked to Techs except OCs, which can be still derived only indirectly from linked Stages. To summarize, the process of elements definition within the database just described provides the direct links between pillars depicted in Figure 135. All the remaining links not directly specified should be intended as indirect.

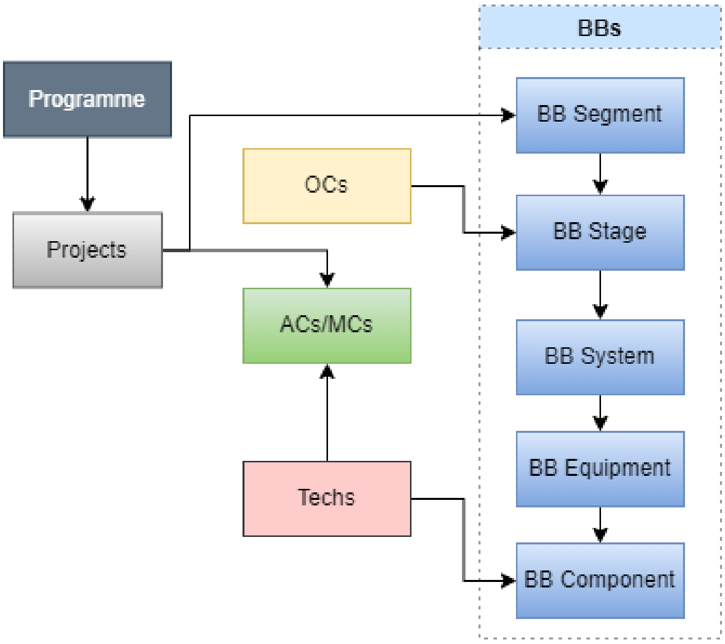


Figure 135: Direct links between elements in HyDat back-end

Basing on the relationships highlighted in Figure 135, it is possible to obtain the HyDat back-end architecture in MySQL depicted in Figure 136. The latter contains all the main Elements' tables previously discussed showing the relationships among them. Please, notice that solid lines in Figure 136 indicate *many-to-many* relationships (in this case a bridge table is also envisaged), while dashed lines stand for *one-to-many* relationships. For sake of clarity, all the Tables previously shown in dedicated Figures are flattened in Figure 136 in order to leave the possibility to show in detail Tables not displayed before or introduced afterwards.

By comparing the links depicted in Figure 135 with those implemented within the back-end (Figure 136), it can be observed that *programmes* Table is linked to *projects* Table through a dashed lined, highlighting the existence of a *one-to-many* relationship between the two tables, meaning that a specific Programme can be linked to several Projects, but a Project can be linked only to a Programme. Similar remarks apply to the connection between *projects* Table and *project_type*

Table (so that a Project can be associated only to a specific project type) and to *funding_scheme* Table, connected to both *programmes* and *projects* Tables. It is also highlighted that in the proposed back-end architecture *contacts* and *partners* Tables have been included to further characterize Programmes in terms of the institutions and individuals involved. Details about the attributes of these Tables can be found in Figure 136. Moreover, according to Figure 135, the link between Projects and ACs/MCs is represented through the bridge tables *projectsactivities_bridge* and *projectsmcs_bridge*, while the connection between Projects and BB Segments is provided by the bridge table *bb_segment_in_project*. Dealing with BBs, all the Tables previously introduced as BB Tables are now properly connected in Figure 136 to reproduce the established BBs hierarchy and represent the belonging of a BB to a certain BB category. In addition, the relationship between OCs and BB Stages is provided by the bridge table *oc_in_bb_stage*. Eventually, *technologycomponent_bridge* links *bb_component* to *technologies*, while *technologymission_bridge* and *technologyactivity_bridge* connect Techs and ACs/MCs. For sake of clarity, as for the BBs hierarchy, the Technology Tree hierarchy is also represented through the connection of Techs Tables mentioned in Section 7.3.1. Furthermore, *missionphases* Table has been included to better characterize the mission phases performed by each Stage. The specific fields of this Table are provided in Figure 136 along with the bridge table *missionphasesstage_bridge* connecting *missionphases* to *bb_stages.*

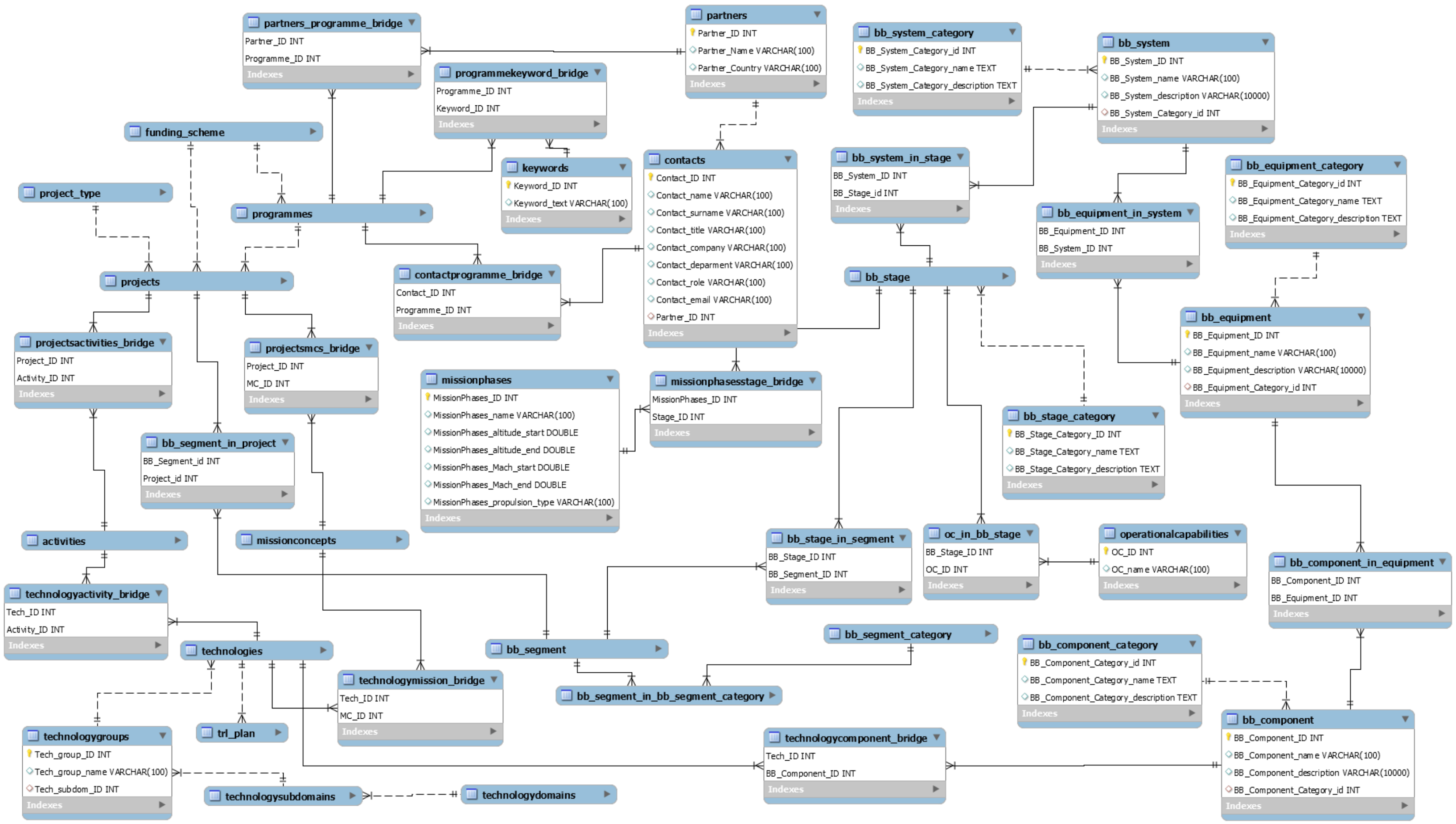


Figure 136: New HyDat back-end Structure

7.4 Complete List of ACs and MCs for Case Study 1

Linked Techs ID	MC Name	Enabling TRL	Target TRL
1	Expression of basic principles for intended use of Low-Speed Intake Ramp Technology	0	1
1	Identification of potential applications of Low-Speed Intake Ramp Technology	0	1
1	Design of Low-Speed Intake Ramp, providing understanding of how the basic principles are used	1	2
1	Formulation of potential application of Low-Speed Intake Ramp Technology	1	2
1	General definition of performance requirements for Low-Speed Intake Ramp Technology	1	2
1,2	Low Speed Intake Design	2	3
1,2	Low Speed Intake Numerical Analysis/Simulation	2	3
1,2	Design of low-speed intake model for wind tunnel test (not yet integrated into engine model)	3	4
1,2	Fabrication of low-speed intake model(s) for wind tunnel test(s)	3	4
1,2	Wind tunnel test(s) of low-speed intake model(s)	3	4
1,2	Design of low-speed intake model to be integrated into propulsion plant wind tunnel model	4	5
1,2	Fabrication of low-speed intake model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
1-16	Propulsion Plant Wind tunnel test(s) to verify critical functions	4	5
1,2	Design of low-speed intake model to be integrated into propulsion plant model	5	6
1,2	Fabrication of low-speed intake model(s) to be integrated into propulsion plant model(s)	5	6

1-22	Sea-level firing test(s) of propulsion plant model(s)	5	6
1,2	Design of low-speed intake model to be integrated into Small Scale Flight Demonstrator	6	7
1,2	Fabrication of low-speed intake model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
1,2	Design of low-speed intake model to be integrated into Mid Scale Flight Demonstrator	6	7
1,2	Fabrication of low-speed intake model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
1,2	Design of low-speed intake model to be integrated into Near Full Scale Flight Demonstrator	7	8
1,2	Fabrication of low-speed intake model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
3	Expression of basic principles for intended use of Low-Speed Intake Duct Technology	0	1
3	Identification of potential applications of Low-Speed Low Speed Intake Duct Technology	0	1
3	Design of Low-Speed Intake Duct, providing understanding of how the basic principles are used	1	2
3	Formulation of potential application of Low-Speed Intake Duct Technology	1	2
3	General definition of performance requirements for Low-Speed Intake Duct Technology	1	2
3	Expression of basic principles for intended use of High-Speed Intake Technology	0	1
3	Identification of potential applications of High-Speed Intake Technology	0	1
3	Design of High-Speed Intake, providing understanding of how the basic principles are used	1	2
3	Formulation of potential application of High-Speed Intake Technology	1	2
3	General definition of performance requirements for High-Speed Intake Technology	1	2
3	High Speed Intake Design	2	3
3	High Speed Intake Numerical Analysis/Simulation	2	3

3	Design of high-speed intake model for wind tunnel test (not yet integrated into engine model)	3	4
3	Fabrication of high-speed intake model(s) for wind tunnel test(s)	3	4
3	Wind tunnel test(s) of high-speed intake model(s)	3	4
3	Design of high-speed intake model to be integrated into propulsion plant wind tunnel model	4	5
3	Fabrication of high-speed intake model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
3	Design of high-speed intake model to be integrated into propulsion plant model	5	6
3	Fabrication of high-speed intake model(s) to be integrated into propulsion plant model(s)	5	6
3	Design of high-speed intake model to be integrated into Small Scale Flight Demonstrator	6	7
3	Fabrication of high-speed intake model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
3	Design of high-speed intake model to be integrated into Mid Scale Flight Demonstrator	6	7
3	Fabrication of high-speed intake model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
3	Design of high-speed intake model to be integrated into Near Full Scale Flight Demonstrator	7	8
3	Fabrication of high-speed intake model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
4	Expression of basic principles for intended use of 2D Nozzle Technology	0	1
4	Identification of potential applications of 2D Nozzle Technology	0	1
4	Design of 2D Nozzle, providing understanding of how the basic principles are used	1	2
4	Formulation of potential application of 2D Nozzle Technology	1	2
4	General definition of performance requirements for 2D Nozzle Technology	1	2
4	2D Nozzle Design	2	3

4	2D Nozzle Numerical Analysis/Simulation	2	3
4	Design of 2D Nozzle model for wind tunnel test (not yet integrated into engine model)	3	4
4	Fabrication of 2D Nozzle model(s) for wind tunnel test (s)	3	4
4	Wind tunnel test(s) of 2D Nozzle model(s)	3	4
4	Design of 2D nozzle model to be integrated into propulsion plant wind tunnel model	4	5
4	Fabrication of 2D nozzle model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
4	Design of 2D nozzle model to be integrated into propulsion plant model	5	6
4	Fabrication of 2D nozzle model(s) to be integrated into propulsion plant model(s)	5	6
4	Design of 2D nozzle model to be integrated into Small Scale Flight Demonstrator	6	7
4	Fabrication of 2D nozzle model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
4	Design of 2D nozzle model to be integrated into Mid Scale Flight Demonstrator	6	7
4	Fabrication of 2D nozzle model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
4	Design of 2D nozzle model to be integrated into Near Full Scale Flight Demonstrator	7	8
4	Fabrication of 2D nozzle model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
5	Expression of basic principles for intended use of 3D Nozzle Technology	0	1
5	Identification of potential applications of 3D Nozzle Technology	0	1
5	Design of 3D Nozzle, providing understanding of how the basic principles are used	1	2
5	Formulation of potential application of 3D Nozzle Technology	1	2
5	General definition of performance requirements for 3D Nozzle Technology	1	2

5	3D Nozzle Design	2	3
5	3D Nozzle Numerical Analysis/Simulation	2	3
5	Design of 3D Nozzle model for wind tunnel test (not yet integrated into engine model)	3	4
5	Fabrication of 3D Nozzle model(s) for wind tunnel test (s)	3	4
5	Wind tunnel test(s) of 3D Nozzle model(s)	3	4
5	Design of 3D nozzle model to be integrated into propulsion plant wind tunnel model	4	5
5	Fabrication of 3D nozzle model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
5	Design of 3D nozzle model to be integrated into propulsion plant model	5	6
5	Fabrication of 3D nozzle model(s) to be integrated into propulsion plant model(s)	5	6
5	Design of 3D nozzle model to be integrated into Small Scale Flight Demonstrator	6	7
5	Fabrication of 3D nozzle model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
5	Design of 3D nozzle model to be integrated into Mid Scale Flight Demonstrator	6	7
5	Fabrication of 3D nozzle model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
5	Design of 3D nozzle model to be integrated into Near Full Scale Flight Demonstrator	7	8
5	Fabrication of 3D nozzle model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
6	Expression of basic principles for intended use of ATR Exhaust Duct Technology	0	1
6	Identification of potential applications of ATR Exhaust Duct Technology	0	1
6	Design of ATR Exhaust Duct, providing understanding of how the basic principles are used	1	2
6	Formulation of potential application of ATR Exhaust Duct Technology	1	2

6	General definition of performance requirements for ATR Exhaust Duct Technology	1	2
6	ATR Exhaust Duct Design	2	3
6	ATR Exhaust Duct Numerical Analysis/Simulation	2	3
6	Design of ATR Exhaust Duct model for wind tunnel test (not yet integrated into engine model)	3	4
6	Fabrication of ATR Exhaust Duct model(s) for wind tunnel test (s)	3	4
6	Wind tunnel test(s) of ATR Exhaust Duct model(s)	3	4
6	Design of ATR Exhaust Duct model to be integrated into propulsion plant wind tunnel model	4	5
6	Fabrication of ATR Exhaust Duct model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
6	Design of ATR Exhaust Duct model to be integrated into propulsion plant model	5	6
6	Fabrication of ATR Exhaust Duct model(s) to be integrated into propulsion plant model(s)	5	6
6	Design of ATR Exhaust Duct model to be integrated into Small Scale Flight Demonstrator	6	7
6	Fabrication of ATR Exhaust Duct model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
6	Design of ATR Exhaust Duct model to be integrated into Mid Scale Flight Demonstrator	6	7
6	Fabrication of ATR Exhaust Duct model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
6	Design of ATR Exhaust Duct model to be integrated into Near Full Scale Flight Demonstrator	7	8
6	Fabrication of ATR Exhaust Duct model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
7	Expression of basic principles for intended use of ATR Variable Throat Technology	0	1
7	Identification of potential applications of ATR Variable Throat Technology	0	1
7	Design of ATR Variable Throat, providing understanding of how the basic principles are used	1	2

7	Formulation of potential application of ATR Variable Throat Technology	1	2
7	General definition of performance requirements for ATR Variable Throat Technology	1	2
7	ATR Variable Throat Design	2	3
7	ATR Variable Throat Numerical Analysis/Simulation	2	3
7	Design of ATR Variable Throat model for wind tunnel test (not yet integrated into engine model)	3	4
7	Fabrication of ATR Variable Throat model(s) for wind tunnel test (s)	3	4
7	Wind tunnel test(s) of ATR Variable Throat model(s)	3	4
7	Design of ATR Variable Throat model to be integrated into propulsion plant wind tunnel model	4	5
7	Fabrication of ATR Variable Throat model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
7	Design of ATR Variable Throat model to be integrated into propulsion plant model	5	6
7	Fabrication of ATR Variable Throat model(s) to be integrated into propulsion plant model(s)	5	6
7	Design of ATR Variable Throat model to be integrated into Small Scale Flight Demonstrator	6	7
7	Fabrication of ATR Variable Throat model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
7	Design of ATR Variable Throat model to be integrated into Mid Scale Flight Demonstrator	6	7
7	Fabrication of ATR Variable Throat model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
7	Design of ATR Variable Throat model to be integrated into Near Full Scale Flight Demonstrator	7	8
7	Fabrication of ATR Variable Throat model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
8	Expression of basic principles for intended use of ATR Fan Technology	0	1
8	Identification of potential applications of ATR Fan Technology	0	1

8	Design of ATR Fan, providing understanding of how the basic principles are used	1	2
8	Formulation of potential application of ATR Fan Technology	1	2
8	General definition of performance requirements for ATR Fan Technology	1	2
8	ATR Fan Design	2	3
8	ATR Fan Numerical Analysis/Simulati on	2	3
8	Design of ATR Fan model for wind tunnel test (not yet integrated into engine model)	3	4
8	Fabrication of ATR Fan model(s) for wind tunnel test(s)	3	4
8	Wind tunnel test(s) of ATR Fan model(s)	3	4
8	Design of ATR Fan model to be integrated into ATR core engine model	4	5
8	Fabrication of ATR Fan model(s) to be integrated into ATR core engine model(s)	4	5
8	Rotating test(s) of ATR Fan model(s) under normal and low-pressure condition before integration into ATR core engine model(S)	4	5
8-11	Integration of ATR core engine model elements	5	6
8-11	Sea-level firing test(s) of ATR core engine model(s)	5	6
8-11	Design of ATR core engine model to be integrated into propulsion plant model	5	6
8-11	Fabrication of ATR core engine model(s) to be integrated into propulsion plant model(s)	5	6
8-11	Design of ATR core engine model to be integrated into Small Scale Flight Demonstrator	6	7
8-11	Fabrication of ATR core engine model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
8-11	Design of ATR core engine model to be integrated into Mid Scale Flight Demonstrator	6	7
8-11	Fabrication of ATR core engine model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7

8-11	Design of ATR core engine model to be integrated into Near Full Scale Flight Demonstrator	7	8
8-11	Fabrication of ATR core engine model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
9	Expression of basic principles for intended use of ATR Turbines Technology	0	1
9	Identification of potential applications of ATR Turbines Technology	0	1
9	Design of ATR Turbines, providing understanding of how the basic principles are used	1	2
9	Formulation of potential application of ATR Turbines Technology	1	2
9	General definition of performance requirements for ATR Turbines Technology	1	2
9	ATR Turbine Design	2	3
9	ATR Turbine Numerical Analysis/Simulation	2	3
9	Design of ATR Turbine model(s) for wind tunnel test (not yet integrated into engine model)	3	4
9	Fabrication of ATR Turbine model(s) for wind tunnel test(s)	3	4
9	Wind tunnel test(s) of subscale ATR Turbine model(s)	3	4
9	Design of ATR Turbine model to be integrated into ATR core engine model	4	5
9	Fabrication of ATR Turbine model(s) to be integrated into ATR core engine model(s)	4	5
9	Test of ATR Turbine model(s) before integration into ATR core engine model(s)	4	5
10	Expression of basic principles for intended use of ATR Combustor Technology	0	1
10	Identification of potential applications of ATR Combustor Technology	0	1
10	Design of ATR Combustor, providing understanding of how the basic principles are used.	1	2
10	Formulation of potential application of ATR Combustor Technology	1	2

10	General definition of performance requirements for ATR Combustor Technology	1	2
10	ATR Combustor Design	2	3
10	ATR Combustor Numerical Analysis/Simulation	2	3
10	Design of ATR Combustor model(s) for wind tunnel test (not yet integrated into engine model)	3	4
10	Fabrication of ATR Combustor model(s) for wind tunnel test(s)	3	4
10	Wind tunnel test(s) of subscale ATR Combustor model(s)	3	4
10	Design of ATR Combustor model to be integrated into ATR core engine model	4	5
10	Fabrication of ATR Combustor model(s) to be integrated into ATR core engine model(s)	4	5
10	Test of ATR Combustor model(s) before integration into ATR core engine model(s)	4	5
11	Expression of basic principles for intended use of Engine Controls Technology	0	1
11	Identification of potential applications of Engine Controls Technology	0	1
11	Design of Engine Controls, providing understanding of how the basic principles are used	1	2
11	Formulation of potential application of Engine Controls Technology	1	2
11	General definition of performance requirements for Engine Controls Technology	1	2
11	Design of Engine Controls	2	3
11	Numerical Analyses/Simulation of Engine Controls	2	3
11	Design of model(s) to evaluate Engine Controls	3	4
11	Fabrication of model(s) to evaluate Engine Controls	3	4
11	Test of model(s) of Engine Controls	3	4

11	Design of Engine Controls to be integrated into ATR core engine model	4	5
11	Fabrication of Engine Controls to be integrated into ATR core engine model(s)	4	5
11	Test of Engine Controls before integration into ATR core engine model(s)	4	5
11	Design of Engine Controls to be integrated into DMR engine model	4	5
11	Fabrication of Engine Controls to be integrated into DMR engine model(s)	4	5
11	Test of Engine Controls before integration into DMR engine model(s)	4	5
11-15	Integration of DMR engine model elements	4	5
11-15	Sea-level firing test(s) of DMR engine model	4	5
11	Design of Engine Controls to be integrated into propulsion plant model	5	6
11	Fabrication of Engine Controls to be integrated into propulsion plant model	5	6
11	Design of Engine Controls to be integrated into Small Scale Flight Demonstrator	6	7
11	Fabrication of Engine Controls to be integrated into Small Scale Flight Demonstrator(s)	6	7
11	Design of Engine Controls to be integrated into Mid Scale Flight Demonstrator	6	7
11	Fabrication of Engine Controls to be integrated into Mid Scale Flight Demonstrator(s)	6	7
11	Design of Engine Controls to be integrated into Near Full Scale Flight Demonstrator	7	8
11	Fabrication of Engine Controls to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
12	Expression of basic principles for intended use of DMR Injection Struts Technology	0	1
12	Identification of potential applications of DMR Injection Struts Technology	0	1
12	Design of DMR Injection Struts, providing understanding of how the basic principles are used	1	2

12	Formulation of potential application of DMR Injection Struts Technology	1	2
12	General definition of performance requirements for DMR Injection Struts Technology	1	2
12	DMR Injection Struts Design	2	3
12	DMR Injection Struts Numerical Analysis/Simulation	2	3
12	Design of DMR Injection Strut model(s) for functional verification in laboratory environment	3	4
12	Fabrication of DMR Injection Strut model(s) for functional verification in laboratory environment	3	4
12	Functional verification of subscale DMR Injection Strut model(s) in laboratory environment	3	4
12	Design of DMR Injection Struts model to be integrated into DMR engine model	4	5
12	Fabrication of DMR Injection Struts model(s) to be integrated into DMR engine model(s)	4	5
12	Test of DMR Injection Struts model before integration into DMR engine model(s)	4	5
12-15	Design of DMR engine model to be integrated into propulsion plant model	5	6
12-15	Fabrication of DMR engine model(s) to be integrated into propulsion plant model(s)	5	6
12-15	Design of DMR engine model to be integrated into Small Scale Flight Demonstrator	6	7
12-15	Fabrication of DMR engine model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
12-15	Design of DMR engine model to be integrated into Mid Scale Flight Demonstrator	6	7
12-15	Fabrication of DMR engine model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7
12-15	Design of DMR engine model to be integrated into Near Full Scale Flight Demonstrator	7	8
12-15	Fabrication of DMR engine model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
13	Expression of basic principles for intended use of Scramjet Combustor Technology	0	1

13	Identification of potential applications of Scramjet Combustor Technology	0	1
13	Design of Scramjet Combustor, providing understanding of how the basic principles are used	1	2
13	Formulation of potential application of Scramjet Combustor Technology	1	2
13	General definition of performance requirements for Scramjet Combustor Technology	1	2
13	Scramjet Combustor Design	2	3
13	Scramjet Combustor Numerical Analysis/Simulation	2	3
13	Design of Scramjet Combustor model(s) for wind tunnel test (not yet integrated into engine model)	3	4
13	Fabrication of Scramjet Combustor model(s) for wind tunnel test(s)	3	4
13	Wind tunnel test(s) of subscale Scramjet Combustor model(s)	3	4
13	Design of Scramjet Combustor model to be integrated into DMR engine model	4	5
13	Fabrication of Scramjet Combustor model(s) to be integrated into DMR engine model(s)	4	5
13	Test of Scramjet Combustor model before integration into DMR engine model(s)	4	5
14	Expression of basic principles for intended use of Ramjet-Scramjet Transition Technology	0	1
14	Identification of potential applications of Ramjet-Scramjet Transition Technology	0	1
14	Design of Ramjet-Scramjet Transition, providing understanding of how the basic principles are used	1	2
14	Formulation of potential application of Ramjet-Scramjet Transition Technology	1	2
14	General definition of performance requirements for Ramjet-Scramjet Transition Technology	1	2
14	Ramjet-Scramjet Transition Design	2	3
14	Ramjet-Scramjet Transition Numerical Analysis/Simulation	2	3

14	Design of Ramjet-Scramjet Transition model(s) for functional verification in laboratory environment	3	4
14	Fabrication of Ramjet-Scramjet Transition model(s) for functional verification in laboratory environment	3	4
14	Functional verification of Ramjet-Scramjet Transition model(s) in laboratory environment	3	4
14	Design of Ramjet-Scramjet Transition model to be integrated into DMR engine model	4	5
14	Fabrication of Ramjet-Scramjet Transition model(s) to be integrated into DMR engine model(s)	4	5
14	Test of Ramjet-Scramjet Transition model before integration into DMR engine model(s)	4	5
15	Expression of basic principles for intended use of PAC Technology	0	1
15	Identification of potential applications of PAC Technology	0	1
15	Preliminary design of Scramjet Combustor with PAC Technology, providing understanding of how the basic principles are used	1	2
15	Formulation of potential application of PAC Technology	1	2
15	General definition of performance requirements for PAC Technology	1	2
15	Scramjet Combustor Design including PAC Technology	2	3
15	Scramjet Combustor Numerical Analysis/Simulation including PAC Technology	2	3
15	Design of Scramjet Combustor model(s) with PAC Technology for combustion test (not yet integrated into engine model)	3	4
15	Fabrication of Scramjet Combustor model(s) with PAC Technology for combustion test(s)	3	4
15	Combustion test(s) of Scramjet Combustor model(s) with PAC Technology	3	4
15	Design of Scramjet Combustor model to be integrated into DMR engine model	4	5
15	Fabrication of Scramjet Combustor model(s) to be integrated into DMR engine model(s)	4	5

15	Test of Scramjet Combustor model before integration into DMR engine model(s)	4	5
16	Expression of basic principles for intended use of Isolator Technology	0	1
16	Identification of potential applications of Isolator Technology	0	1
16	Preliminary design of Isolator, providing understanding of how the basic principles are used.	1	2
16	Formulation of potential application of Isolator Technology	1	2
16	General definition of performance requirements for Isolator Technology	1	2
16	Isolator Design	2	3
16	Isolator Numerical Analysis/Simulation	2	3
16	Design of isolator model for wind tunnel test (not yet integrated into engine model)	3	4
16	Fabrication of isolator model(s) for wind tunnel test(s)	3	4
16	Wind tunnel test(s) of isolator model(s)	3	4
16	Design of isolator model to be integrated into propulsion plant wind tunnel model	4	5
16	Fabrication of isolator model(s) to be integrated into propulsion plant wind tunnel model(s)	4	5
16	Design of isolator model to be integrated into propulsion plant model	5	6
16	Fabrication of isolator model(s) to be integrated into propulsion plant model(s)	5	6
16	Design of isolator model to be integrated into Small Scale Flight Demonstrator	6	7
16	Fabrication of isolator model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
16	Design of isolator model to be integrated into Mid Scale Flight Demonstrator	6	7
16	Fabrication of isolator model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7

16	Design of isolator model to be integrated into Near Full Scale Flight Demonstrator	7	8
16	Fabrication of isolator model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
17	Expression of basic principles for intended use of ATR Pumps Technology	0	1
17	Identification of potential applications of ATR Pumps Technology	0	1
17	Design of ATR Pumps, providing understanding of how the basic principles are used	1	2
17	Formulation of potential application of ATR Pumps Technology	1	2
17	General definition of performance requirements for ATR Pumps Technology	1	2
17	ATR Pumps Design	2	3
17	ATR Pumps Numerical Analysis/Simulation	2	3
17	Design of ATR pump model(s) for functional verification in laboratory environment	3	4
17	Fabrication of ATR pump model(s) for functional verification in laboratory environment	3	4
17	Functional verification of ATR pump model(s) in laboratory environment	3	4
17	Functional verification of ATR pump model(s) to assess critical functions	4	5
17	Design of ATR pump model to be integrated into propulsion plant model	5	6
17	Fabrication of ATR pump model(s) to be integrated into propulsion plant model(s)	5	6
17	Design of ATR pump model to be integrated into Small Scale Flight Demonstrator	6	7
17	Fabrication of ATR pump model(s) to be integrated into Small Scale Flight Demonstrator(s)	6	7
17	Design of ATR pump model to be integrated into Mid Scale Flight Demonstrator	6	7
17	Fabrication of ATR pump model(s) to be integrated into Mid Scale Flight Demonstrator(s)	6	7

17	Design of ATR pump model to be integrated into Near Full Scale Flight Demonstrator	7	8
17	Fabrication of ATR pump model(s) to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
18	Expression of basic principles for intended use of Intake Ramps Actuators Technology	0	1
18	Identification of potential applications of Intake Ramps Actuators Technology	0	1
18	Design of Intake Ramps Actuators, providing understanding of how the basic principles are used	1	2
18	Formulation of potential application of Intake Ramps Actuators Technology	1	2
18	General definition of performance requirements for Intake Ramps Actuators Technology	1	2
18	Design of Intake Ramps Actuators	2	3
18	Numerical Analysis/Simulation of Intake Ramps Actuators	2	3
18	Design of Intake Ramps Actuator model(s) for functional verification in laboratory environment	3	4
18	Fabrication of Intake Ramps Actuator model(s) for functional verification in laboratory environment	3	4
18	Functional verification of Intake Ramps Actuator model(s) in laboratory environment	3	4
18	Functional verification of Intake Ramps Actuator model(s) to assess critical functions	4	5
18	Design of Intake Ramps Actuators to be integrated into propulsion plant model	5	6
18	Fabrication of Intake Ramps Actuators to be integrated into propulsion plant model	5	6
18	Design of Intake Ramps Actuators to be integrated into Small Scale Flight Demonstrator	6	7
18	Fabrication of Intake Ramps Actuators to be integrated into Small Scale Flight Demonstrator(s)	6	7
18	Design of Intake Ramps Actuators to be integrated into Mid Scale Flight Demonstrator	6	7
18	Fabrication of Intake Ramps Actuators to be integrated into Mid Scale Flight Demonstrator(s)	6	7

18	Design of Intake Ramps Actuators to be integrated into Near Full Scale Flight Demonstrator	7	8
18	Fabrication of Intake Ramps Actuators to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
19	Expression of basic principles for intended use of Variable Throat Actuators Technology	0	1
19	Identification of potential applications of Variable Throat Actuators Technology	0	1
19	Design of Variable Throat Actuators, providing understanding of how the basic principles are used.	1	2
19	Formulation of potential application of Variable Throat Actuators Technology	1	2
19	General definition of performance requirements for Variable Throat Actuators Technology	1	2
19	Design of Variable Throat Actuators	2	3
19	Numerical Analysis/Simulation of Variable Throat Actuators	2	3
19	Design of Variable Throat Actuator model(s) for functional verification in laboratory environment	3	4
19	Fabrication of Variable Throat Actuator model(s) for functional verification in laboratory environment	3	4
19	Functional verification of Variable Throat Actuator model(s) in laboratory environment	3	4
19	Functional verification of Variable Throat Actuator model(s) to assess critical functions	4	5
19	Design of Variable Throat Actuators to be integrated into propulsion plant model	5	6
19	Fabrication of Variable Throat Actuators to be integrated into propulsion plant model	5	6
19	Design of Variable Throat Actuators to be integrated into Small Scale Flight Demonstrator	6	7
19	Fabrication of Variable Throat Actuators to be integrated into Small Scale Flight Demonstrator(s)	6	7
19	Design of Variable Throat Actuators to be integrated into Mid Scale Flight Demonstrator	6	7
19	Fabrication of Variable Throat Actuators to be integrated into Mid Scale Flight Demonstrator(s)	6	7

19	Design of Variable Throat Actuators to be integrated into Near Full Scale Flight Demonstrator	7	8
19	Fabrication of Variable Throat Actuators to be integrated into Near Full Scale Flight Demonstrator(s)	7	8
20	Assessment of Engine Cooled Materials (CMC) and related manufacturing processes for manufacturability and availability	2	3
20	Definition of supply chain requirements for Engine Cooled Materials (CMC)	2	3
20	Characterization of Engine Cooled Materials (CMC) performance and related manufacturing process parameters at elementary level	3	4
20	Characterization of representative Cooled Materials (CMC) performance and process parameters in relation to their end-use into Engine	4	5
20	Characterization of Cooled Materials (CMC) performance and process parameters in relation to their end-use into Engine	5	6
21	Assessment of Engine Cooled Materials (Metals) and related manufacturing processes for manufacturability and availability	2	3
21	Definition of supply chain requirements for Engine Cooled Materials (Metals)	2	3
21	Characterization of Engine Cooled Materials (Metals) performance and related manufacturing process parameters at elementary level	3	4
21	Characterization of representative Cooled Materials (Metals) performance and process parameters in relation to their end-use into Engine	4	5
21	Characterization of Cooled Materials (Metals) performance and process parameters in relation to their end-use into Engine	5	6
22	Assessment of Engine Uncooled Materials and related manufacturing processes for manufacturability and availability	2	3

22	Definition of supply chain requirements for Engine Uncooled Materials	2	3
22	Characterization of Engine Uncooled Materials performance and related manufacturing process parameters at elementary level	3	4
22	Characterization of representative Uncooled Materials performance and process parameters in relation to their end-use into Engine	4	5
22	Characterization of Uncooled Materials performance and process parameters in relation to their end-use into Engine	5	6
1-22	Flight test(s) of Small-Scale Flight Demonstrator(s)	6	7
1-22	Flight test(s) of Mid Scale Flight Demonstrator(s)	6	7
1-22	Flight test(s) of Near Full Scale Flight Demonstrator(s)	7	8
1-22	STRATOFLY MR3 Mission(s)	8	9

7.5 Ordered List of ACs and MCs for Case Study 1

Preliminary design of Scramjet Combustor with PAC Technology, providing understanding of how the basic principles are used
Formulation of potential application of PAC Technology
General definition of performance requirements for PAC Technology
Scramjet Combustor Design including PAC Technology
Scramjet Combustor Numerical Analysis/Simulation including PAC Technology
Design of Scramjet Combustor model(s) with PAC Technology for combustion test (not yet integrated into engine model)
Fabrication of Scramjet Combustor model(s) with PAC Technology for combustion test(s)
Combustion test(s) of Scramjet Combustor model(s) with PAC Technology
Design of Scramjet Combustor model to be integrated into DMR engine model
Test of Scramjet Combustor model before integration into DMR engine model(s)
Design of 3D nozzle model to be integrated into propulsion plant wind tunnel model
Fabrication of 3D nozzle model(s) to be integrated into propulsion plant wind tunnel model(s)
Functional verification of Intake Ramps Actuator model(s) to assess critical functions
Design of Intake Ramps Actuators to be integrated into propulsion plant model
Fabrication of Intake Ramps Actuators to be integrated into propulsion plant model
Design of Ramjet-Scramjet Transition model to be integrated into DMR engine model
Fabrication of Ramjet-Scramjet Transition model(s) to be integrated into DMR engine model(s)
Test of Ramjet-Scramjet Transition model before integration into DMR engine model(s)
Integration of DMR engine model elements
Sea-level firing test(s) of DMR engine model
Design of high-speed intake model to be integrated into propulsion plant wind tunnel model
Fabrication of high-speed intake model(s) to be integrated into propulsion plant wind tunnel model(s)

Design of isolator model to be integrated into propulsion plant wind tunnel model
Fabrication of isolator model(s) to be integrated into propulsion plant wind tunnel model(s)
Propulsion Plant Wind tunnel test(s) to verify critical functions
Design of DMR engine model to be integrated into propulsion plant model
Fabrication of DMR engine model(s) to be integrated into propulsion plant model(s)
Design of 3D nozzle model to be integrated into propulsion plant model
Fabrication of 3D nozzle model(s) to be integrated into propulsion plant model(s)
Design of high-speed intake model to be integrated into propulsion plant model
Fabrication of high-speed intake model(s) to be integrated into propulsion plant model(s)
Design of isolator model to be integrated into propulsion plant model
Fabrication of isolator model(s) to be integrated into propulsion plant model(s)
Sea-level firing test(s) of propulsion plant model(s)
Design of ATR core engine model to be integrated into Small Scale Flight Demonstrator
Fabrication of ATR core engine model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of ATR Exhaust Duct model to be integrated into Small Scale Flight Demonstrator
Fabrication of ATR Exhaust Duct model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of ATR Variable Throat model to be integrated into Small Scale Flight Demonstrator
Fabrication of ATR Variable Throat model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of Variable Throat Actuators to be integrated into Small Scale Flight Demonstrator
Fabrication of Variable Throat Actuators to be integrated into Small Scale Flight Demonstrator(s)
Design of DMR engine model to be integrated into Small Scale Flight Demonstrator
Fabrication of DMR engine model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of 3D nozzle model to be integrated into Small Scale Flight Demonstrator
Fabrication of 3D nozzle model(s) to be integrated into Small Scale Flight Demonstrator(s)

Design of Intake Ramps Actuators to be integrated into Small Scale Flight Demonstrator
Fabrication of Intake Ramps Actuators to be integrated into Small Scale Flight Demonstrator(s)
Design of high-speed intake model to be integrated into Small Scale Flight Demonstrator
Fabrication of high-speed intake model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of Engine Controls to be integrated into Small Scale Flight Demonstrator
Fabrication of Engine Controls to be integrated into Small Scale Flight Demonstrator(s)
Design of isolator model to be integrated into Small Scale Flight Demonstrator
Fabrication of isolator model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of low-speed intake model to be integrated into Small Scale Flight Demonstrator
Fabrication of low-speed intake model(s) to be integrated into Small Scale Flight Demonstrator(s)
Design of ATR pump model to be integrated into Small Scale Flight Demonstrator
Fabrication of ATR pump model(s) to be integrated into Small Scale Flight Demonstrator(s)
Flight test(s) of Small-Scale Flight Demonstrator(s)
Design of DMR engine model to be integrated into Mid Scale Flight Demonstrator
Fabrication of DMR engine model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of 3D nozzle model to be integrated into Mid Scale Flight Demonstrator
Fabrication of 3D nozzle model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of ATR core engine model to be integrated into Mid Scale Flight Demonstrator
Fabrication of ATR core engine model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of ATR Exhaust Duct model to be integrated into Mid Scale Flight Demonstrator
Fabrication of ATR Exhaust Duct model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of ATR Variable Throat model to be integrated into Mid Scale Flight Demonstrator
Fabrication of ATR Variable Throat model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of Intake Ramps Actuators to be integrated into Mid Scale Flight Demonstrator

Fabrication of Intake Ramps Actuators to be integrated into Mid Scale Flight Demonstrator(s)
Design of Variable Throat Actuators to be integrated into Mid Scale Flight Demonstrator
Fabrication of Variable Throat Actuators to be integrated into Mid Scale Flight Demonstrator(s)
Design of high-speed intake model to be integrated into Mid Scale Flight Demonstrator
Fabrication of high-speed intake model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of Engine Controls to be integrated into Mid Scale Flight Demonstrator
Fabrication of Engine Controls to be integrated into Mid Scale Flight Demonstrator(s)
Design of isolator model to be integrated into Mid Scale Flight Demonstrator
Fabrication of isolator model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of low-speed intake model to be integrated into Mid Scale Flight Demonstrator
Fabrication of low-speed intake model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Design of ATR pump model to be integrated into Mid Scale Flight Demonstrator
Fabrication of ATR pump model(s) to be integrated into Mid Scale Flight Demonstrator(s)
Flight test(s) of Mid Scale Flight Demonstrator(s)
Design of DMR engine model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of DMR engine model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of 3D nozzle model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of 3D nozzle model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of ATR core engine model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of ATR core engine model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of ATR Exhaust Duct model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of ATR Exhaust Duct model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of ATR Variable Throat model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of ATR Variable Throat model(s) to be integrated into Near Full Scale Flight Demonstrator(s)

Design of Intake Ramps Actuators to be integrated into Near Full Scale Flight Demonstrator
Fabrication of Intake Ramps Actuators to be integrated into Near Full Scale Flight Demonstrator(s)
Design of Variable Throat Actuators to be integrated into Near Full Scale Flight Demonstrator
Fabrication of Variable Throat Actuators to be integrated into Near Full Scale Flight Demonstrator(s)
Design of high-speed intake model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of high-speed intake model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of Engine Controls to be integrated into Near Full Scale Flight Demonstrator
Fabrication of Engine Controls to be integrated into Near Full Scale Flight Demonstrator(s)
Design of isolator model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of isolator model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of low-speed intake model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of low-speed intake model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of 2D nozzle model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of 2D nozzle model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Design of ATR pump model to be integrated into Near Full Scale Flight Demonstrator
Fabrication of ATR pump model(s) to be integrated into Near Full Scale Flight Demonstrator(s)
Flight test(s) of Near Full Scale Flight Demonstrator(s)
STRATOFLY MR3 Mission(s)

7.6 NASA RMAT (Ebeling, 1993a)

This Section summarizes the logic suggested by (Ebeling, 1993a) to calculate vehicle Reliability (Figure 137).

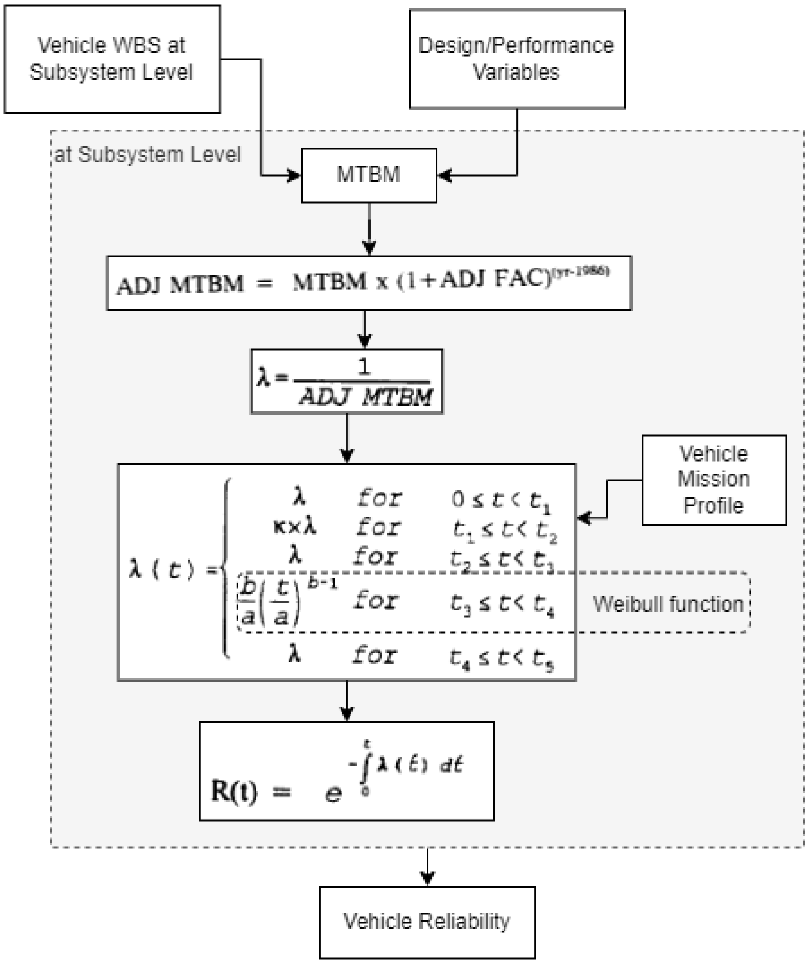


Figure 137: NASA RMAT Graphical Overview

Starting from the Mean Time Between Maintenance (MTBM), it is defined as "*the length of time in flying hours between maintenance actions on a particular subsystem or component*" (Ebeling, 1993a). As highlighted in Figure 137, MTBM estimation is performed in RMAT at subsystem level basing on a well-defined Work Breakdown Structure (WBS). Going back to MTBM assessment, it can be performed at subsystem level (basing on the PBS just discussed) by means of dedicated parametric equations. The latter, obtained by (Ebeling, 1993a) through regression analysis of military aircraft MTBM data, are function of vehicle design characteristics such as dry weight and wingspan. In addition, (Ebeling, 1993a) reports Space Shuttle Orbiter MTBM data which can be used alternatively to the MTBM equations. The MTBM calculation allows to estimate the reliability of the whole vehicle. Notably, the MTBM is turned into an Adjusted (ADJ) MBTM to take into account the technological improvement achieved in the expected development year (yr) with respect the baseline year which MTBM equations are referred to (i.e., 1986). At this purpose, a proper adjustment factor (ADJ) is introduced in order to model the envisaged increase in MTBM. ADJ MBTM is used to calculate a constant failure rate (λ) which is then further adjusted to consider the effect on failure rate due to the space environment encountered during flight. This is performed by assuming a variation in failure rate for each subsystem based on the generic mission profile in Figure 138. Notably, the failure rate is expected to rise during launch as a result of the increased vibration and stresses, whilst it decreases in orbit following a Weibull failure rate function. Please, notice that in Figure 137 κ is called launch factor, whilst a and b are the Weibull scale and shape parameters ($a > 0$ and $0 < b < 1$). Then, by assuming an exponential reliability function, the reliability of each subsystem at mission completion (i.e., t_5 in the generic mission profile) can be assessed and vehicle reliability is computed by multiplying subsystems reliabilities.

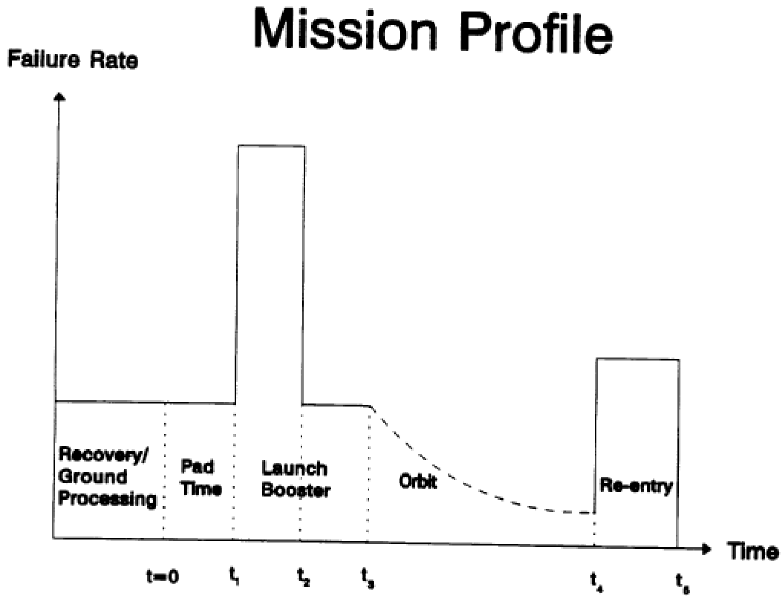


Figure 138: Mission Profile from NASA RMAT (Ebeling, 1993b)

References

Andrews, E. H. (1994). *NASA's Hypersonic Research Engine Project - A Review*.

Andrews, J. (2000). RLV design issues for future commercial space applications. *Space 2000 Conference and Exposition*.

Andrews, J., & Andrews, D. (2000). Low cost options for 2nd and 3rd generation reusable launch vehicles. *36th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, *July*. https://doi.org/10.2514/6.2000-3824

Approach and Landing Test Evaluation Team. (1978). *Space Shuttle Orbiter Approach and Landing Test Final Evaluation Report* (Issue February). http://www.klabs.org/DEI/References/general/alt_final_report.pdf

ARINC Research Corporation. (1971). *Engineering Design Handbook, System Analysis and Cost-effectiveness*. https://play.google.com/books/reader?id=LCguAAAAYAAJ&pg=GBS.RA1-SA2-PA74&hl=it&printsec=frontcover

ATA (Air Transport Association of America). (1957). *Standard Method of Estimating Direct Operating Costs of Transport Airplanes*.

Augenstein, B. W., & Harris, E. D. (1993). *The National Aerospace Plane (NASP): Development Issues for the Follow-on Vehicle*.

Balesdent, M. (2011). *Multidisciplinary Design Optimization of Launch Vehicles* (Issue May). Ecole Centrale de Nantes (ECN).

Berry, W. (1993). *Reusable Launchers* [Cranfield Institute of Technology]. https://dspace.lib.cranfield.ac.uk/bitstream/handle/1826/3902/W_Berry_Thesis_1993.pdf?sequence=1&isAllowed=y

Bilardo, V. J., Curran, F. M., Hunt, J. L., Lovell, N. T., Maggio, G., Wilhite, A. W., & Mckinney, L. E. (2003). The Benefits of Hypersonic Airbreathing Launch Systems for Access to Space. *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference*, *July*, 1–14.

Bilbro, J. W. (2008). Using the Advancement Degree of Difficulty (AD2) as an input to Risk Management. *Multi-Dimensional Assessment of Technology Maturity Technology Maturity Conference*.

Blanchard, & Fabrycky. (2015). *Systems Engineering and Analysis* (Fifth Edit). Pearson.

Blanvillain, E., & Gallic, G. (2015). HIKARI : Paving the Way towards high speed air transport. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*.

Blue Origin. (2022a). *New Glenn*. 2022. https://www.blueorigin.com/new-glenn/

Blue Origin. (2022b). *New Shepard*. 2022. https://www.blueorigin.com/new-shepard/

Bonnal, C., & Caporicci, M. (2000). Future reusable launch vehicles in Europe : the FLTP (Future Launchers Technologies Programme). *Acta Astronautica*, *47*.

Boone, T. R., & Miller, D. P. (2016). Capability and Cost-Effectiveness of Launch Vehicles. *New Space*, *4*(3), 168–189. https://doi.org/10.1089/space.2016.0011

Booz-Allen & Hamilton. (1967). *Supersonic transport financial planning study*.

Borromee, J., & Thevenot, D. (1986). HM 60 Vulcain- Ariane V main engine. *37th IAF International Astronautical Congress*.

Bowcutt, K. (2003). Hypersonic Technology Status and Development Roadmap. *Presentation to AIAA HyTASP Program Committee*. https://engineering.purdue.edu/~aae519/hypersonics-news/TFAB HyTASP-dec03.pdf

Bowcutt, K., Gonda, M., Hollowell, S., & Ralston, T. (2002). Performance, operational and economic drivers of reusable launch vehicles. *38th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*.

Brevault, L., Balesdent, M., Wuilbercq, R., Subra, N., Bonnal, C., Dodds, M., Taylor, N., Varvill, R., Wuilbercq, R., & Oriol, S. (2020). Conceptual design of a Two-Stage-To-Orbit vehicle using SABRE engines. *8th European Conference for Aeronautics and Aerospace Sciences (EUCASS)*, *11*, 8440. https://doi.org/10.13009/EUCASS2019-454

Browder, B., & Newman, D. (2019). How to build a spaceport: Analyzing spaceport feasibility via financial analysis. *Proceedings of the International Astronautical Congress, IAC*.

Bryson, J. M. (2004). What to do When Stakeholders Matter, A Guide to

Stakeholder Identification and Analysis Techniques. *Public Management Review*, *6*(1), 21–53.

Burns, B. R. A. (1990). HOTOL space transport for the twenty-first century. *Proceedings of the Institution of Mechanical Engineers, Part G: Journal of Aerospace Engineering*, *204*(2), 101–110. https://doi.org/10.1243/PIME_PROC_1990_204_216_02

Carvalho, M. M., Fleury, A., & Lopes, A. P. (2013). An overview of the literature on technology roadmapping (TRM): Contributions and trends. *Technological Forecasting and Social Change*, *80*(7), 1418–1437. https://doi.org/10.1016/J.TECHFORE.2012.11.008

Chase, R. L. (1978). *Earth-to-Orbit Reusable Launch Vehicles*.

Chase, R. L. (2009). The Quest for a Robust, Responsive, Reliable, Efficient And Low Cost Space Access Capability. *16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference*, 1–22.

Clegg, W. B., & Janik, K. D. (1967). Costing the Aerospace Transporter. *Spaceflight*, *9*(4), 130–140.

Cook, S., & Hueter, U. (2003). NASA's integrated space transportation plan - 3rd generation reusable launch vehicle technology update. *Acta Astronautica*, *53*(4–10), 719–728. https://doi.org/10.1016/S0094-5765(03)00113-9

Cotterman, H., Forsberg, K., & Mooz, H. (2005). *Visualizing project management: models and frameworks for mastering complex systems*. John Wiley & Sons.

Cresto Aleina, S. (2018). *Design methodologies for space systems in a System of Systems (SoS) architecture*.

Cresto Aleina, S., Fusaro, R., Viola, N., Longo, J., & Saccoccia, G. (2017). Technology roadmaps derivation methodology for European hypersonic and re-entry space transportation systems. *21st AIAA International Space Planes and Hypersonics Technologies Conference, Hypersonics 2017*, 1–16. https://doi.org/10.2514/6.2017-2345

Cresto Aleina, S., Fusaro, R., Viola, N., Rimani, J., Longo, J., & Saccoccia, G. (2017). Comprehensive methodology for technology roadmaps generation and update for the European Hypersonic and Re-entry space transportation scenario. *Proceedings of the International Astronautical Congress, IAC*, *3*, 1446–1455.

Cresto Aleina, S., Levrino, L., Viola, N., Fusaro, R., & Saccoccia, G. (2015). The importance of technology roadmaps for a successful future in space exploration. *9th IAA Symposium on the Future of Space Exploration*.

Cresto Aleina, S., Viola, N., Fusaro, R., Longo, J., & Saccoccia, G. (2018). Basis for a methodology for roadmaps generation for hypersonic and re-entry space transportation systems. *Technological Forecasting and Social Change*, *128*(April), 208–225. https://doi.org/10.1016/j.techfore.2017.12.004

Cresto Aleina, S., Viola, N., Fusaro, R., & Saccoccia, G. (2016). Effective methodology to derive strategic decisions from ESA exploration technology roadmaps. *Acta Astronautica*, *126*, 316–324. https://doi.org/10.1016/j.actaastro.2016.05.012

Cresto Aleina, S., Viola, N., Fusaro, R., & Saccoccia, G. (2017). Approach to technology prioritization in support of moon initiatives in the framework of ESA exploration technology roadmaps. *Acta Astronautica*, *139*, 42–53. https://doi.org/10.1016/J.ACTAASTRO.2017.06.029

Cresto Aleina, S., Viola, N., Fusaro, R., Saccoccia, G., & Vercella, V. (2019). Using the ESA exploration technology roadmaps in support of new mission concepts and technology prioritization. *Acta Astronautica*, *154*, 170–176. https://doi.org/10.1016/j.actaastro.2018.04.035

Czysz, P., & Vandenkerckhovet, J. (2001). Transatmospheric Launcher Sizing. In *Scramjet Propulsion* (pp. 979–1103). https://doi.org/10.2514/5.9781600866609.0979.1103

Davis, P., Bond, A., & Varvill, R. (1999). The SKYLON Spaceplane. *IEE Colloquium (Digest)*, *129*, 13–18.

Davis, P., Hempsell, M., & Varvill, R. (2015). Progress on SKYLON and SABRE. *66th International Astronautical Congress*.

Deneu, F., Malassigne, M., & Baiocco, P. (2005). Promising solutions for fully reusable two-stage-to-orbit. *Acta Astronautica*, *56*, 729–736. https://doi.org/10.1016/j.actaastro.2004.11.003

DoD (Department of Defense). (2001). *Systems Engineering Fundamentals Guide*. https://doi.org/10.1016/j.cmpb.2010.05.002

Dorrington, G. (1990). Comparisons of rocket and air-breathing vehicle concepts for earth-to-orbit transportarion. *AIAA/SAE/ASME/ASEE 26th Joint Propulsion Conference*. https://doi.org/10.2514/6.1990-2702

Dreyer, L., Bjelde, B., Doud, D., & Lord, K. (2011). SpaceX - Continuing to Drive Launch Costs Down and launch Opportunities Up for the Small Sat Community. *25th Annual AIAA/USU Conference on Small Sateliites*.

Dreyfuss, D. (1966). The economic impact of reusable orbital transports on the cost of planned manned space programs, 1970-1999. *AIAAA 3rd Annual Meeting*. https://doi.org/https://doi.org/10.2514/6.1966-862

Dujarric, C., Caporicci, M., Sacher, P., & Kuczera, H. (1997). Conceptual Studies and Technology Requirements for a New Generation of European Launchers. *Acta Astronautica*, *41*(98), 219–228.

Ebeling, C. (1993a). *Enhanced methods for determining operational capabilities and support costs of proposed space systems*.

Ebeling, C. (1993b). *Life cycle cost modeling of conceptual space vehicles.* https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19940018856.pdf

Ebeling, C. (2003). *Reliability and Maintainability Analysis Tool (RMAT) Training*.

ECSS (European Cooperation for Space Standardization). (2004). *Space engineering - Systems Engineering Part 1: Requirements and process*.

ECSS (European Cooperation for Space Standardization). (2017). *Technology readiness level (TRL) guidelines*.

Erbland, P. J. (2004). *Current and Near-Term RLV / Hypersonic Vehicle Programs*.

ESA-ESTEC (European Space Agency-European Space Research and Technology Centre). (2011). *ESA generic product tree*. https://www.google.com/url?sa=t&rct=j&q=&esrc=s&source=web&cd=&cad=rja&uact=8&ved=2ahUKEwj55e2i8ZHwAhWH-aQKHZzoDdYQFjAAegQIAxAD&url=http%3A%2F%2Femits.sso.esa.int%2Femits-doc%2Fe_support%2FESA_Generic_Product_Tree_June_2011.pdf&usg=AOvVaw0vjSVZazyuQkhoEMV

ESA. (2011). *IXV*. https://www.esa.int/ESA_Multimedia/Images/2011/12/IXV

ESA. (2015). ESA 's TRP and GSTP Technology Programmes. *REACH Workshop*. https://indico.esa.int/event/81/attachments/2607/3018/TRP__GSTP_Presentation_REACH_Workshop_22_April_2015.pdf

ESA. (2020a). ESA Technology Tree. In K. Fletcher (Ed.), *ESA Technology Tree, version 4.0 (ESA STM-277 3rd ed., April 2020)*. ESA Communications.

ESA. (2020b). *European Space Technology Master Plan (ESTMP)*.

ESA. (2021). *Test tanks fuelled for ESA's Themis reusable first stage*. https://www.esa.int/Enabling_Support/Space_Transportation/Future_space_transportation/Test_tanks_fuelled_for_ESA_s_Themis_reusable_first_stage

ESA. (2022). *FLPP preparing for Europe's next-generation launcher*. https://www.esa.int/Enabling_Support/Space_Transportation/New_Technologies/FLPP_preparing_for_Europe_s_next-generation_launcher

Favaloro, N., Pezzella, G., Carandente, V., Scigliano, R., Cicala, M., Morani, G., & Steelant, J. (2015). Design analysis of the high-speed experimental flight test vehicle HEXAFLY-international. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2015*, *July*. https://doi.org/10.2514/6.2015-3607

Ferretto, D. (2020). *Innovative Model Based Systems Engineering approach for the design of hypersonic transportation systems*.

Feustel-Buechel, J., & Wamsteker, W. (1990). ESA's Space Transportation Programme. *International Astronomical Union Colloquium*, *123*, 333–338. https://doi.org/https://doi.org/10.1017/S0252921100077241

Freeman, D. C., & Talay, T. A. (1996). Reusable Launch Vehicle Technology Program. *47th International Astronautical Congress*.

Freeman, D. C., Talay, T. A., & Austin, R. E. (1997). Reusable launch vehicle technology program. *Acta Astronautica*, *41*(11), 777–790. https://doi.org/10.1016/S0094-5765(97)00197-5

Freeman, D. C., Talay, T. A., Stanley, D. O., & Wilhite, A. W. (1995). Design options for advanced manned launch systems (AMLS). *Journal of Spacecraft and Rockets*, *32*(2), 241–249. https://doi.org/10.2514/6.1990-3816

Fusaro, R., Aleina, S. C., Viola, N., Longo, J., & Saccoccia, G. (2017). Database on Hypersonic Transportation Systems : a versatile support for the Technology Roadmap generation and Conceptual Design Activities. *21st AIAA International Space Planes and Hypersonics Technologies Conference*. https://doi.org/10.2514/6.2017-2440

Fusaro, R., Vercella, V., Ferretto, D., Viola, N., & Steelant, J. (2020). Economic and environmental sustainability of liquid hydrogen fuel for hypersonic transportation systems. *CEAS Space Journal*, *12*(3), 441–462. https://doi.org/10.1007/s12567-020-00311-x

Fusaro, R., Viola, N., Ferretto, D., Vercella, V., Fernandez Villace, V., & Steelant, J. (2020). Life cycle cost estimation for high-speed transportation systems. *CEAS Space Journal*, *12*(2), 213–233. https://doi.org/10.1007/s12567-019-00291-7

Fusaro, R., Viola, N., Ferretto, D., Vercella, V., & Steelant, J. (2020). Life-cycle cost estimation for high-speed vehicles: From engineers' to airlines' perspective. *AIAA AVIATION 2020 FORUM*, *1 PartF*. https://doi.org/10.2514/6.2020-2860

Futron. (2005). *Feasibility Study of a Florida Commercial Spaceport*.

Gaubatz, W., Schmidt, M., & Smiljanic, R. (1996). Translating SSTO system operability and supportability requirements into measures of system effectiveness. *Space Programs and Technologies Conference*.

Geschka, H., & Hahnenwald, H. (2013). Scenario-Based Exploratory Technology Roadmaps - A Method for the Exploration of Technical Trends. In M. Moehrle, R. Isenmann, & R. Phaal (Eds.), *Technology Roadmapping for Strategy and Innovation* (pp. 123–136). Springer, Berlin, Heidelberg. https://doi.org/https://doi.org/10.1007/978-3-642-33923-3_8

Goehlich, R. A., & Koelle, H. . (2002). Cost Estimation of the NAL Spaceplane (Modeling of a Vehicle Fleet Life-Cycle). *IAF Abstracts, 34th COSPAR Scientific Assembly*.

Gregory, T., Bowles, J., & Ardema, M. (1994). Two stage to orbit airbreathing and rocket system for low risk, affordable access to space. *SAE Technical Papers*, *412*. https://doi.org/10.4271/941168

Gregory, T., Williams, L. J., & Wilcox, D. E. (1971). Airbreathing launch vehicle for earth orbit shuttle-performance and operation. *Journal of Aircraft*, *8*(9), 724–731. https://doi.org/10.2514/3.59163

Hammond, W. (1999). Space Transportation: A Systems Approach to Analysis and Design. In *Space Transportation: A Systems Approach to Analysis and Design*. https://doi.org/10.2514/4.862380

Hammond, W. (2001). Design Methodologies for Space Transportation Systems. In *Design Methodologies for Space Transportation Systems*. https://doi.org/10.2514/4.861734

Heald, D. A. (1995). Should Commercial Launch Vehicles Be Reusable? *31st AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*.

Hempsell, M. (2013). Progress on SKYLON and SABRE. *Proceedings of the International Astronautical Congress, IAC*, *11*.

Hempsell, M., & Longstaff, R. (2010). The Requirement Generation Process for the SKYLON Launch System. *JBIS - Journal of the British Interplanetary Society*, *63*(4), 122–128.

Hempsell, M., Longstaff, R., & Bond, A. (2009). Skylon Users' Manual. *Reaction Engines Ltd.*, *1.1*, 44.

Hirshorn, S. R., Voss, L. D., & Bromley, L. K. (2017). *NASA systems engineering handbook*. https://www.nasa.gov/seh/index.html

Humphries Sr, W., Blair, J. C., Ryan, R. S., & Schutzenhofer, L. a. (2001). Launch Vehicle Design Process: Characterization, Technical Integration, and Lessons Learned. In *Technical Memorandum* (Issue May). papers2://publication/uuid/59C388F4-87C6-45AF-9B4B-DA971DFE2726

Hunt, J. L., Pegg, R. J., & Petley, D. H. (1999). Airbreathing hypersonic vision-operational-vehicles design matrix. *World Aviation Conference*. https://doi.org/10.4271/1999-01-5515

Hunt, J. L., & Wagner, A. (1997). Systems Challenges for Hypersonic Vehicles. *AGARD Conference*.

INCOSE. (2015). *SYSTEMS ENGINEERING HANDBOOK, A GUIDE FOR SYSTEM LIFE CYCLE PROCESSES AND ACTIVITIES* (D. D. Walden, G. J. Roedler, K. J. Forsberg, H. R. Douglas, & T. M. Shortell (eds.); Fourth Edi). Wiley.

ISECG. (2018). *The Global Exploration Roadmap*.

ISPA. (2008). *Parametric Estimating Handbook* (4th Editio, Issue April). ISPA/SCEA Joint Office. http://www.ispacost.org/PEIWeb/cover.htm

Jenkins, D. R., Landis, T., & Miller, J. (2003). *American X-Vehicles* (Issue 31).

Johnson, D. B., & Robinson, J. S. (2005). X-43D conceptual design and feasibility study. *A Collection of Technical Papers - 13th AIAA/CIRA International Space Planes and Hypersonic Systems and Technologies Conference*, *3*, 1902–1913. https://doi.org/10.2514/6.2005-3416

Jones, H. W. (2018). The Recent Large Reduction in Space Launch Cost. *48th International Conference on Environmental Systems*, *July 2018*, 81. https://ttu-ir.tdl.org/handle/2346/74082

Kanama, D. (2013). Development of Technology Foresight: Integration of Technology Roadmapping and the Delphi Method. In M. Moehrle, R. Isenmann, & R. Phaal (Eds.), *Technology Roadmapping for Strategy and Innovation* (pp. 151–171). Springer, Berlin, Heidelberg. https://doi.org/https://doi.org/10.1007/978-3-642-33923-3_10

Kian Manaesh Rad, E., & Sun, M. (2014). Taxonomy of project complexity indicators in energy megaprojects. *International Scientific Conference People, Buildings and Environment*. https://pureapps2.hw.ac.uk/portal/en/publications/taxonomy-of-project-complexity-indicators-in-energy-megaprojects(8b5ce182-eb87-46c1-925e-16a1c2be105c).html

Kobayashi, H., Sato, T., Taguchi, H., Fujita, K., Sawai, S., Tanatsugu, N., Kojima, T., Okai, K., & Maru, Y. (2004). Development status of Mach 6 turbojet engine in JAXA. *International Astronautical Federation - 55th International Astronautical Congress 2004*, *11*, 7129–7135. https://doi.org/10.2514/6.iac-04-s.5.04

Koelle, D. E. (1989). Launch cost analyses for reusable space transportation systems (Sänger II). *Acta Astronautica*, *19*(2), 191–197. https://doi.org/10.1016/0094-5765(89)90101-X

Koelle, D. E. (1991). *TRANSCOST: statistical-analytical model for cost estimation and economic optimization of space transportation systems*.

Koelle, D. E. (2013). *Handbook of cost engineering and design of space transportation systems* (Revision 4). TRANSCOST Systems, Ottobrunn (DE).

Koelle, D. E. (1988). Sanger II, a Hypersonic Flight and Space Transportation System. *16th ICAS Congress*, 687–693.

Koelle, D. E., & Kuczera, H. (1989). Sänger II, an advanced launcher system for Europe. *Acta Astronautica*, *19*(1), 63–72. https://doi.org/10.1016/0094-5765(89)90009-X

Koelle, H. H., & Huber, W. G. (1961). Economy of Space Flight. In *Handbook of astronautical engineering*.

Kojima, T., Taguchi, H., Kobayashi, H., & Sato, T. (2015). Starting characteristics of hypersonic pre-cooled turbojet inlet. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2015*, 3595. https://doi.org/10.2514/6.2015-3595

Kokan, T., Olds, J., Hutchinson, V., & Reeves, J. (2004). Aztec: A TSTO hypersonic vehicle concept utilizing TBCC and HEDM propulsion technologies. *40th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, 3728.

Korthals-Altes, S. W. (1986). *The aerospace plane: technological feasibility and policy implicatons* [Massachusetts Institute of Technology]. https://dspace.mit.edu/bitstream/handle/1721.1/15033/15338304-MIT.pdf?sequence=2

Kuczera, H., & Johnson, C. (1999). *The Major Results of the FESTIP System Study*. *c*. https://doi.org/10.2514/6.1999-6001

Lane, J. (2007). Design Processes and Criteria for the X-51A Flight Vehicle Airframe. *UAV Design Processes / Design Criteria for Structures*, *2007*, 1–14.

Longstaff, R., & Bond, A. (2011). The SKYLON Project. *17th AIAA International Space Planes and Hypersonic Systems and Technologies Conference 2011*, *2*, 1–10. https://doi.org/10.2514/6.2011-2244

Love, J. E., & Young, W. R. (1966). *Survey of Operation and Cost Experience of the X-15 Airplane as a Reusable Space Vehicle*.

Machin, R., Stein, J., & Muratore, J. (1999). An overview of the x-38 prototype crew return vehicle development and test program. *15th Aerodynamic Decelerator Systems Technology Conference*, *c*, 20–37. https://doi.org/10.2514/6.1999-1703

Mandell, H. C. (1983). *ASSESSMENT OF SPACE SHUTTLE PROGRAM COST ESTIMATING METHODS*. University of Colorado.

Mankins, J. C. (2009). Technology readiness assessments : A retrospective. *Acta Astronautica*, *65*(9–10), 1216–1223. https://doi.org/10.1016/j.actaastro.2009.03.058

Melle, K., Rappillard, S., & Demaison, V. (2019). Development and Test Firing of a One-Piece Additively Manufactured Liquid Rocket Engine. *Ecole Supérieure Des Techniques Aéronautiques et de La Construction Automobile*, 1. https://www.pegasus-europe.org/wp-content/uploads/Student_Conference/papers/2019/Paper_Melle_Rap.pdf

Moehrle, M. G. (2013). TRIZ-based technology roadmapping. In M. Moehrle, R. Isenmann, & R. Phaal (Eds.), *Technology Roadmapping for Strategy and Innovation: Charting the Route to Success* (pp. 137–150). Springer, Berlin, Heidelberg. https://doi.org/10.1007/978-3-642-33923-3_9

Moehrle, M. G., Isenmann, R., & Phaal, R. (2013). Technology Roadmapping for Strategy and Innovation. In *Technology Roadmapping for Strategy and Innovation*. https://doi.org/10.1007/978-3-642-33923-3

Moses, P. L. (2003). X-43C Flight Demonstrator Project Overview. *Joint JANNAF Subcommittee Meeting: 27th Airbreathing*.

Mroczek, A. J. (2014). *Determining The Cost Effectiveness Of Nano-Satellites*. Naval Postgraduate School, Monterey (CA).

Musk, E. (2017a). Becoming a Multiplanet Species (Presentation). *International Astronautical Federation - 68th International Astronautical Congress 2017*. https://www.spacex.com/media/making_life_multiplanetary-2017.pdf

Musk, E. (2017b). Making Humans a Multi-Planetary Species. *New Space*, *5*(2), 46–61. https://doi.org/10.1089/space.2017.29009.emu

Musk, E. (2017c). Making Life Multiplanetary. *68th International Astronautical Congress*. https://www.spacex.com/media/making_life_multiplanetary_transcript_2017.pdf

NASA. (1994). *Access to Space Study Summary Report*.

NASA. (2001). *X-37 Demonstrator to Test Future Launch Technologies in Orbit and Reentry Environments*. https://www.nasa.gov/centers/marshall/news/background/facts/x37.html

NASA. (2009). *Past Projects: X-43A Hypersonic Flight Program*. https://www.nasa.gov/centers/dryden/history/pastprojects/HyperX/index.html

NASA. (2010). *X-51A Makes Longest Scramjet Flight*. https://www.nasa.gov/topics/aeronautics/features/X-51A.html

NASA. (2012). *The Delta Clipper Experimental: Flight Testing Archive*. https://www.hq.nasa.gov/pao/History/x-33/dc-xa.htm

NASA. (2014). *NASA Armstrong Fact Sheet: X-33*. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-067-

DFRC.html

NASA. (2015). *2015 NASA Technology Roadmaps*. https://www.nasa.gov/sites/default/files/atoms/files/2015_nasa_technology_roadmaps_ta_0_introduction_crosscutting_index.pdf

NASA. (2016a). *Expanded Guidance for NASA Systems Engineering: Crosscuting Topics, Special Tools and Appendices* (Vol. 2, Issue March 2016). https://ntrs.nasa.gov/search.jsp?R=20170007238

NASA. (2016b). *Orbital Sciences Corporation X-34*. https://www.nasa.gov/centers/armstrong/history/experimenatl_aircraft/X-34.html

NASA. (2017). *NASA Armstrong Fact Sheet: B-52B "Mothership" Launch Aircraft*. https://www.nasa.gov/centers/armstrong/news/FactSheets/FS-005-DFRC.html

NASA. (2020a). *NASA and SpaceX Complete Certification of First Human-Rated Commercial Space System*. https://www.nasa.gov/feature/nasa-and-spacex-complete-certification-of-first-human-rated-commercial-space-system

NASA. (2020b). *NASA Technology Taxonomy* (Issue July 2015).

NASA. (2022a). *Boeing X-40A*. 2016. https://www.nasa.gov/centers/armstrong/history/experimental_aircraft/X-40A.html

NASA. (2022b). *NASA TechPort*. https://techport.nasa.gov/home

Nau, R. A. (1967). A comparison of fixed wing reusable booster concepts. *SAE Technical Papers*. https://doi.org/10.4271/670384

Neumann, R. D., Patterson, J. L., & Sliski, N. J. (1978). Aerodynamic Heating to the Hypersonic Research Aircraft X-24C. *AIAA 16th Aerospace Sciences Meeting*.

Nix, M. B. (2005). *Development and application of a model for the analysis of trades between space launch system operation and acquisition costs*.

Noor, A., & Venneri, S. (1997). Future Aeronautical and Space Systems. In *Future Aeronautical and Space Systems*. https://doi.org/10.2514/4.866449

Northrop Grumman. (2022). *Northrop Grumman Successfully Launches Pegasus XL Rocket for the US Space Force*.

https://www.northropgrumman.com/space/pegasus-rocket/

Olds, J., Ledsinger, L., Bradford, J., Charania, A., McCormick, D., & Komar, D. (1999). Stargazer-A TSTO Bantam-X vehicle concept utilizing rocket-based combined-cycle propulsion. *9th International Space Planes and Hypersonic Systems and Technologies Conference*, 4888.

Parkinson, R. C. (1995). Cost sensitivity as a selection issue for future economic space transportation systems. *International Aerospace Planes and Hypersonics Technologies*, *April*. https://doi.org/10.2514/6.1995-6122

Parnell, G. S., & Trainor, T. E. (2009). Using the swing weight matrix to weight multiple objectives. *19th Annual International Symposium of the International Council on Systems Engineering, INCOSE 2009*, *1*, 283–298. https://doi.org/10.1002/j.2334-5837.2009.tb00949.x

Pecht, M. (2009). Product reliability, maintainability, and supportability handbook. In M. Pecht (Ed.), *Angewandte Chemie International Edition, 6(11), 951–952.* (Second Edi). CRC Press.

Petrick, I. J., & Echols, A. E. (2004). Technology roadmapping in review: A tool for making sustainable new product development decisions. *Technological Forecasting and Social Change*, *71*(1–2), 81–100. https://doi.org/10.1016/S0040-1625(03)00064-7

Phaal, R., Farrukh, C., & Probert, D. R. (2013). Fast-Start Roadmapping Workshop Approaches. In M. Moehrle, R. Isenmann, & R. Phaal (Eds.), *Technology Roadmapping for Strategy and Innovation* (pp. 91–106). Springer, Berlin, Heidelberg. https://doi.org/https://doi.org/10.1007/978-3-642-33923-3_6

Purvis, B., Mao, Y., & Robinson, D. (2019). Three pillars of sustainability: in search of conceptual origins. *Sustainability Science*, *14*, 681–695. https://doi.org/10.1007/s11625-018-0627-5

REL (Reaction Engines Ltd.). (2009). *SKYLON Requirement Specification*.

REL (Reaction Engines Ltd.). (2022). *SABRE. The engine that changes everything*. https://reactionengines.co.uk/advanced-propulsion/sabre/

Repic, E. M., Olson, G. A., & Milliken, R. J. (1973). *A methodology for hypersonic transport technology planning*. https://ntrs.nasa.gov/api/citations/19730023221/downloads/19730023221.pdf

Root, M., & Fuller, G. (1963). Astro-An Available Economical Solution to the

High Cost of Space Flight. *AIAA Summer Meeting 1963*, 260. https://doi.org/https://doi.org/10.2514/6.1963-263

Roskam, J. (1990). Airplane Desing Part VIII. In Roskam Aviation and Engineering Corp. (Ed.), *Airplane Design*.

Rupert, K. F. (1961). Aero-Space Plane. *Joint Meeting of the Bumblebee Aerodynamic Composite Design and Propulsion Panels, Presentation*.

Saccoccia, G. (2012). Coordinated ESA initiatives on technologies for space exploration. *Global Space Exploration Conference*.

Saccoccia, G. (2014). ESA Coordination Activities on Space Exploration Technology Roadmaps. *IAA-SEC 2014–WA1493, International Space Exploration Forum*.

Sacher, P. W. (2010). *The Engineering Design of Engine / Airframe Integration for the SÄNGER Fully Reusable Space Transportation System*. https://apps.dtic.mil/sti/pdfs/ADA592434.pdf

Sammut-Bonnici, T., & Galea, D. (2015). PEST Analysis. In *Wiley Encyclopedia of Management*. https://doi.org/10.4324/9780429265617-9

Sato, T., Taguchi, H., Kobayashi, H., Kojima, T., Okai, K., Fujita, K., Masaki, D., Hongo, M., & Ohta, T. (2007). Development study of precooled-cycle hypersonic turbojet engine for flight demonstration. *Acta Astronautica*, *61*(1–6), 367–375. https://doi.org/10.1016/j.actaastro.2007.01.012

Sawai, S., Sato, T., Kobayashi, H., Tanatsugu, N., & Ohtsuka, H. (2003). Flight Test Plan for ATREX Engine Development. *12th AIAA International Space Planes and Hypersonic Systems and Technologies*, 7027.

Schuh, G., Wemhöner, H., & Orilski, S. (2013). Technological Overall Concepts for Future-Oriented Roadmapping. In *Technology Roadmapping for Strategy and Innovation* (pp. 107–121). Springer, Berlin, Heidelberg.

Seedhouse, E. (2015). Virgin Galactic: The first ten years. In *Virgin Galactic: The First Ten Years*. https://doi.org/10.1007/978-3-319-09262-1

Sippel, M. (2007). Introducing the SpaceLiner Vision. *7th International Symposium on Launcher Technologies*, 1–10.

Sippel, M., Stappert, S., & Koch, A. (2019). Assessment of multiple mission reusable launch vehicles. *Journal of Space Safety Engineering*, *6*(3), 165–180. https://doi.org/10.1016/j.jsse.2019.09.001

Sippel, M., Trivailo, O., Bussler, L., Lipp, S., Valluchi, C., Kaltenhäuser, S., & Molina, R. (2016). Evolution of the SpaceLiner towards a Reusable TSTO-Launcher. *Proceedings of the International Astronautical Congress, IAC*.

Snead, J. M. (2006). Achieving near-term, aircraft-like reusable space access. *Space 2006 Conference*, *2*(May), 797–841. https://doi.org/10.2514/6.2006-7283

Sninsky, R. (2020). *Standard Prices for Aerospace Energy Category Items*. https://www.dla.mil/Portals/104/Documents/Energy/Standard Prices/Aerospace Prices/E_2020Oct1AerospaceStandardPrices_200831.pdf?ver=2020-09-01-110258-683

Sorto-Ramos, E. E., Seyed-Alavi, K., & Chudoba, B. (2020). A parametric comparison of ssto and tsto space access vehicles concepts. *AIAA Scitech 2020 Forum*, *1 PartF*. https://doi.org/10.2514/6.2020-0549

SpaceX. (2020). *Starship User Guide* (Issue March). https://www.spacex.com/media/starship_users_guide_v1.pdf%0Ahttps://www.spacex.com/sites/spacex/files/starship_users_guide_v1.pdf

SpaceX. (2021). *Flight Test Starship SN15*. https://www.spacex.com/vehicles/starship/

SpaceX. (2022). *Starship*. https://www.spacex.com/vehicles/starship/

St Germain, B. D., Olds, J. R., McIntire, J., Nelson, D. K., Weglian, J. E., & Ledsinger, L. A. (2001). Starsaber : A Small Payload-Class TSTO Vehicle Concept Utilizing Rocket-Based Combined Cycle Propulsion. *37th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*.

Stanley, D. O., Wilhite, A. W., Englund, W. C., & Laube, J. R. (1992). Comparison of Single-Stage and Two-Stage Airbreathing Launch Vehicles. *Journal of Spacecraft and Rockets*, *29*(5), 735–740.

Steelant, J. (2008a). ATLLAS: Aero-Thermal loaded material investigations for high-speed vehicles. *15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, *April 2008*. https://doi.org/10.2514/6.2008-2582

Steelant, J. (2008b). LAPCAT : High-Speed Propulsion Technology. *Advances on Propulsion Technology for High-Speed Aircraft*, *12*(1), 1–38.

Steelant, J. (2009). Sustained hypersonic flight in Europe: Technology drivers for

LAPCAT II. *16th AIAA/DLR/DGLR International Space Planes and Hypersonic Systems and Technologies Conference*, *October 2009*. https://doi.org/10.2514/6.2009-7240

Steelant, J. (2011). European Activities on High Speed Vehicles : Feasibility Studies and Technological Challenges for Hypersonic Cruisers. *Proceedings of the 7th European Symposium on Aerothermodynamics for Space Vehicles (ESA SP-692)*, *2011*(May).

Steelant, J., & Langener, T. (2014). The LAPCAT-MR2 hypersonic cruiser concept. *29th Congress of the International Council of the Aeronautical Sciences, ICAS 2014*.

Steelant, J., Langener, T., Di Matteo, F., Hannemann, K., Riehmer, J., Kuhn, M., Dittert, C., Scheuerpflug, F., Jung, W., Marini, M., Pezzella, G., Cicala, M., & Serre, L. (2015). Conceptual design of the high-speed propelled experimental flight test vehicle HEXAFLY. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2015*, *July*. https://doi.org/10.2514/6.2015-3539

Steelant, J., Varvill, R., Defoort, S., Hannemann, K., & Marini, M. (2015). Achievements obtained for sustained hypersonic flight within the LAPCAT-II project. *20th AIAA International Space Planes and Hypersonic Systems and Technologies Conference, 2015*, *July*. https://doi.org/10.2514/6.2015-3677

Sziroczak, D., & Smith, H. (2016). A review of design issues specific to hypersonic flight vehicles. *Progress in Aerospace Sciences*, *84*, 1–28. https://doi.org/10.1016/j.paerosci.2016.04.001

Tang, M., & Chase, R. L. (2008). The quest for hypersonic flight with air-breathing propulsion. *15th AIAA International Space Planes and Hypersonic Systems and Technologies Conference*, *May*. https://doi.org/10.2514/6.2008-2546

Trivailo, O. (2015). *Innovative cost engineering approaches, analyses and methods applied to spaceliner-an advanced, hypersonic, suborbital spaceplane case-study*. https://titania.eng.monash.edu/pgrad-projects/OT_PhD_Thesis.pdf

Tumino, G., & Gerard, Y. (2006). *IXV: the Intermediate eXperimental Vehicle*.

Vacchi, M., Siligardi, C., Demaria, F., Cedillo-González, E. I., González-Sánchez, R., & Settembre-Blundo, D. (2021). Technological sustainability or sustainable technology? A multidimensional vision of sustainability in manufacturing. *Sustainability (Switzerland)*, *13*(17), 1–18. https://doi.org/10.3390/su13179942

Viola, N., Aleina, S. C., Fusaro, R., Saccoccia, G., & Longo, J. (2016). Technology roadmaps preparation for European hypersonic and re-entry space transportation systems. *Proceedings of the International Astronautical Congress, IAC*.

Viola, N., Corpino, S., Fioriti, M., & Stesina, F. (2012). Functional Analysis in Systems Engineering: Methodology and Applications. *Systems Engineering - Practice and Theory*. https://doi.org/10.5772/34556

Viola, N., Cresto Aleina, S., Fusaro, R., Vercella, V., & Saccoccia, G. (2018). Space systems engineering tools for technology roadmapping activities: TrIS, technology roadmapping strategy, and HyDaT, database on hypersonic transportation systems. *Proceedings of the International Astronautical Congress, IAC*.

Viola, N., Fusaro, R., Saracoglu, B., Schram, C., Grewe, V., Martinez, J., Marini, M., Hernandez, S., Lammers, K., Vincent, A., Hauglustaine, D., Liebhardt, B., Linke, F., & Fureby, C. (2021). Main Challenges and Goals of the H2020 STRATOFLY Project. *Aerotecnica Missili & Spazio*, *100*(2), 95–110. https://doi.org/10.1007/s42496-021-00082-6

Viola, N., Fusaro, R., & Vercella, V. (2022). Technology roadmapping methodology for future hypersonic transportation systems. *Acta Astronautica*, *195*(March), 430–444. https://doi.org/10.1016/j.actaastro.2022.03.038

Viola, N., Fusaro, R., Vercella, V., & Saccoccia, G. (2020). Technology RoadmappIng Strategy, TRIS: Methodology and tool for technology roadmaps for hypersonic and re-entry space transportation systems. *Acta Astronautica*, *170*, 609–622. https://doi.org/10.1016/j.actaastro.2020.01.037

Virgin Galactic. (2021a). *Virgin Galactic announces first fully crewed spaceflight*. https://www.virgin.com/about-virgin/latest/virgin-galactic-announces-first-fully-crewed-spaceflight

Virgin Galactic. (2021b). *Virgin Galactic Announces Fourth Quarter and Full Year 2020 Financial Results*. https://www.virgingalactic.com/news/virgin-galactic-announces-fourth-quarter-and-full-year-2020-financial

Voland, R. T., Huebner, L. D., & McClinton, C. R. (2006). X-43A Hypersonic vehicle technology development. *Acta Astronautica*, *59*(1–5), 181–191. https://doi.org/10.1016/j.actaastro.2006.02.021

Wallace, J., Olds, J., Charania, A. C., & Woodcock, G. (2003). A study of ARTS: A dual-fuel reusable launch vehicle with launch assist. *39th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*. https://doi.org/10.2514/6.2003-5269

Wertz, J. R., & Larson, W. J. (2005). *Space Mission Analysis and Design* (Third Edit). Kluwer Academic Publishers.

Willyard, C. H., & McClees, C. W. (1987). Motorola's Technology Roadmap Process. *Research Management*, *30*(5), 13–19. https://doi.org/10.1080/00345334.1987.11757057

WSEIAC. (1966). *Weapon System Effectiveness Industry Advisory Commitee (WSEIAC) Chairman's Final Report*.

Zandbergen, B. T. C. (2015). Simple mass and size estimation relationships of pump fed rocket engines for launch vehicle conceptual design. *6th European Conference for Aeronautics and Space Sciences (EUCASS)*. https://www.researchgate.net/publication/279711349